Analysis of the impact of rock hardness on the seismic response characteristics of CAP1400 nuclear island structure

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Abstract. With the rapid development of the nuclear power industry, appropriate sites for nuclear power plants have become a scarce resource. The construction of a nuclear power plant is subject to stringent requirements of site selection, and it is necessary to ensure that the plant will have sufficient seismic resistance. In this study, targeting the CAP1400 nuclear island structure as the research object, a three-dimensional finite element model of the dynamic interaction between the nuclear island structure and the foundation is established by considering the nonlinear characteristics of rocks using ABAQUS software. Our objective is to analyse the impact of rock hardness on the acceleration, displacement and floor response spectrum of the nuclear island structure caused by earthquake based on a total of 4 types of rock foundations with different degrees of hardness. The results show that, with the increase of rock hardness, the acceleration of the nuclear island structure increases, the displacement decreases, while the peak of floor response spectrum increases and moves towards the short period (high frequency band) direction. The seismic response of the nuclear island structure increases with the increase of elevation, and the greatest level of response is observed at the cooling water tank of the shield building, which therefore should be targeted as the key for seismic design. For rock foundations with high hardness, the seismic design for the nuclear island structure can follow the standard for rigid foundations so as to ignore the effect of the soil-structure dynamic interaction.

1. Introduction
CAP1400 is a large-scale, advanced passive nuclear power technology in China formulated based on AP1000. With the CAP1400 demonstration project settled in Rongcheng of Shandong Province, China will gradually form the nuclear power plant construction pattern dominated by the CAP1400 nuclear island structure. The site selection and survey for nuclear power engineering projects will certainly extend from coastal areas to inland areas, and will inevitably encounter a variety of site selection problems in non-bedrock areas [1]. The AP1000 standard, which is on the basis of hard rock sites, requires the shear wave velocity to be greater than 2400m/s [2-3]. To date, the existing nuclear power plants are mainly built on hard rocks, so there is very limited knowledge and experience on the seismic response characteristics of nuclear power structures built on soft rock foundations as well as the impact of soft rock foundations on the structure-foundation dynamic interaction in nuclear power plants.
In recent years, scholars both at home and abroad have carried out some preliminary research on the structure-foundation dynamic interaction of nuclear power plants. Bhauamik applied the non-linear Winkler foundation beam method to simulate the soil-structure interaction, which mainly focused on the analysis of seismic response of the nuclear island reactor shear wall, without investigating the impact of the change in site conditions [4]. Kim based on a new boundary analysis method, analysed the seismic response characteristics of the nuclear reactor structure under soil-structure interaction, but the centralized mass model they adopted for the structure is a bit too simple[5]. Lv Tao analysed the seismic response characteristics of the building structural foundation of nuclear power plants under earthquakes by considering the foundation-base dynamic interaction, and compared the influence of different levels of rock hardness on the acceleration response spectrum of the foundation; however, they did not perform any seismic response analysis for the nuclear island structure [6]. Jin Yuhao targeting the CPR1000 stacked reactor building structure as the research object, applied equivalent linearity to simulate the nonlinearity of the soil body and analysed the seismic response of the nuclear island building structure under different foundation conditions [7], the centralized mass reduction model they adopted is similar to that adopted by Kim. Li Xiaojun applied the one-dimensional soil layer model to analyse the site effects of designing ground motion according to the 5 types of non-hard rock sites in the design of AP1000 nuclear island structure foundation, namely firm rock (FR), soft rock (SR), upper bound of soft-to-medium soil (SMS-UB), soft-to-medium soil (SMS) and soft soil (SS) [8].

It can be seen that the nuclear power plant models established in aforementioned studies are relatively simple and mainly based on a single type of foundation, and thus, the integrity of the nuclear power plant structure could not be properly investigated. Therefore, this paper, targeting the CAP1400 nuclear island structure as the research object, intends to consider the nonlinear characteristics of rocks and establish a three-dimensional nonlinear seismic response model for the nuclear island structure-rock foundation system based on rock foundations of different levels of hardness. The objective of this study is to analyse the impact of rock hardness on the acceleration, displacement and response spectrum of the nuclear island shield building and containment vessel, in order to provide necessary reference for the site selection and seismic design of nuclear power plants both at home and abroad.

2. Establishment of finite element model

2.1. CAP1400 nuclear island(NIS) model

The CAP1400 nuclear island structure mainly consists of the shield building (SB), the steel containment vessel (SCV), the internal structure, and the auxiliary building (AB), which is collectively located on a raft foundation with a thickness of about 1.8m. The NIS has approximately a height of 87.75m, a length of 90.80m, and a width of 57.70m. The lower part of the SB adopts a reinforced concrete structure, while the upper part adopts a steel plate concrete structure. The outer diameter of the SB is about 47.97m and the wall thickness is about 1.10m. The SCV is about 65.70m in height and 39.70m in diameter, with the internal structure consisting of the reinforced concrete base, the reactor cooling circuit, the voltage stabilizer, the crane beam, etc. The auxiliary building nearby the SB usually adopts the reinforced concrete shear wall structure.

The CAP1400 NIS model is established using the ABAQUS finite element software. The SB, the auxiliary building and the SCV are simulated by the vessel element. The concrete base and the concrete foundation inside the vessel are simulated by the solid element. The internal reactor cooling equipment and the crane beam are simulated by the beam element. The equipment installation floor inside the vessel and the nuclear island raft foundation are simulated by the vessel element. Figure 1(a) shows the three-dimensional finite element model of the NIS. The NIS has a buried depth of 11.7m; the foundation has a depth of 50m, a length of 550m, and a width of 540m, and adopts the viscoelastic artificial boundary [9]. Figure 1(b) illustrates the overall finite element model of the NIS-rock foundation.
2.2. Calculation parameters

In order to analyse the seismic response characteristics of the CAP1400 nuclear island structure on rock foundations of different levels of hardness, we selected 4 types of rock formations from the general site selection scenarios of nuclear power plants, which are referred to as “soft rock”, “medium-soft rock”, “medium-hard rock” and “hard rock” according to the level of rock hardness. Then, the modified constitutive model based on the Davidenkov skeleton curve, which was proposed by Zhao DF [10-11], was adopted for analysis. The relevant calculation parameters are presented in Table 1. The unit weight of the concrete structure and the steel plate is 2500kg/m$^3$ and 7800kg/m$^3$, the elastic modulus is 34.5GPa and 210GPa, and the Poisson’s ratio is 0.2 and 0.3, respectively.

| Rock hardness       | Density (kN/m$^3$) | Shear wave velocity (m/s) | Elastic modulus (GPa) | Poisson’s ratio | Parameters of the constitutive model |
|---------------------|-------------------|---------------------------|-----------------------|-----------------|-------------------------------------|
| Soft rock           | 22.0              | 835                       | 16.8                  | 0.40            | A: 1.465, B: 0.394, $\gamma_r$/%: 43.72 |
| Medium-soft rock    | 24.0              | 1150                      | 21.5                  | 0.36            | A: 1.637, B: 0.356, $\gamma_r$/%: 50.42 |
| Medium-hard rock    | 25.5              | 1900                      | 25.7                  | 0.33            | A: 1.768, B: 0.321, $\gamma_r$/%: 56.38 |
| Hard rock           | 26.0              | 2500                      | 29.2                  | 0.32            | A: 1.912, B: 0.304, $\gamma_r$/%: 62.27 |

2.3. Input of seismic ground motion

The site selection of nuclear power plants is subject to very stringent requirements. In most cases, there would not be any seismic fault zone around, so it is mainly necessary to consider the impact of far-field ground motion. Therefore, in this study, the SUCHIL wave of the Michoacan earthquake in Mexico was used. This seismic wave is 226.4 km away from the causative fault, belonging to a typical far-field ground motion, and it contains rich low-frequency components. The original acceleration time history and Fourier spectrum are shown in Figure 2. The ground motion strength for the bed rock was set to be 0.20g, which was input along the direction where the structural rigidity of the nuclear island is relatively weak.
3. Analysis of seismic time history

3.1. Acceleration

In this paper, two observation points were selected for the NIS: Point A at the top of the SB and Point B at the top of the SCV. Figure 3 presents the acceleration time history of the observation points on different rock sites. It can be seen that the acceleration time history curves are similar under different working conditions, but the acceleration response at the top of the SB is stronger than that at the top of the SCV. This is mainly because the upper part of the SB is of a sloped roof structure, which is about 20m higher than the SCV. In view of that the cooling water tank on the top of the SB is an important part of the NIS [12], it is necessary to attach a particular importance to the seismic design of the SB.

Figure 3. Acceleration time history of the NIS observation points

Figure 4 illustrates the relationship between the peak acceleration and height for the SB and the SCV. It can be seen that the peak acceleration at the bottom of the NIS decreases with the increase of the elevation, while the peak acceleration at the bottom of the SCV decreases more significantly. This is mainly attributed to an extremely high stiffness of the base plate of the NIS. As the height increases further, the peak acceleration of the SB and the SCV is constantly increasing. Specifically, the SB exhibits a sudden change at the height of 35m under the influence of the auxiliary building. The peak acceleration reaches to the maximum value at the top of the SB and the SCV.

Figure 4. Relationship between peak acceleration and height for NIS

According to Figure 4, different levels of rock hardness exert different effects on the acceleration of the NIS. As the rock hardness increases, that is, the shear wave velocity increases, the peak acceleration of the NIS exhibits an increasing trend, with the increasing amplitude getting smaller, which means the NIS built on a harder rock site is subject to a stronger seismic response. The peak
acceleration of the NIS built on a hard rock site is only slightly larger than that of the NIS built on a medium-hard rock site, and its increasing amplitude can be neglected. Therefore, the NIS seismic built on hard rock site can be designed according to the standard for rigid foundation.

3.2. Displacement

Figure 5 presents the displacement time history of the NIS at the observation points. It can be seen that the displacement time history curves of the SB and the SCV are similar to each other, while the former has a stronger response. The NIS exhibits an obvious swing phenomenon, which may impact the piping system and equipment inside the SCV. This warrants serious attention from the equipment engineers and structural designers of the nuclear power plants.

Figure 6 illustrates the relationship between the peak displacement and height for the SB and the SCV. It can be seen that the peak displacement of the SB is basically greater than that of the SCV. Overall, the peak displacement exhibits an increasing trend with the increase of the elevation, except that a slight decrease is observed at the bottom. The increasing trend of the peak displacement at the sloped roof of the SB appears to be slower. The softer the rock foundation, the greater the peak displacement of the SB and the SCV is. Specifically, the peak displacement of the NIS built on a soft rock site is significantly greater than that of the NIS built on other sites, that is, the amplitude is larger and can be up to 6 cm, but this is compliant with the elasticity design requirement for the NIS [2].

Figure 5. Displacement time history of the NIS at the observation points

Figure 6. Relationship between peak displacement and height for the NIS
4. Analysis of floor response spectrum

The acceleration response spectrum can reflect the impact of the input ground motion on the upper structure. The seismic design of the nuclear power plant must be based on the response spectrum [13]. For this reason, Figure 7 shows the floor response spectrum of the NIS at the observation points (represented by the normalized response spectrum, i.e., the dynamic coefficient $\beta$ spectrum). It can be seen that, in the short-term period (0-0.2s), the floor response spectrum of the NIS built on a harder rock foundation is greater, while in the mid-term period (0.2-1.5s), the floor response spectrum of the NIS built on a softer rock foundation becomes greater. In the long-term period (>1.5s), the floor response spectrum of the NIS has appeared to be very small, and the effect of rock hardness can be neglected. With the increase of the shear wave velocity, the peak of floor response spectrum of the NIS exhibits an increasing trend and gradually moves towards the short-term period direction (high frequency band). More specifically, the floor response spectrum of the NIS built on a medium-hard rock site and built on a hard rock site is consistent with each other, but only the peak of response spectrum slightly increases; the period of excellence remains unchanged.

Figure 7. Floor response spectrum of the NIS at the observation points

According to Figure 7, the peak of floor response spectrum of the SB is greater than that of the SCV, which reflects the amplification effect of the SB and SCV on the input ground motion. With the increase of the foundation stiffness, i.e., the shear wave velocity, the period of excellence of the floor response spectrum of the SB has a slighter reduction (0.07s), while that of the SCV has a bigger reduction (0.20s). This is because the SB is of a reinforced concrete structure, while the SCV is made of steel plate. The difference between the two different structural systems leads to a significant difference in the period of excellence.

5. Conclusions

In this paper, the ABAQUS software is used to calculate and analyse the dynamic interaction between the NIS and the foundation system for 4 types of rock sites, namely soft rock, medium-soft rock, medium-hard rock, and hard rock. On such basis, we investigated the impact of rock hardness on the seismic response of the NIS and obtained the following conclusions:

(1) As the hardness of rock foundation increases gradually, both the acceleration response and the peak of floor response spectrum of the NIS increase and move towards the short-period direction (high-frequency band). For the observation points at different elevations of the SB and SCV, the acceleration shows an increasing trend with the increase of elevation.

(2) The displacement of the SB and SCV also shows an increasing trend with the elevation. As the foundation hardness increases, the displacement of the SB and SCV shows a decreasing trend, that is, the amplitude of the NIS built on a hard rock foundation is smaller. This is why hard rock sites are the first choice for nuclear power plants.

(3) In view of that the cooling water tank is installed on the top of the NIS, where a greater acceleration and displacement is observed, special attention must be paid during seismic design. For a hard rock foundation, the seismic response and seismic analysis of the NIS can be considered
according to the standard for a rigid foundation, while there is no need to take the dynamic interaction between the NIS and the foundation into account.

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References
[1] Kong XJ, Lin G. (2013) Research advances on engineering structural seismic safety of nuclear power plant. Strategic Study of CAE, 15: 62-74.
[2] Westinghouse Electric Company. (2009) AP1000 design control document, Revision17. Nuclear Regulatory Commission, Maryland.
[3] Leonardo T.S., Richard S.O., Sener T., Diego P.R. (2007) Finite element modeling of the AP1000 nuclear island for seismic analyses at generic soil and rock sites. Nuclear Engineering and Design, 237: 1474-1485.
[4] Lopamudra Bhaumik, Prishati Raychowdhury. (2013) Seismic response analysis of a nuclear reactor structure considering nonlinear soil-structure interaction. Nuclear Engineering and Design, 265: 1078-1090.
[5] Kim J.M., Lee E.H., Lee S.H. (2016) Boundary reaction method for nonlinear analysis of soil–structure interaction under earthquake loads. Soil Dynamics and Earthquake Engineering, 89: 85-90.
[6] Lv T, Yang QY, Geng XY, Chen LW, Yang LJ, Li HB. (2010) Study of influence of rock hardness on characteristic of seismic response of bedrock-foundation of nuclear power plants. Rock and Soil Mechanics, 31: 1319-1325.
[7] Jin YH, Yin XQ, Wang GX. (2015) Effects of different ground condition on seismic response of nuclear island. Journal of Huaqiao University (Natural Science), 36: 710-715.
[8] Li XJ, Hou CL, Dai ZJ, Mei ZH. (2015) Research on site effects of soil layers and bedrock on designing the foundation of NIS. Rock and soil mechanics, 36: 2201-2208.
[9] Zhang XL, Li XI, Chen GX, Zhou ZH. (2016) An improved method of the calculation of equivalent nodal forces in viscous-elastic artificial boundary. Chinese Journal of Theoretical and Applied Mechanics, 48: 1126-1135.
[10] Zhao DF, Ruan B, Chen GX. (2017) Validation of modified irregular loading-unloading rules based on Davidenkov skeleton curve and its equivalent shear strain algorithm implemented in ABAQUS. Chinese Journal of Geotechnical Engineering, 39: 888-895.
[11] Martin P.P., Seed H.B. (1982) One-dimensional dynamic ground response analyses. Journal of the Geotechnical Engineering Division, 108: 935-952.
[12] Park J.B., Lee S.J., Lee E.H., Park N.C., Kim Y.B. (2019) Seismic responses of nuclear reactor vessel internals considering coolant flow under operating conditions. Nuclear Engineering and Technology, 51: 1658-1668.
[13] USNRC. (1973) Design response spectra for seismic design of nuclear power plants. Nuclear Regulatory Commission, Maryland.