The Key Influence Factors Analysis in Soft Ground Improvement About a Nuclear Power Plant

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ABSTRACT: Study on the diameter and the arrangement of rock-socketed piles in soft ground improvement is of great important influence factors for the seismic safety evaluation of nuclear power plant. Combined with a proposed nuclear power plant structure engineering project, according to the actual situation, the influencing factor of the rock-socketed piles diameter and the arrangement of rock-socketed piles are compared and analyzed. The influence law of the seismic response of the nuclear power plant structure is obtained. In the analysis process we use the method of numerical simulation to establish rock-socketed pile-soil-structure dynamic interaction calculation model of nuclear island under the condition of soft soil foundation calculation model. The experience and conclusions can be for reference under the similar conditions for the optimization design of rock-socketed piles in the soft soil.

Keywords: rock-socketed piles; arrangement form; replacement ratios

1 INTRODUCTION

With the rapid development of nuclear power industry, China’s nuclear power site resources increasingly tense, bedrock site has basically covered the potential nuclear site area, and inland nuclear power construction of soft soil foundation become an inevitable trend[1-3]. However, nonlinear characteristics of soft soil under the action of earthquake effect are obvious, dynamic analysis is more complicated, and the nuclear plant structure in the soft soil seismic adaptability cannot meet the standard requirement of design. So, the seismic adaptability of the nuclear structure in composite foundation (after the soft soil foundation treatment) has become an important restriction factor of inland nuclear power plant location, and is a key technical problems need to solve. In particular, establish a reasonable and efficient pile-soil-structure dynamic interaction calculation model is the important link to obtain reasonable soft soil foundation treatment scheme and it is also the important link of the earthquake response of the structure.

At present, the rock-socketed pile has the characteristics of large capacity, small single pile and pile group settlement, and good seismic performance, which can make full use of the bearing capacity of rock and concrete compressive strength. So, it is widely used in the soft soil foundation treatment. For a long time, scholars at home and abroad [4-7] have widely studied for pile-soil structure dynamic interaction calculation model and the influence factors of optimal placement of the pile. But the study on the nonlinear characteristics of soil, infinite foundation radiation damping effects still has many problems. Ge Zhang et al.[8] using the ANSYS finite element calculation software, the soil by Drucker-Prager yield criterion, boundary for the fixed boundary, set up a numerical model of joint bearing of piles and soil under different displacement rates for analysis and calculation. Lin Zhiyong et al. [9] established a pile-soil interaction 3D calculation model by FLAC3D, which the foundation soil uses Mohr-Coulomb model simulation to analyze the different pile length and pile diameter on the influence of their interaction, also uses the fixed boundary without regard to the radiation damping effect on the foundation of infinite domain. Xiaowei Yang et al. [10] considering the coordinate deformation between pile and soil, establish a pile-soil-structure dynamic interaction 2D calculation model to analyze seismic response of the model on different pile spacing cases. The lateral border around the model is elastic damping boundary, the bottom boundary using fixed boundary.

To solve the above problems, this paper combined
with the actual structure of the soft soil foundation treatment of a nuclear plant project. Taking SuperFLUSH software as the computing platform, establish rock-socketed piles-soil-nuclear power plant structure interaction calculation model. Equivalent linear method is adopted in this model to describe nonlinear characteristics of near field foundation. By introducing viscous artificial boundary to simulate the radiation damping effect of infinite foundation, the effect of pile group effect is considered in a fully coupled manner in the finite element framework. And then, based on this model and the comparison of nuclear plant structural response spectrum analysis, the influence rules of different pile diameters and arrangements on the structure of nuclear power plant are explored in the form of pile diameter and arrangement, and the scheme of pile foundation for this project is given. The research results can provide reference for the design of embedded pile in soft soil foundation treatment under similar conditions.

2 NUMERICAL MODEL OF PILE-SOIL-STRUCTURE DYNAMIC INTERACTION

As shown in Figure 1, the pile-soil-structure dynamic interaction model is composed of the finite element model of the generalized structure, and the viscous artificial boundary model which is set up in the outer boundary absorption wave energy. Generalized structure consists of nuclear island plant structure, which needs to consider the inhomogeneous and nonlinear characteristics of near-field ground and rock socketed pile part. The key technologies of the model are as follows:

2.1 Viscous artificial boundary model

In practical engineering, the foundation is a semi-infinite body, while the calculation area is usually limited. So when the wave analysis is carried out, artificial boundary conditions must be set up to consider the influence of boundary to the wave propagation. The damping coefficient of the viscous boundary along the truncated boundary is independent of the frequency, the method is simple and the physical concept is clear. It is a general method to simulate the infinite domain dynamic model of foundation, and it is widely used in engineering, and is also one of the artificial boundaries recommended by ASCE4-98.

Firstly, the viscous boundary [11] is applied to achieve the purpose of absorbing boundary reflection wave by arranging a series of dampers on the outer boundary, and the stress boundary conditions of the actual wave field are simulated by the equivalent load. Taking 2D model as an example, the calculation formula of normal viscous force and shear viscosity is:

\[ \tau_n = -\rho C_p v_n \]  
\[ \tau_s = -\rho C_s v_s \]  

Among them: \( v_n \) and \( v_s \) are normal and tangential velocity components on the boundary, \( \rho \) is mass density, \( C_p \) and \( C_s \) are wave velocity of P wave and S wave.

For ground motion inputs, the observed ground motion is often in the vicinity of the earth’s surface. If the observed ground motion is input into the model, the ground motion at the bottom of the model needs to be calculated.

In addition, it also needs to obtain the response of the boundary to the multi-layer heterogeneous foundation. Therefore, free field response analysis [12] must be performed. In this paper, the finite element method is used to analyze the free field response, and the motion vectors at the grid matching nodes are obtained, which is known as the input condition of the artificial boundary model.

2.2 Equivalent linear model of soil

Compared to the nuclear power plant site in rock under strong earthquake linearization, carry out the analysis of the nuclear island seismic safety evaluation on soft soil foundation is more complicated, especially how to consider under strong earthquake action of soil nonlinear dynamic characteristics is the key technical problems. In this paper, the nonlinear characteristics of soil are simulated based on the equivalent linear method [13] in the seismic analysis of nuclear power structure. The equivalent shear modulus and equivalent damping ratio are obtained by equivalent shear strain, and the nonlinear problem is simplified to a linear iterative problem. Equivalent shear modulus and damping ratio are used in each calculation. After obtaining the equivalent shear strain, the shear strain of the unit is checked to meet the convergence require-
ment. If it does not meet the requirements, according to the relationship curve $G / \gamma$ and $D / \gamma$ (See Figure 2), modified shear modulus and damping ratio are in the range of convergence error to the result.

![Figure 2. The equivalent linearization technique.](image)

### 2.3 Pile-soil dynamic interaction model

In order to effectively simulate the geometrical position and shape of the pile, the influence of the pile-soil-pile dynamic interaction on the dynamic response of the pile groups and the superstructure is reflected, and the nonlinear deformation and mechanical properties of the soil are conveniently considered. In this paper, we based on the Super FLUSH computing platform, in the finite element framework to consider the effect of pile group and the main use of quasi-three-dimensional dynamical analysis. Compared with true three-dimensional analysis, its modeling process is simple, which has high computational efficiency and good results. It’s worth mentioning that quasi-three-dimensional analysis has relatively mature application experience in the world.

![Figure 3. The arrangement plan of rock-socketed piles.](image)

In order to realize the dynamic interaction analysis of quasi-three-dimensional finite element, we regard equivalent stiffness as simplified principle. To ensure the smaller change of structure dynamic characteristics, the three-dimensional pile group-raft foundation is for the equivalent of two simplified model. First of all, according to rock-socketed pile layout (See Figure 3), the rock-socketed pile in the range of a pile in the three-dimensional model is projected along the Y axis and the X axis respectively. The number of piles in the range of each pile spacing on the X-Z plane and Y-Z plane is obtained. Then, the rock-socketed piles in each pile spacing in the plane are simplified as a single pile in a two-dimensional model. The fault area and moment of inertia of the simplified rock pile are obtained according to the formula (3) and (4).

$$S_s = S \times \frac{n}{b_s}$$  \hspace{1cm} (3)

$$I_s = I \times \frac{n}{b_s}$$  \hspace{1cm} (4)

Among them: $S_i$ and $I_i$ are sectional area and moment of inertia of simplified pile; $n$ is the number of roots before the simplified rock pile; $b_s$ is the width of the raft plate corresponding to the simplified pile along the X axis or the Y axis direction.

### 3 ENGINEERING SURVEY

Based on the background of a AP1000 reactor building for the dynamic response analysis of the nuclear island building structure under earthquake. The nuclear power plant foundation is uneven soft soil foundation, composed of different types of silty clay and sand. The characteristics of the horizontal layers are obvious. There are 8 layers, the thickness of each layer, the dynamic shear modulus and other parameters are shown in Table 1. The variation of shear modulus ratio and damping ratio with shear strain of all kinds of soil is obtained. The relationship between $G / \gamma$ and $D / \gamma$ in the soil layer is shown in Figure 4.

![Figure 4. The curve of $G / \gamma$ and $D / \gamma$ with every layer of soil.](image)

### 3.1 Calculation model

For the AP1000 reactor, the structure is mainly composed of the containment building, shielding factory
and auxiliary plant. These plants share the same raft foundation, and the 3D finite element model of the plant structure is shown in Figure 5. In this model, lumped mass beam element model is used to simulate, the mass and moment of inertia are concentrated on each node, and the geometric moment of inertia and shear area between adjacent nodes are expressed by the beam, and structure in X and Y direction asymmetry. Therefore, based on the first section, the model of dynamic interaction of pile-soil-structure is established. Based on the simplified principle of equal stiffness and quality, the upper part of the nuclear island plant structure respectively along the raft plate in the length direction and the width direction is simplified, and formed the X-Z plane model and the Y-Z plane model. As shown in Figure 6 and 7.

### Table 1. Physical parameters of geotechnical materials in dynamic analysis.

<table>
<thead>
<tr>
<th>Lithology</th>
<th>Depth</th>
<th>Thickness</th>
<th>Dynamic shear modulus/ GPa</th>
<th>Dynamic Poisson's ratio</th>
<th>Density g/cm$^3$</th>
<th>Damping ratio/ %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silty clay</td>
<td>5</td>
<td>5</td>
<td>0.02</td>
<td>0.50</td>
<td>1.95</td>
<td>3.9</td>
</tr>
<tr>
<td>Silty sand</td>
<td>8</td>
<td>3</td>
<td>0.07</td>
<td>0.49</td>
<td>2.01</td>
<td>2.5</td>
</tr>
<tr>
<td>Silty silty clay</td>
<td>10</td>
<td>2</td>
<td>0.05</td>
<td>0.49</td>
<td>1.88</td>
<td>3.9</td>
</tr>
<tr>
<td>Silty clay</td>
<td>21</td>
<td>11</td>
<td>0.12</td>
<td>0.49</td>
<td>1.98</td>
<td>3.9</td>
</tr>
<tr>
<td>Silty clay</td>
<td>27</td>
<td>6</td>
<td>0.13</td>
<td>0.48</td>
<td>1.91</td>
<td>3.0</td>
</tr>
<tr>
<td>Silty clay</td>
<td>40</td>
<td>13</td>
<td>0.19</td>
<td>0.48</td>
<td>1.98</td>
<td>3.2</td>
</tr>
<tr>
<td>Silty sand</td>
<td>44</td>
<td>4</td>
<td>0.21</td>
<td>0.47</td>
<td>2.03</td>
<td>2.5</td>
</tr>
<tr>
<td>Basalt</td>
<td>47</td>
<td>6.04</td>
<td>0.28</td>
<td>2.45</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Raft Island width is 78.03m, and plate thickness is 1.8m. The foundation finite element calculation model of the left and right boundary extends 2 times the width of the raft, and the calculated depth is 47m. The raft and foundation are simulated by plane four node element, in order to ensure that the high frequency of passing through the system is not cut off, the finite element mesh height is about 3m, which meets the requirements of grid height.

As mentioned before, the parameters of the corresponding post fault area and the moment of inertia are calculated according to the formula (3) and (4).

### 3.2 Site seismic wave

Figure 8 shows the acceleration time history curve of horizontal and vertical seismic ground motion in the structure of nuclear reactor. The peak acceleration of horizontal ground motion is 2.82m/s$^2$, the peak acceleration of vertical ground motion is 2.59m/s$^2$, total 40s, time step 0.01s.
4 ANALYSIS OF KEY FACTORS SUCH AS PILE DIAMETER

Through the proposed dynamic interaction model, for ground preprocessing scheme embedded rock pile with different replacement ratio and different arrangement form, this section considers the influence of key factors under the action of strong earthquakes of nuclear power plant response analysis.

In the analysis of the calculation results, the elevation 66.50m is selected to be in the top surface of the raft (node 11), and the elevation 265.00m is shielded from the bottom of the air inlet (node 160) and the top of the water tank at the elevation 333.13m (node 310), whose specific location refers Figure 6-7. Compared with the floor acceleration response spectrum of 5% damping ratio under different working conditions, it is located in the bottom, middle and top of the reactor, the result is representative.

4.1 Analysis of floor response spectrum under the same arrangement of pile with different replacement ratio

The replacement ratio is the ratio of the cross section area of the pile and the foundation of the pile foundation. The change of the replacement rate will change the value of the composite modulus and the compound Poisson’s ratio of treatment foundation accordingly. The different replacement rate is actually the analysis of the characteristics of different composite modulus and Poisson’s ratio of the composite foundation. Under the condition of the arrangement form and the pile length, the following conditions are analyzed.

According to the requirements of the foundation bearing capacity of the project, for the construction of the Embedded Pile 212, the pile spacing is 3.949m, and the layout and the size of the raft are shown in Figure 3. Embedded pile length is 37.41m, embedded basalt 2m. The diameters of the pile design are 1.10m, 1.30m, 1.50m, 1.70m and 1.90m. The change range of area replacement ratio is 6.14%~18.30%. The main calculation parameters are shown in Table 2. Above five kinds of working conditions and without pile, the 5% damping ratio acceleration response spectrum on nodes 11, 160 and 310 in the X, Y, Z three directions and the response spectrum of AP1000 standard design is compared with the results shown in Figure 9-11.

As it can be seen from Figure 9-11, with the increase of elevation, the response of nodes 310, 160 and 11 showed a gradually increasing trend, and the variation law of each node response spectrum curve was basically the same. In the horizontal direction, the treatment of pile foundation made the peak value of the acceleration spectrum of the low frequency band reduced, and the amplitude of the high frequency band is enlarged. In X direction, under the condition of undisturbed soft soil foundation, low frequency response spectrum of the node 310, 160 and 11 in the vicinity of the frequency 0.9Hz (0.7~1.0Hz) is more than the AP1000 standard design response spectrum envelope curve. Under the condition of site foundation by pile foundation treatment, the peak value of the nodes 11, 160 and 310 are not more than AP1000 standard design response spectrum envelope curve. In Y direction, the low frequency response spectrum of the node 310, 160 and 11 in the vicinity of the frequency 0.95Hz (0.9~1.0Hz) is slightly more than the AP1000 standard design response spectrum envelope curve. Among them, under the condition of no pile, the maximum is exceeded, which is 0.1g. In horizontal direction, the high frequency response spectrum of the node 310 and 11 in the vicinity of the frequency 5.5Hz (5~6Hz) is slightly more than the AP1000 standard design response spectrum envelope curve. The response spectrum of the node 160 is not more than AP1000 standard design response spectrum envelope curve at high frequency. In Z direction, the response spectrum value of the node 310, 160 and 11 under the condition of no pile, from the low frequency band 2.2Hz band began to exceed the AP1000 standard design response spectrum envelope curve. With the
increase of the diameter of the embedded pile, the frequency of the response spectrum envelope of the AP1000 standard design is gradually moving to high frequency.

It is easy to find that with the increase of the diameter of the embedded rock pile, the peak value of the low frequency segment of the reaction spectrum of the node showed a decreasing trend on two horizontal directions. In X direction, the magnitude of the reduction is about 2%, and the amplitude is increased with the increase of the replacement rate. In Y direction, the magnitude of the reduction is 0.5% or so. When the diameter is larger than 1.5m, the value of the reduced amplitude is no longer increase obviously, and evens the trend of the amplitude value decreases. In the vertical direction, the response spectrum of the node is similar to that of the horizontal direction, but the change trend is less than that of the horizontal direction. The results show that the block rock pile different replacement rate, at 11.4% replacement ratio, the key points of the nuclear island power response varies greatly. It is greater than this value, even if the replacement rate increases. The increasing phenomenon of the nuclear island amplitude of low frequency amplitude decreases is not obvious.

4.2 Analysis of floor response spectrum of different pile arrangement under the same replacement ratio

How reasonable arrangement of pile embedded in, is the need to consider the key influence factor, namely in the same area replacement ratio, changes the pile number, analysis of characteristics of composite
foundation influence on the dynamic response of the nuclear island. The following conditions under the same replacement rate analyze the foundation under different arrangement form. Choose to maintain the area of the replacement rate of 11.56% and pile length 37.41m unchanged; only change the arrangement form of the rock embedded pile. In order to facilitate the research, the analysis of the arrangement form of different rock embedded piles is in accordance with the design of the square raft. The main calculation parameters are shown in Table 3. Above six kinds of working conditions and without pile, the 5% damping ratio acceleration response spectrum on nodes 11, 160 and 310 in the X, Y, Z three directions and the response

Table 3. The main parameters in different arrangement.

<table>
<thead>
<tr>
<th>Working condition</th>
<th>Raft size / m×m</th>
<th>Pile diameter/ m</th>
<th>Pile spacing/ m</th>
<th>Pile distribution / Row x row</th>
<th>Replacement rate/ %</th>
</tr>
</thead>
<tbody>
<tr>
<td>WC. 1</td>
<td>77.420×32.235</td>
<td>2.405</td>
<td>7.778</td>
<td>10×7</td>
<td>11.56</td>
</tr>
<tr>
<td>WC. 2</td>
<td>77.420×32.235</td>
<td>2.905</td>
<td>9.600</td>
<td>8×6</td>
<td>11.56</td>
</tr>
<tr>
<td>WC. 3</td>
<td>77.420×32.235</td>
<td>5.809</td>
<td>12.90</td>
<td>6×2</td>
<td>11.56</td>
</tr>
<tr>
<td>WC. 4</td>
<td>77.420×32.235</td>
<td>7.115</td>
<td>20.01</td>
<td>4×2</td>
<td>11.56</td>
</tr>
<tr>
<td>WC. 5</td>
<td>77.420×32.235</td>
<td>10.062</td>
<td>42.03</td>
<td>2×2</td>
<td>11.56</td>
</tr>
<tr>
<td>WC. 6</td>
<td>77.420×32.235</td>
<td>20.125</td>
<td></td>
<td>1×1</td>
<td>11.56</td>
</tr>
</tbody>
</table>

Figure 12. Comparison of acceleration response spectrum for node 11.

Figure 13. Comparison of acceleration response spectrum for node 160.

Figure 14. Comparison of acceleration response spectrum for node 310.

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spectrum of AP1000 standard design is compared with the results shown in Figure 12-14. As can be seen from Figure 12-14, under different conditions, the response spectrum curve of nodes 11, 160 and 310 in the horizontal direction X is more obvious than that in the horizontal direction Y and the vertical direction Z. In the horizontal direction, the pile foundation treatment made the low frequency section acceleration spectrum peak has the certain reduction, and the high frequency section amplitude has certain amplification. In the X direction, the working condition 2 compared to the working condition 1, the working condition 3 compared to the working condition 2 and the working condition 4 compared to the working condition 3 for the node 11,160 and 310, the decrease amplitude of the low frequency band is 1.1%, 1.8% and 3.4%. Compared to the operating conditions of 1~3, the frequency of the low frequency peak is obviously increased on working condition 4 and condition 5. In the Y direction, the response spectrum curve of the node 11, 160 and 310 under the condition of 3~5 is the same. The working condition 2 compared to the working condition 1, the working condition 3 compared to the working condition 2 and the working condition 6 compared to the working condition 5 for the node 11,160 and 310, the decrease amplitude of the low frequency band is 0.1%, 1.4% and 3.3%. In the vertical direction, the change tendency of the response spectrum curve is not very obvious.

5 CONCLUSION

How to carry on the numerical simulation of the treatment scheme of soft soil foundation rock and find the influence of key factors such as pile diameter and arrangement form is the core content of site evaluation of inland nuclear power plant foundation seismic adaptability.

In this paper, the radiation damping effect of infinite foundation is simulated by viscous artificial boundary, nonlinear simulation of near field soil using equivalent linear model, and within the framework of the finite element coupled to considering the influence of pile group effect, establish the condition of soft soil subgrade under pile - soil - structure dynamic mutual numerical calculation model. And based on this model, combined with a proposed nuclear power plant design projects, to nuclear power plant on the soft soil foundation embedded rock pile with different replacement ratio and the same replacement rate of different layout of the foundation for the research of the influence law of nuclear power plant structure. Through the comparative analysis of different conditions of the nuclear power plant response analysis, the following conclusions can be obtained:

Due to the strengthening of rock embedded piles, the stiffness of the foundation significantly increased, resulting in the pile raft foundation compared to the pile foundation, the peak of the low frequency segment of the node response spectrum has a significant reduction. After the pile foundation treatment, the most of acceleration response spectrum of the node 11, 160 and 310 is lower than the corresponding AP1000 standard design envelope spectrum, which can meet the design requirements.

In the case of different rock socketed pile replacement ratio, with embedded rock pile diameter increases, foundation stiffness also increases, the foundation frequency improved, so in the lower frequency response decreases gradually, and in the higher frequency response increases. Among them, at 11.4% replacement rate, the key point of the nuclear island power response change is large, and the value is greater than after, even with increasing replacement ratio, influence the response of the nuclear island gradually becomes smaller.

In the same rock socketed pile replacement rate, according to the results of theoretical analysis, the stiffness of pile raft foundation is obviously improved when the diameter of embedded pile is larger than 10m. But considering the influence factors of construction technology and project cost, it is recommended to use the arrangement form of the diameter of the embedded pile with the diameter of 2.905m.

For the actual project, based on the above discussion, after a lot of numerical analysis of the key factors of the optimal selection (The paper is only a part of the typical results), and considering the construction technology of super large diameter rock embedded pile which is larger than 3m in diameter, and the influence of the engineering cost is complicated. We recommend use the parameter values used in this project: Area replacement rate is 11.4%; the arrangement of the pile is under the working condition 2, 8 column x 6 row forms.

REFERENCES


