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SEISMIC RESPONSE ANALYSIS OF NUCLEAR ISLAND BUILDING CONSIDERING PILE-SOIL-STRUCTURE INTERACTION

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ABSTRACT

When the bearing capacity of soft soil site cannot meet the design requirement of a nuclear power plant (NPP), adoption of pile foundation is a good choice. However, the pile, soil and superstructure constitute a soil-structure interaction (SSI) system. The interaction among pile, soil and superstructure can affect the seismic response of the superstructure to some extent. To study this effect, two SSI analyses were performed based on preliminary pile foundation plan, taking a Chinese NPP on soft soil site as example. The only difference between two analyses is the existence of pile group. The analysis model consists of soil of a certain region, pile foundation and the nuclear island building. Artificial transmission boundary was set around the soil model. The location of input motion is at the bottom of soil model. LS-DYNA was selected for SSI analysis due to the large size of finite element model. It is observed from comparison results of two analyses that the existence of pile group doesn't affect the horizontal stiffness of the SSI system significantly, the frequency of the peak of horizontal in-structure response spectra (ISRS) didn't move apparently. However, the vertical stiffness of the SSI system has been affected significantly, the frequency of the peak of vertical ISRS moved apparently. This mainly due to that the horizontal stiffness of pile group is small if compared with that of the whole SSI system, while the contribution to the whole SSI system from the vertical stiffness of pile group is not negligible. The peak acceleration and zero-period acceleration (ZPA) were increased to some extent due to the existence of pile group. This probably because the vertical response was stimulated by high frequency energy component of the input motion due to the increase of vertical stiffness of whole SSI system.

INTRODUCTION

The analysis input parameters used in this paper mainly refer to the site specific parameters of a Chinese AP1000 project. The site of the project belongs to soft soil site. The foundation soil is silt, the bearing capacity characteristic value of which is 140kPa, and the shear wave velocity is 190m/s. According to the preliminary analysis result, the bearing capacity of the nature competent soil doesn't meet the requirement of standard design. Therefore, pile foundation scheme is selected with the consideration of safety and technical feasibility. In this scheme, end bearing piles with diameter of 1.5m are adopted. The length of the pile is about 42m including 2m embedded into the basalt layer under the soft soil layer. The total number of the pile is 212. The spacing between piles is about 4m×4m. The layout of the pile is shown in figure 1.

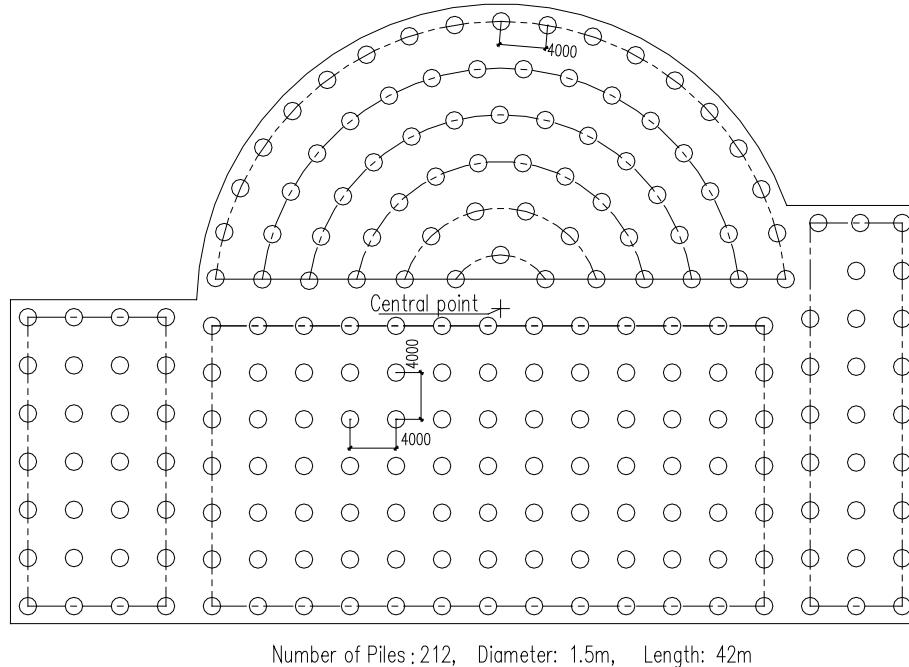


Figure 1. Layout of the pile group

The adoption of pile foundation changed not only the foundation type of standard design but also the dynamic characteristic of foundation soil. To study this effect on the seismic response of the superstructure from the change of foundation type, it is necessary to perform two independent analysis, one of which adopt nature competent soil (hereafter refer to undisturbed soil) as foundation soil and another adopt pile foundation. By comparing the seismic response from two analyses, some preliminary conclusion is drawn.

There is no mature experience related to the adoption of pile foundation on the design of nuclear power plant. Also, there are few public literatures on the design of pile foundation of nuclear power plants sitting on a soft soil site. Thus, the analysis in this paper has important significance for reference of design of nuclear power plant buildings with pile foundation.

ANLYSIS METHODOLOGY

Research Approach

Based on the target of the study, two analyses were performed:

- 1) Seismic SSI analysis with only undisturbed soil as foundation soil, the output of the analysis is the in-structure response spectra (ISRS) of the superstructure;
- 2) Seismic SSI analysis with undisturbed soil as foundation soil, but the foundation type of the superstructure is changed to pile foundation. The output of the analysis is the in-structure response spectra (ISRS) of the superstructure;

The effect on the seismic response of the superstructure from the change of foundation type was studied by comparing the seismic response from two analyses.

SSI Analysis Methodology

Generally, there are two methods of seismic SSI analysis, direct method and substructure method. The analysis in this paper belonged to direct method. The analysis finite element model (FE model) included

the models of the superstructure, soil and pile groups. The seismic response was obtained through one-step dynamic analysis.

In the analysis, a group of artificial transmitting boundaries were set around the soil model to avoid the reflection of the seismic wave at the boundary of soil. Figure 2 showed the FE model used in direct analysis, including the artificial transmitting boundaries.

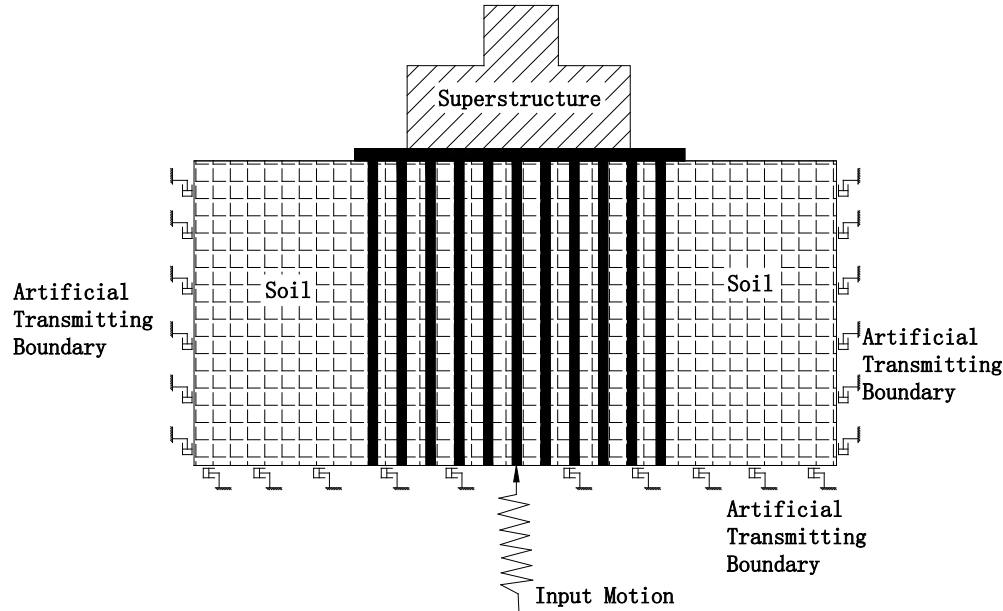


Figure 2. Finite element model with artificial transmitting boundary for direct method

According to the preliminary evaluation of the size of FE model, the number of nodes of the FE exceeds 500000. Therefore, software based on explicit dynamic analysis method, LS-DYNA, was used for SSI analysis.

Nonlinearity of Soil

In general, the strain of the soft soil is rather large under the action of earthquake, which leads to the decrease of the shear modulus of the soil and the increase of the damping. This is known as the nonlinearity of soil. A widely accepted method to consider this nonlinearity is equivalent linear method.

For the analysis of this paper, a self-developed program based on the equivalent linear theory was used. After 5 to 6 times iterations, the convergent shear modulus and damping value are determined and used in the subsequent SSI analysis in LS-DYNA.

Rayleigh Damping

Based on the calculation software, Rayleigh damping was adopted in SSI analysis. Figure 3 provides the equation of Rayleigh damping and its variation with the change of vibration frequency.

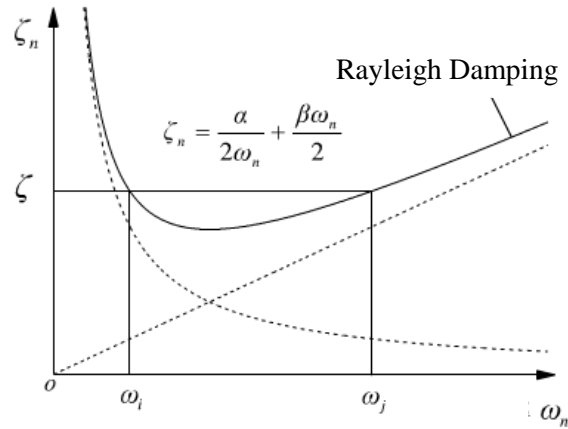


Figure 3. Rayleigh damping and its equation

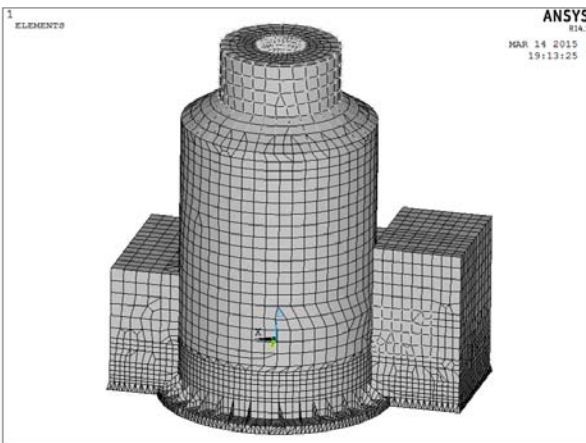
In the Rayleigh damping equation, α is mass proportionality coefficient and β is stiffness proportionality coefficient. To obtain α and β , two controlling frequencies shall be determined.

ANLYSIS INPUT

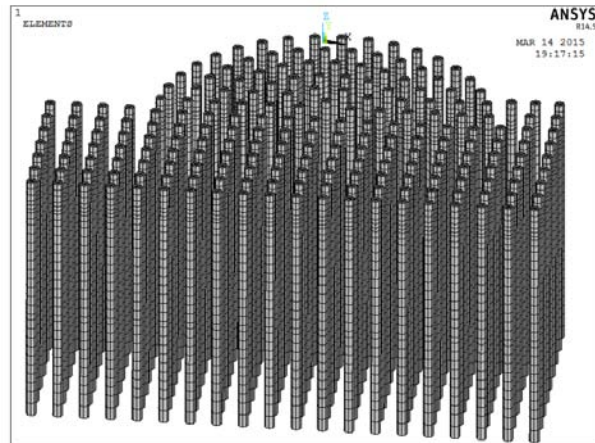
Description of Models

According to the sensitivity analysis result prior to this study, the total size of the soil model was finally determined in the premise of ensuring analysis accuracy and minimizing the calculation time. In vertical direction, the depth of the soil model is about 49m (42m above the basalt layer). To reduce the quantity of the nodes, the mesh of the soil model is non-uniform in horizontal direction. Within 10 meter range from the boundary of the superstructure, the element size of the soil model is about 0.6m~1.2m. For the range between 10m ~ 20m, the element size is about 1.5 ~ 2.5m. In the region which a distance of 20m away from the superstructure, the element size increased gradually.

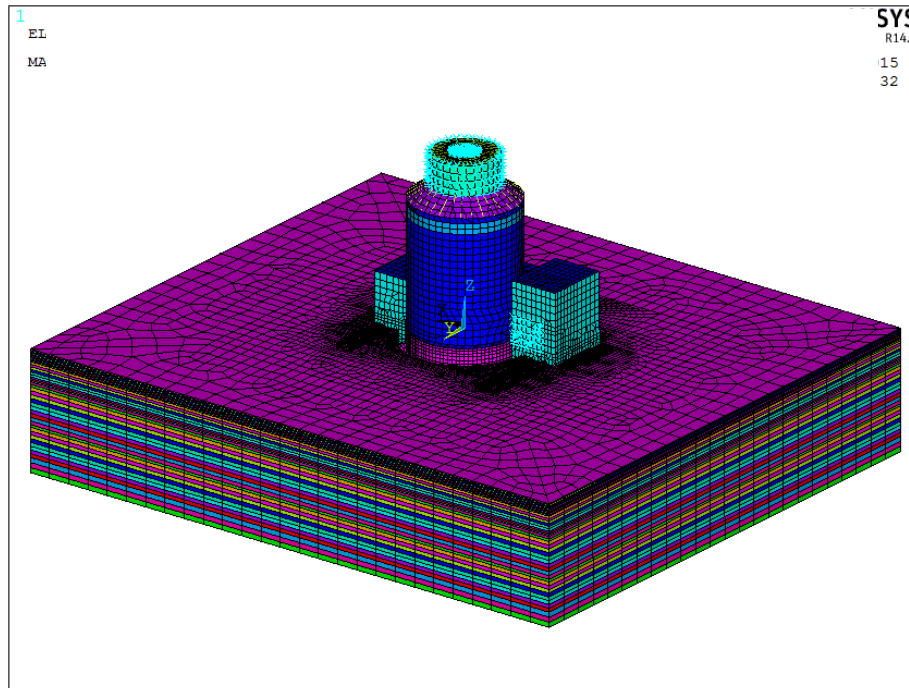
Solid element is used for simulating piles, the cap and the base slab, while shell element is used for the superstructure. Figure 5 showed the FE model for the second SSI analysis mentioned above, including the model of superstructure, the pile groups and the soil. For the first SSI analysis, the model of the pile groups was excluded.



(a)



(b)



(c)

Figure 4. FE model used for the second SSI analysis
(a) model of the superstructure; (b) model of the piles; (c) combined model

Input Control Motions

As per the adopted analysis approach, the site specific response spectra at the top of the basalt layer were used as target response spectra, which are shown in figure 5. A set of three regulatory compliant acceleration time histories (H1, H2, and V) that are compatible to these target RS are developed for seismic time history analysis, which were used in the sequent SSI analysis.

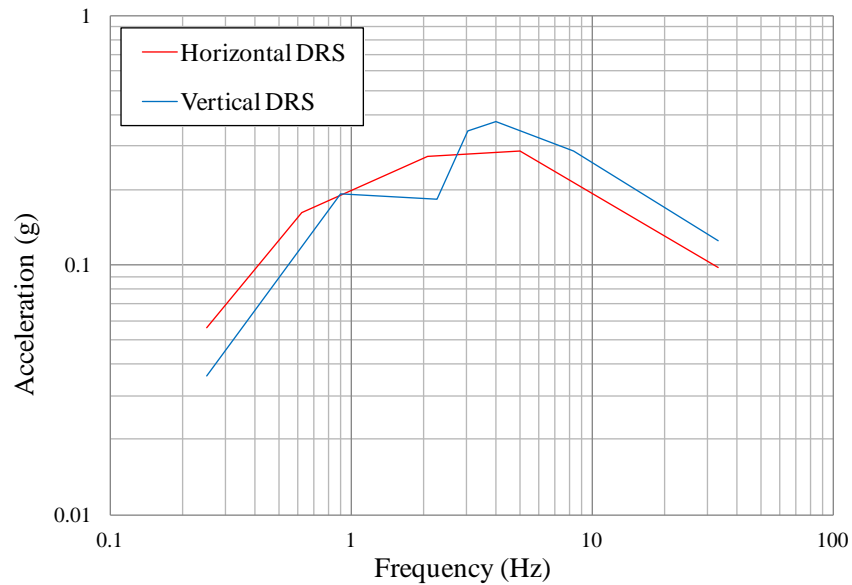


Figure 5. Target response spectra at the top of the basalt layer

Soil Profiles

The geological data of a typical borehole were adopted to perform equivalent linear analysis for two horizontal directions respectively. The dynamic modulus and damping ratios after 5 to 6 times iterations were shown in figure 6 and used as the undisturbed soil in two SSI analyses. It should be noted that the velocity and damping of the basalt layer were not included in the following figures for clear observation of soil dynamic properties.

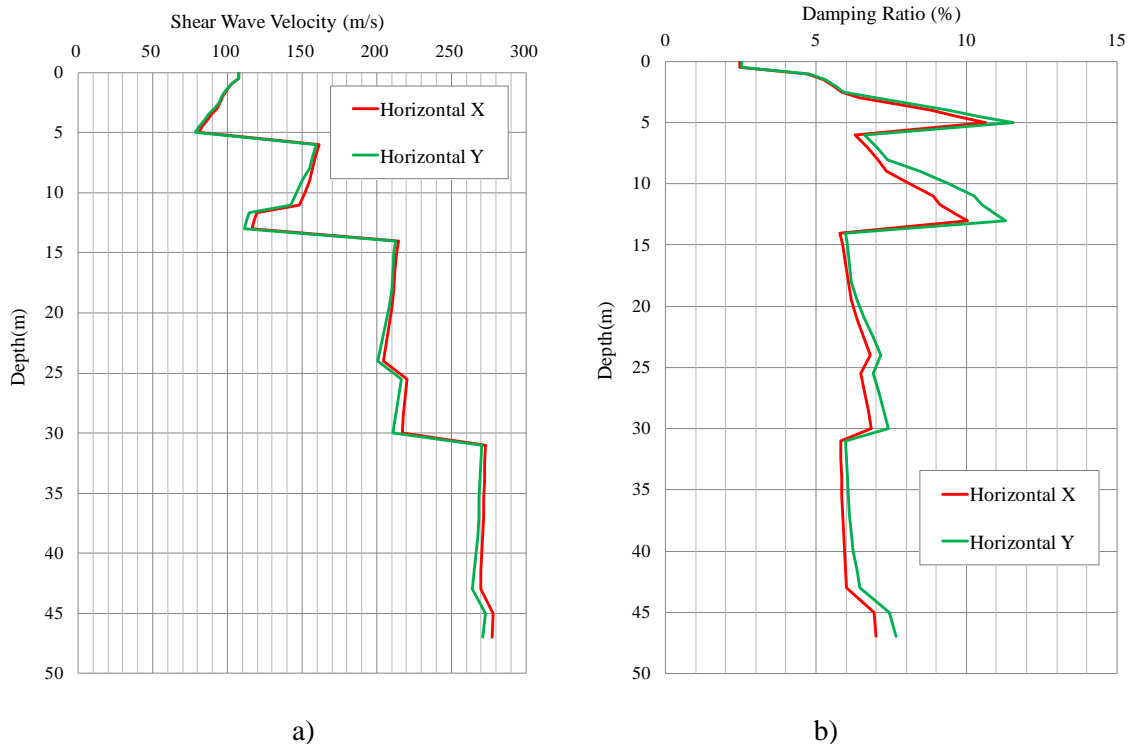


Figure 6. Dynamic property parameters obtained by equivalent linear method

Damping

According to *Code for Seismic Design of Nuclear Power Plants and Seismic analysis of safety-related nuclear structures and commentary*, the target damping was 7% for reinforced concrete structure and 5% for steel structure^{[1],[2]}. For the soil, damping values after equivalent linear calculation were used.

The region between the controlling frequencies for determining Rayleigh damping was appropriate to cover the main vibration modes of the study object and different from study objects.

ANALYSIS RESULTS

The ISRS results of characteristic nodes obtained from two SSI analyses were compared. This paper presents some comparison results, as shown in Figure 7 to 10, for the three typical locations: elevations of 99' and 160' at Containment Internal Structure (CIS), elevation of 230' at Auxiliary and Shielding Building (ASB). In the figures, responses of undisturbed soil are denoted as red solid lines while that of pile foundation as black solid lines.

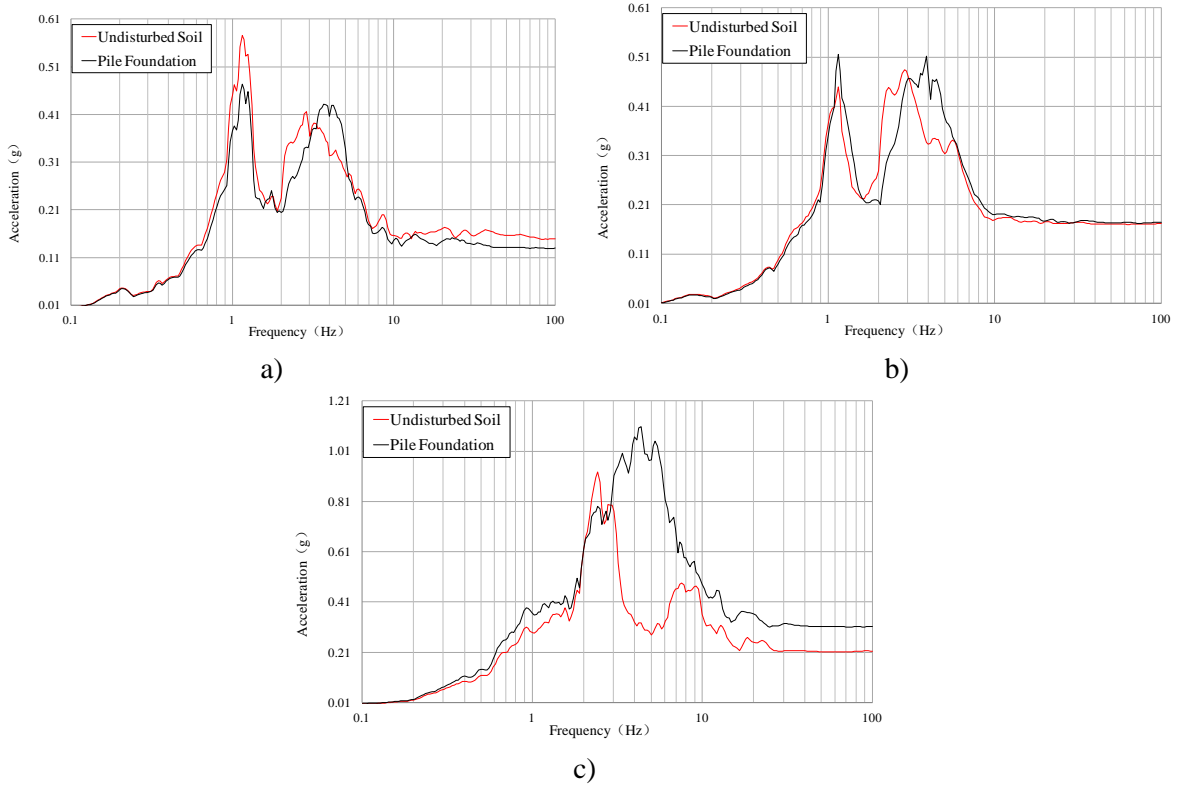


Figure 7. Response of 99' at CIS, a) Horizontal X Direction b) Horizontal Y Direction c) Vertical Direction

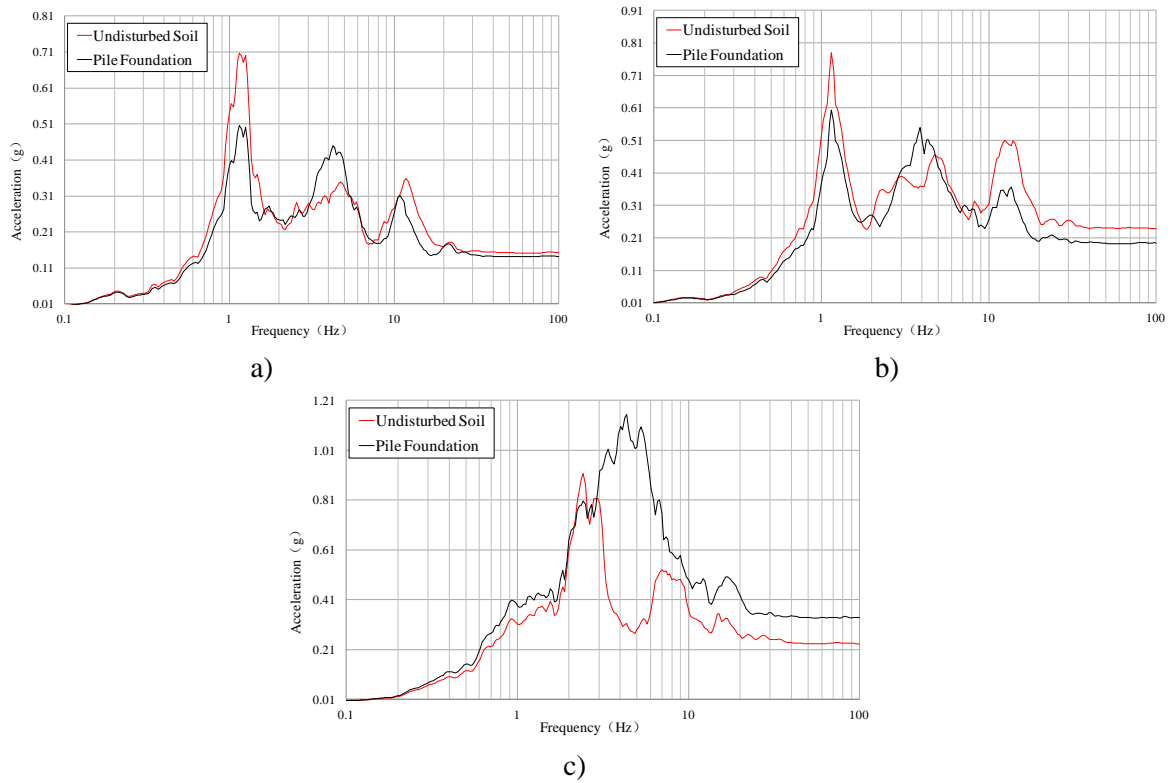


Figure 8. Response of 160' at CIS a) Horizontal X Direction b) Horizontal Y Direction c) Vertical Direction

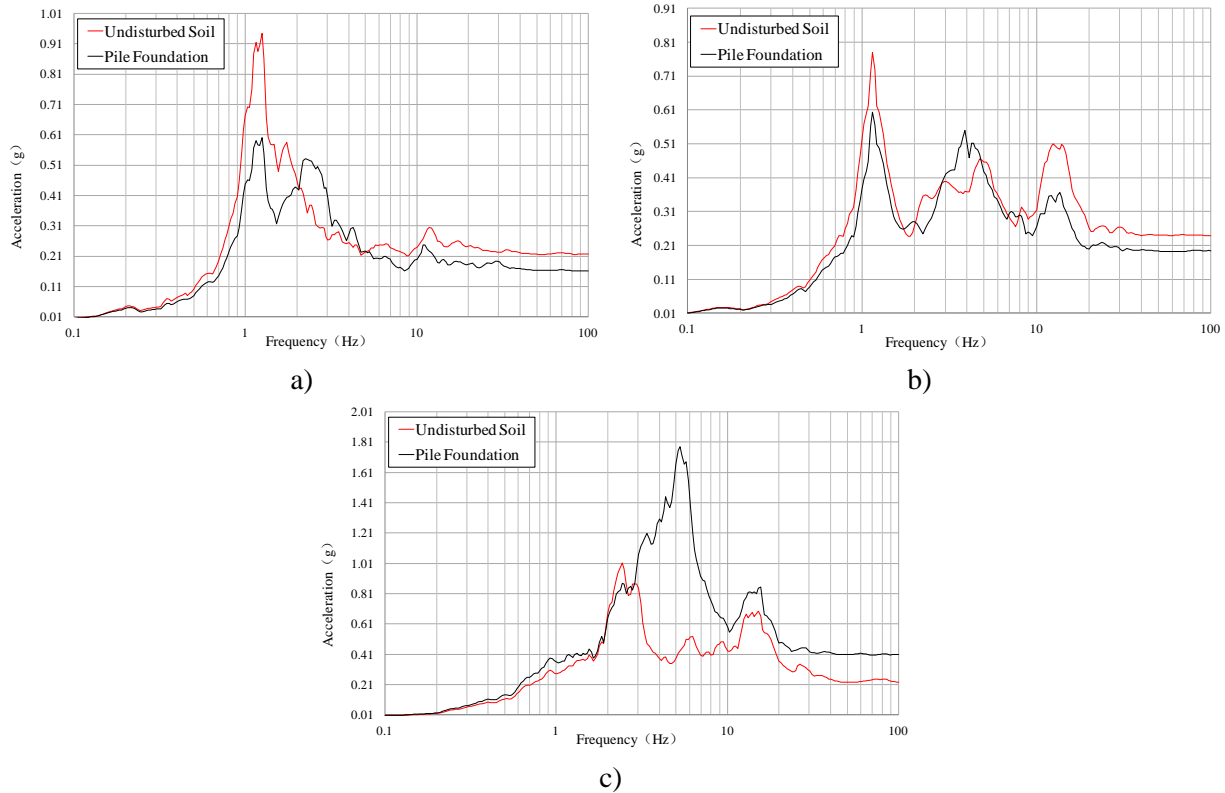


Figure 9. Response of 230' at ASB a) Horizontal X Direction b) Horizontal Y Direction c) Vertical Direction

These figures showed that the frequencies shift of the peak value of vertical response spectra were more than that of horizontal response spectra. This means that the vertical stiffness of whole SSI system change significantly while the horizontal stiffness didn't.

CONCLUSION

It is observed from comparison results of ISRS at various locations that :

- 1) Compared to undisturbed soil, the frequencies shift of the peak value of vertical response spectra were more than that of horizontal response spectra. This means that the vertical stiffness of whole SSI system change significantly while the horizontal stiffness didn't;
- 2) There are two obvious peaks in the response spectra of both two analyses;
- 3) For response in horizontal X and Y direction, the peak value decreased at 1.3HZ when compared with undisturbed soil condition. The decrease in X direction is more significant than Y direction;
- 4) For vertical direction, the peak acceleration values of response spectra of pile foundation condition exceeded that of undisturbed soil condition;
- 5) The ZPAs for two horizontal directions were lower than those of undisturbed soil condition, while ZPAs for vertical direction were slightly higher than undisturbed soil condition.

Based on the above-mentioned results, the effect from the pile foundation was concluded as:

The existence of pile group doesn't affect the horizontal stiffness of the SSI system significantly, the frequency of the peak of horizontal in-structure response spectra (ISRS) didn't move apparently. However, the vertical stiffness of the SSI system has been affected significantly, the frequency of the peak of vertical ISRS moved apparently. This mainly due to that the horizontal stiffness of pile group is small if compared with that of the whole SSI system, while the contribution to the whole SSI system from

the vertical stiffness of pile group is not negligible. The peak acceleration and zero-period acceleration (ZPA) were increased to some extent due to the existence of pile group. This was mainly caused by the combining action of the increase of the vertical stiffness of whole SSI system and the high frequency component in the earthquake.

FUTURE PROSPECT

As the rapid development of nuclear power engineering, less and less rock site is available to be selected. Besides, site selection for nuclear power plants needs to consider several complicated factors. Therefore, soft soil site sometimes become potential site. This phenomenon exists not only in China but also in international nuclear power engineering field. The probable problem due to soft soil is that the bearing capacity or settlement cannot meet the design requirement. Thus, the application of pile foundation in NPP buildings is a tendency. It is expected that the analysis method and conclusions in this paper has important significance for reference of design of NPP buildings with pile foundation.

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