The Dynamic Response Analysis of Pseudo Three Dimensional of Nuclear Island Plant Structure under Non-lithology Foundation Condition

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Abstract. Building nuclear power plant structure on lithology ground or soft ground has become an inevitable and popular trend in the development of nuclear island plant structure. It leads the seismic analysis of non-lithology foundation to be the key technical issues to choose the nuclear power plant site. In order to solve the engineering practicality issues of seismic analysis of non-lithology foundation and the issues of simplifying the complex nuclear power plant structure, the three-dimensional (3D) finite element model of the AP1000 nuclear power plant structure has been simplified to two-dimensional model in this paper based on ANSYS software. The principle of the simplification is that the mass and stiffness of models should be equivalent. Then establish the pseudo 3D model in SuperFLUSH software to explore the mechanism of the earthquake loads and seismic response characteristics of nuclear power plant structure. Finally, compare the frequency characteristics and compare the true three-dimensional results of SASSI software with the results of SuperFLUSH software to verify the rationality and effectiveness of the simplification.

Introduction

China has become the world's electricity production and consumption power since 1990s. Nuclear power is an important form of optimizing the energy structure and has great potential for development. At present, the sites of nuclear power plant in China are choosing the rock foundation in coastal areas in order to ensure the safety and economy. However, the power grid capacity has been greatly developed with the growth of the domestic economy, power resources has appeared in short supply phenomenon in inland. The rapid development of nuclear power will inevitably lead to nuclear power site resources become increasingly tense. So in the non-rock foundation and even on the soft soil foundation construction of nuclear power plant has become the inevitable trend of the development of nuclear power[1,2].

The design of nuclear power plants tend to use standard design so far, which leads to the nuclear island building foundation seismic adaptability become important constraints on nuclear power plant site selection, and it is also a key technical problem to be solved. However, in order to solve the complex non rock foundation of nuclear power plant structure and seismic response of equipment need to fully consider of structure foundation dynamic interaction, soil non homogeneity and nonlinear, geometry structure of the ground surface and the interaction between pile and soil structure dynamic interaction.

At present, there are many practical experiences and research results in the world.
ASCE4-86 standard of America puts forward some international general calculation model and program. Some programs are recommended to use, such as CLASSI, SASSI, FLUSH, ALUSH and other programs. The program of CLASSI and SASSI can be used as a true three-dimensional dynamic analysis. 

There are some limitations in the calculation of degrees of freedom which is difficult to carry out large scale computation. The three-dimensional structure model of the nuclear island grid is relatively simple rules, but it is difficult to do fine division and the calculation efficiency is low. In addition, the program of CLASSI and SASSI using the sub structure method. It is difficult to consider soil nonlinearity and pile soil interaction if the non-lithology foundation carries out the study of pile foundation treatment. So they are not suitable for engineering applications. The program of FLUSH and ALUSH program is mainly used the method of three-dimensional dynamic analysis. Its modeling process is simple and the computation efficiency is high by comparing with the true three-dimensional analysis. And the results are in good agreement with the true three-dimensional calculation. It is worth to explain that the quasi three-dimensional analysis has more mature application experience in the world. Such as, the professor of Utaka takekazu [3] who comes from Japan has applied the quasi three-dimensional analysis to the seismic and stability analysis of nuclear power station and other buildings. He concluded that the quasi three-dimensional analysis and true three-dimensional dynamic analysis of the results of the accuracy of the equivalent, but it is more efficient and easier to achieve. However, the form of the current nuclear plant structure is becoming increasingly complex, such as AP1000 nuclear island includes the security shell factory that locates on the common raft foundation, shield workshop, auxiliary workshop and so on. Compared with the CPR1000 nuclear plant, their structures are more complex and more types of components. Therefore, how to carry out the upper nuclear plant structure simplified equivalent is particularly important. In addition, the program of FLUSH and ALUSH use the rigid foundation assumption and the absorption of the reflected wave energy has some limitations. But the rigid base setting depth must be using sensitivity analysis to determine. 

In order to better satisfy the engineering practicability of seismic adaptability analysis of the non-lithologic foundation and the equivalent simplified requirements of the complex structure of nuclear plant. AP1000 nuclear plant structure as the research object, and based on ANSYS software in the paper. The three-dimensional finite element model of the nuclear island is equivalent to two plane simplified model by using the simplified principle of stiffness—quality. And the reasonable validity is verified by the vibration frequency characteristic. Then based on all equivalent simplified models and SuperFLUSH program as a computing platform, by setting the viscous artificial boundary on the surface of the base model imitate semi-infinite space, and by using the equivalent linear method imitate the nonlinear characteristics of the near field ground. The analysis model of quasi three dimensional seismic response of nuclear plant structure is established under the condition of non-rock foundation. To discuss Mechanism of earthquake load and the response characteristics of the nuclear island building structure by model, and compared with the SASSI program true three-dimensional. The validity and practicability of the proposed three-dimensional calculation model is studied and verified in this paper.

The Calculation Model and Dynamic Characteristics of Nuclear Island Plant Structure

In this paper, the AP1000 nuclear power plant reactor plant as the research object. This
structure consists of four parts: shield factory, steel safety shell, internal structure and auxiliary workshop, and they are located on a raft foundation with a thickness of 1.8m and belong to I type anti earthquake structure. The upper part of the shield factory is a steel plate embedded concrete structure, and the lower part is a reinforced concrete structure. The wall of internal structure is steel plate concrete. The wall of inner security shell, auxiliary workshop, floor and others are all concrete structures. And the geometric moment of inertia and shear area between adjacent nodes are expressed by beam of the connected nodes. Structure is asymmetric in X and Y direction. In order to facilitate the comparative study, the bottom of raft foundation is fully restrained.

**Establishment of Quasi Three Dimensional Equivalent Simplified Model**

**The Simplification Principle of Equal Stiffness and Mass**

The simplified principle of nuclear island structure model: Keeping the overall mass and the overall stiffness of the before and after simplification model, the simplified plane model and the dynamic characteristic of the original three dimensional model are consistent. Also the simplified model can’t fully reflect the high order local vibration because of three-dimensional model contains complex high order local vibration. However, low-frequency modal response of the structure influence is bigger in the dynamic analysis of the nuclear island, it just considers the principal vibration characteristics of the two plane model are equivalent.

![Figure 1. The three-dimensional finite element model of the AP1000 nuclear island plant structure.](image)

Based on the center of raft foundation as a simplified reference point, this paper uses the general finite element software ANSYS and the center of the raft foundation are simplified as the reference point. The two planes "X-Z" and "Y-Z" plane are used to simplify the original solid model. Firstly, coordinate transformation of 3D model is carried out, and then projected it onto the XZ plane and YZ plane. The formula 1 and 2 will be used to revise moment of inertia of the original model of BEAM4 beam element and MASS21 mass element.

\[
I = I' + \Delta d^2 \times A. \\
J = J' + \Delta d^2 \times A.
\]

\(\Delta d\) is the distance between the center of the unit and the projection plane and A is the unit area.

Then, three-dimensional beam element of BEAM4 in three-dimensional model is replaced by two-dimensional beam element of BEAM3. Three-dimensional mass element of MASS21 by changing the unit's own Keyoption into two-dimensional mass unit. Finally, equivalent the
model of the rotation inertia, shear coefficient, mass, sectional area and other parameters to raft foundation unit width of corresponding plane normal direction, so as to obtain the equivalent simplified model, two planes of the equivalent simplified model as shown in Fig. 2 and Fig.3.

![Figure 2. Calculation model of nuclear island plant structure in plane XZ.](image)

![Figure 3. Calculation model of nuclear island plant structure in plane YZ.](image)

**Calculation Result Analysis**

The frequency of the simplified model before and after the model is shown in Table 1, the bottom of the nuclear island structure using the same full constraint in the calculation. As can be seen from the table, the two-dimensional model and the original three-dimensional model of the vibration characteristics is good agreement in the 0.1~12Hz frequency range after simplified. But the difference between the two is increased slightly with the increase of the degree of order. Compared simplified model in the X-Z plane with simplified model in the Y-Z plane, the model is better consistent with the former, the anastomosis of the former is better than that of the latter. Because of the model can’t simulate the crane girder stiffness in the Y-Z plane and it can only be simplified as the quality point (Upper crossbeam in Fig. 1). It will have a certain effect on the frequency of vibration.

<table>
<thead>
<tr>
<th>order</th>
<th>Original 3D model frequency (Hz)</th>
<th>X-Z plane simplified model frequency (Hz)</th>
<th>Y-Z plane simplified model frequency (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.1356</td>
<td>--</td>
<td>0.1356 (1)</td>
</tr>
<tr>
<td>2</td>
<td>0.1356</td>
<td>0.1356 (1)</td>
<td>--</td>
</tr>
<tr>
<td>3</td>
<td>0.1356</td>
<td>--</td>
<td>0.1356 (2)</td>
</tr>
<tr>
<td>4</td>
<td>0.1356</td>
<td>0.1356 (2)</td>
<td>--</td>
</tr>
<tr>
<td>5</td>
<td>2.8267</td>
<td>--</td>
<td>2.9851 (3)</td>
</tr>
<tr>
<td>6</td>
<td>3.0218</td>
<td>3.0328 (3)</td>
<td>--</td>
</tr>
<tr>
<td>7</td>
<td>3.6056</td>
<td>--</td>
<td>3.7071 (4)</td>
</tr>
<tr>
<td>8</td>
<td>5.2016</td>
<td>5.2204 (4)</td>
<td>--</td>
</tr>
<tr>
<td>9</td>
<td>5.2159</td>
<td>--</td>
<td>5.4269 (5)</td>
</tr>
<tr>
<td>10</td>
<td>5.9416</td>
<td>--</td>
<td>5.5880 (6)</td>
</tr>
</tbody>
</table>
The Analysis Model of Quasi Three Dimensional Seismic Response of Nuclear Plant under The Condition of Non-Rock Foundation

Nonlinear Simulation of Soil

Seismic response analysis of non-rock foundation in nuclear plant structure is more complexity complex than linearization treatment of nuclear power plant batholith under strong earthquake linearization. In particular, how to consider the influence of the nonlinear dynamic characteristics of the soil under strong earthquake is the key technical problem to be solved. In this paper, the equivalent linear method [4] is used to simulate the nonlinear characteristics of soil.

![Dynamic model based on non-lithology foundation.](image)

The equivalent linear method transforms the nonlinear problem into a simple linear problem to solve the problem, and it keeps the total stiffness constant of the iteration. It can meet the requirements of the 5 iteration based on the abundant engineering experience. This method greatly reduces the amount of work and computation under the premise of satisfying the requirement of engineering precision. Formula 3 is the calculation formula of unit equivalent shear strain $\gamma_{eff}$.

$$\gamma_{eff} = 0.65 \gamma_{max}.$$  \hspace{1cm} (3)

Where $\gamma_{max}$ is the maximum shear strain in the strain time history.

Soil Structure Dynamic Interaction

Soil structure dynamic interaction analysis [5] is another important link under seismic design and analysis of nuclear engineering in the condition of non-lithologic foundation. At present, calculation model for dynamic interaction of infinite foundation is mainly include the artificial boundary method [6], boundary element method [7], scaled boundary finite element method [8] and other methods.

Viscous boundary[9] is a kind of artificial boundary that proposed by Lysmer and Kuhlemeyer. The idea of this method is through arranged a series of damper in boundary to absorb boundary reflection wave energy (as shown in Fig. 4). And the equivalent load force $P$ is applied to satisfy the boundary stress condition. Formula 3 and formula 4 are the computational formula of normal and shear stresses of the artificial boundary.

$$\sigma_x = -\rho CV x \dot{U}_x.$$ \hspace{1cm} (4)

$$\tau_{xy} = -\rho CV x \dot{U}_y.$$ \hspace{1cm} (5)
Where $\hat{U}_X$ and $\hat{U}_T$ is respectively the normal and tangential velocity components on the boundary. In boundary node total field speed $\hat{U}$ minus free foundation of node velocity $\hat{U}_f$ to consider finite element structure by the surrounding caused seismic wave dynamic dissipation; $\rho$ is the mass density; $V_p$ and $V_s$ is respectively P wave and S wave velocity.

**Establishment of Seismic Response Analysis Model**

Based on the above discussion, the model of seismic response analysis under the condition of non-lithology is shown in Fig. 5. It mainly includes the simulation of the far field region and the generalized structure. Effective input for the viscous boundary is by using analysis of free foundation using one dimensional finite element method. Through implementation of the viscous boundary (as shown in Fig. 5) to calculate the combination of finite element model in the three dimensional (thickness direction) and free foundation, and it consideres the energy to fluctuations in the three-dimensional direction dispersion effect.

**Verified by example**

Based on the above calculation model, this section has a seismic response analysis of AP1000 nuclear island. Verify the rationality and efficiency of the model established in this paper by comparing with study three dimensional dynamic analysis of SASSI program. In the numerical example, the mesh density of the finite element model is guaranteed to have 4-8 nodes in each wavelength. The model is shown in Fig. 5.

![Figure 5. The three-dimensional finite element model in SASSI.](image)

**Foundation Parameter**

**Table 2. Valuing scheme for dynamic parameters of foundation soil.**

<table>
<thead>
<tr>
<th>Layer number</th>
<th>Layer thickness (m)</th>
<th>Damping ratio (%)</th>
<th>Density (g/cm$^3$)</th>
<th>Shear wave velocity (m/s)</th>
<th>Modulus of elasticity (Gpa)</th>
<th>Poisson's ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3</td>
<td>2.5</td>
<td>2.01</td>
<td>190</td>
<td>0.07</td>
<td>0.49</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>3.9</td>
<td>1.88</td>
<td>161</td>
<td>0.05</td>
<td>0.49</td>
</tr>
<tr>
<td>3</td>
<td>11</td>
<td>3.9</td>
<td>1.98</td>
<td>246</td>
<td>0.12</td>
<td>0.49</td>
</tr>
<tr>
<td>4</td>
<td>6</td>
<td>3.0</td>
<td>1.91</td>
<td>262</td>
<td>0.13</td>
<td>0.48</td>
</tr>
<tr>
<td>5</td>
<td>13</td>
<td>3.2</td>
<td>1.98</td>
<td>313</td>
<td>0.19</td>
<td>0.48</td>
</tr>
<tr>
<td>6</td>
<td>4</td>
<td>2.5</td>
<td>2.03</td>
<td>335</td>
<td>0.21</td>
<td>0.47</td>
</tr>
<tr>
<td>7</td>
<td>3</td>
<td>2.81</td>
<td>2.45</td>
<td>1569</td>
<td>6.04</td>
<td>0.28</td>
</tr>
</tbody>
</table>

The site of AP1000 nuclear island foundation is inhomogeneous and non-lithologic foundation, and it is composed of different types of clay, sand and other components. The horizontal layer is divided into 7 layers and the thickness, shear wave velocity and other parameters of each layer are shown in Table 2. Model only carries on the dynamic analysis of XZ plane and YZ plane because of the
foundation is layer distribution. The range of foundation calculation model is the center of foundation of building raft foundation, both sides of the horizontal direction is extended to 2 times of the width of the raft and the depth of the vertical direction is the rectangular geometry of 42m as the computational domain. The finite element model is carried out by using isoperimetric element of tetrahedral in the XZ direction. The finite element model consists of 1140 nodes and 1062 elements. The model is shown in Fig. 6. The ground layer and materials in the YZ direction is same as the direction of XZ.

![Figure 6. The model of foundation.](image)

**Seismic Wave Input**

The earthquake ground motion curve of level and vertical of nuclear reactor building site is obtained by the engineering site seismic safety evaluation report, as shown in Fig. 7. The peak acceleration of horizontal to ground motion is in the X direction and the peak acceleration of horizontal is 1.84m/s² in the Y direction. The peak acceleration of vertical ground motion is 1.94m/s², its total is 40s and the time step is 0.01s.

![Figure 7. Time-history of input ground motion.](image)

**Nonlinear characteristics of soil**

The main parameters of soil dynamic characteristics are shear modulus G and damping ratio D, which are the function of shear strain Y. The relationship between $G-\gamma$ and $D-\gamma$ of the ground layer in this example is shown in Fig. 8.
Interpretation of Result

Two working conditions are simulated in order to investigate the rationality of simplified equivalent nuclear plant structure and correlation between the analyses of quasi three-dimensional and true three-dimensional. 1) To establish the model of three-dimensional dynamic interaction based on the SuperFLUSH software. 2) Establish the true three-dimensional non-lithologic structure foundation model by using SASSI program.

As shown in Fig. 9, it has a contrast in horizontal X direction, Y direction and vertical Z direction of op surface node 11 and upper node 81 of the nuclear structure raft under each working condition. The direction of X is the long side direction of the raft, the direction of Y is the direction of the short side of the raft and the direction of Z is the vertical direction.

In this paper, the peak frequency and peak acceleration of node 11 are 1.3Hz and 1.2g in the horizontal direction of X. The corresponding peak frequency and peak acceleration of SASSI are 1.22Hz and 1.4g. The two model is calculated to obtain the zero period spectrum are respectively 0.35g and 0.34g. In the vertical direction of Z, the two model is in good agreement in the 0.1~1.5Hz low frequency band, and there is a certain difference in the acceleration spectrum in the frequency band near the peak with the increase of frequency. Its biggest difference is a difference of 0.4g. Such as the results of the node 11 of two models are respectively 0.20g and 0.27g.

The results indicate that the shape of acceleration response spectrum of quasi three dimensional models is in good agreement with the acceleration response spectrum of SASSI program, especially the peak frequency is basically consistent. But there are only some differences in amplitude, it's because of because of the different ways of considering soil structure interaction in two kinds of models. The SSI method in SASSI software mainly is the flexible volume method and the flexible contact method. In addition, the consistency of acceleration response spectrum peak frequency shows the rationality of simplified equivalent nuclear plant structure. So pseudo three-dimensional seismic response analysis results are reasonable and reliable structure of nuclear plan.
Calculation Cost Analysis

Table 3 is the comparison of model calculation table. We can see that the modeling time and solution time of the three-dimensional model of SASSI are larger than that of the quasi three-dimensional analysis model, and in the number of nodes and units, storage capacity is also far beyond the quasi three-dimensional analysis mode.

<table>
<thead>
<tr>
<th>Item compared</th>
<th>Element number</th>
<th>Node number</th>
<th>Modeling time (d)</th>
<th>Solution time (h)</th>
<th>Archive file Capacity(MB)</th>
<th>Data file Capacity(MB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Three-dimensional</td>
<td>846</td>
<td>88</td>
<td>7</td>
<td>72</td>
<td>1000</td>
<td>102</td>
</tr>
<tr>
<td>Quasi three dimensional</td>
<td>271</td>
<td>28</td>
<td>0.2</td>
<td>0.5</td>
<td>20</td>
<td>535</td>
</tr>
</tbody>
</table>

Conclusions

(1) The frequency of the model is compared with the simplified model, we can find that the two-dimensional model is in good agreement with the vibration characteristics of the original three-dimensional model in the 0.1~12Hz frequency range. Their differences are increased with the increase of the frequency order, but the overall difference is not large. Low frequency modes have great impact on the structure response in the dynamic analysis of the actual nuclear plant structure. So dynamic response analysis can be used to simplify the model.

(2) The calculated acceleration response spectrum shape and peak frequency are in agreement with the results calculated by SASSI software, and the amplitude only has a certain difference. It not only further shows the rationality of simplified structure of upper island, but also proves that the proposed 3D model of AP1000 nuclear island seismic response analysis is effective and reliable.

(3) By comparing the computational cost of the proposed three-dimensional model and the true three-dimensional model, we can find that the quasi three-dimensional model is superior to the three-dimensional model in the aspects of modeling, solving, data processing and storage capacity. So adequate attention should be paid to the quasi three dimensional analysis in the actual engineering calculation with the island site ground conditions are becoming more and more complicated.

References


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