Influence of Soil Secondary Nonlinearity Effect on Seismic Response of Nuclear Island Structure

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Abstract: The effect of soil-pile-structure interaction (SPSI) is becoming one of the key issues in the seismic design of the nuclear island structures built on non-bedrock sites. The 3D lumped-mass stick (LMS) model of the AP1000 nuclear island structure considering the SPSI effect is developed to represent the steel containment vessel, the containment internal structures, and the coupled shield and auxiliary buildings supported by the pile-raft foundation. To improve the calculation efficiency, the 3D model is simplified into the equivalent 2D models in the X-Z and the Y-Z planes through vector decomposition of the 3D components and their interactions. The soil nonlinear behavior is termed the soil primary nonlinearity effect and the soil secondary nonlinearity effect (SSNE). The influence of SSNE caused by the effect of SPSI on the seismic responses of the AP1000 nuclear island structure is studied using various bedrock motions. The results show that: (1) Compared with the vertical seismic responses of the nuclear island structure, the SSNE of the horizontal responses is more obvious, and is stronger for bedrock motions with intense high-frequency components; (2) The influence of SSNE on the responses of the nuclear island structure has a positive correlation with its heights and bedrock motion levels; (3) Because of the SSNE, the peak accelerations and the peak relative displacements of the nuclear island structure decrease and increases respectively; while the 5% damped spectral accelerations of the nuclear island structure decrease in the shorter periods and increase in the mid-long periods. (4) For the peak relative displacements, the shorter the predominant periods of bedrock motions are, the higher the proportion of SSNE in the nonlinear effect of SPSI is. In general, the existence of SSNE will increase the flexibility and the energy consumption of the SPSI system of the nuclear island structure, and thus it is inappropriate to overlook SSNE arbitrarily.

1. Introduction

Considering the rapid development of nuclear power plants (NPPs) projects and the condition limitation of NPP site selection, more and more nuclear power facilities will be built on non-bedrock sites. The seismic response of NPP on non-bedrock sites is much more complex than that on rock sites, thus the seismic response characteristics of NPPs build on non-bedrock site is indispensable [1]. A variety of soil-structural interaction (SSI) effects on the seismic responses of the nuclear island structure have been investigated in recent years. The influence of SSI may cause great amplification of seismic response of the nuclear island structure [2-3]. Chen and Maslenikov investigated the seismic responses of the nuclear reactor facility considering the SSI effect and found that the floor response...
spectra are highly sensitive to soil stiffness [4]. Tunon-Sanjur et al. established the lumped-mass stick (LMS) model and the fine finite shell and solid element model of the nuclear island structure, combined with the equivalent linear model of soil for considering the SSI effects, to analyze and compare the floor response spectra in the programs ANSYS and SASSI [2]. Wang et al. simulated the AP1000 nuclear island structure with shell and solid elements, analyzed the 3D seismic responses of the viscoelastic system of soil-nuclear island structure, and found that the influence of SSI effect on the seismic responses of the nuclear island structure built on soil site cannot be overlooked [5]. Farahani et al. discussed the seismic responses of the nuclear island structure which was built on a soil site and considering degraded concrete stiffness [6]. The results of the excitation of three-way earthquake motions shown that the influence of SSI on the response of the nuclear island structure is significant, especially for the earthquake motions with intense high-frequency components. The previous studies for the seismic responses of the nuclear island structure built on soil sites were mostly limited in the equivalent linear approach to consider the soil nonlinearity in the free field, but not to consider the influence of the soil secondary nonlinearity effect (SSNE) caused by SSI. Sometimes, the soils are also regarded as some kind of equivalent viscoelastic material, and the effect of soil nonlinearity on the seismic responses of NPPs is not considered.

Due to the condition limitation of NPP site selection, some NPPs will be built on non-bedrock sites improved by group piles. The effect of soil-pile-structure interaction (SPSI) is becoming one of the key issues in the nuclear island structure seismic design, but no similar research results have been reported in the literature. There are three nonlinear behaviors in a nonlinear SSI problem that should be independently validated: soil nonlinearity, structural nonlinearity, and contact interface nonlinearities (sliding and/or separation) [7]. It is similar to a nonlinear SPSI problem and this paper only focuses on the soil nonlinearity with elastic structure and rigid interactions between the structures, piles, and soils. It is considered that the primary material nonlinearity of soil under free field conditions is the soil primary nonlinearity. The further change in soil primary nonlinearity, which is induced by the interaction between the overlying structure, the foundation, and the site, is considered as the soil secondary nonlinearity.

In this way, it is a question whether the influence of SSNE derived from the effect of SPSI on the seismic responses of the nuclear island structure can be reasonably overlooked or not. Therefore, the significance of SSNE and its influence on the seismic response of the nuclear island structure is worth pursuing.

In this paper, an AP1000 nuclear island structure supported by a pile-raft foundation is taken as the research object, a 3D lumped-mass stick model is developed to represent the steel containment vessel, the containment internal structures, and the coupled shield and auxiliary buildings of the AP1000 nuclear island structure [8]. To improve the calculation efficiency, the 3D model is simplified to two equivalent 2D models in the X-Z and the Y-Z planes through vector decomposition of the 3D parts and their interactions. The large-scale 2D numerical analysis of the seismic responses of the nuclear island structure supported by pile-raft foundation subjected to bedrock motions is carried out on the ABAQUS platform [9]. In addition, two methods are adopted: 1. The one-step method: performing the time-transient response analysis of the soil-pile-raft foundation- nuclear island structure system using the stress-strain hysteresis formulation for describing the nonlinearity of the soil. 2. The two-step method: Firstly, carrying out the nonlinear site response of the free field, then using the equivalent viscoelastic parameters of soils obtained from the first step to calculate the time-transient responses of the equivalent 2D models of the soil-pile-raft foundation- nuclear island structure system. The calculation cases of the two methods and the cases in the rigid ground condition are compared, thus, the influence of the SSNE that derived from the effect of SPSI on the seismic responses of the nuclear island structure can be investigated and highlighted.
2. Geological conditions and numerical modeling

2.1. Site condition
The AP1000 NPP has been planned to be built on the soft soil site near a coast in China. The soil layers are composed of the the Quaternary Holocene ocean-land cross sediments and the Quaternary upper Pleistocene ocean-land cross sediments. The top layer consists of silty clay with a low Vs of 105 m/s. The underlying substrata mainly consist of interbedded layers of silty clay with silty sand interbed (Vs = 102 m/s) and soft silty clay (Vs = 239 m/s), three layers of different kinds of silty clay (top to bottom, Vs = 237 m/s, Vs = 254 m/s, Vs = 325 m/s), a mass of silty sand (Vs = 346 m/s) and a layer of vesicular basalt (Vs = 1360 m/s). These soils are classified according to the unified soil classification system and the shear wave velocities are measured through the down-hole PS logging method. The underlying weathered bedrock (dense basalt) has a high Vs close to 2500 m/s, which is regarded as the bedrock for AP1000 NPP following ASCE/SEI43-05 [10-11]. To improve the calculation efficiency, the site as shown in Figure 1 is regarded as a horizontal stratified isotropic soil site because of the low fluctuation in the stratigraphic section.

![Figure 1. Stratigraphic section of the nuclear island site.](image)

2.2. Bedrock motions and artificial boundary condition
Based on the results of the seismic hazard analysis for the AP1000 NPP site using the deterministic method and probabilistic method, two seismic design levels of the AP1000 NPP were selected, i.e., the horizontal peak accelerations (PAs) at seismic bedrock interface are 0.10 $g$ and 0.20 $g$ for the SL-1 level and the SL-2 level, respectively, here, $g$ denotes the gravitational acceleration. According to the AP1000 design control document, the vertical peak acceleration is conservatively assumed to be the same as those of the two horizontal directions, i.e., the three-way peak accelerations at the seismic bedrock interface are the same.

Given the magnitude and epicenter distance similarity with the historical earthquakes in the near region of the NPP site, two bedrock records (2016 Aizuwakamatsu earthquake and 1985 Michoacán earthquake) are selected as input bedrock motions in the numerical modeling. Both EW and UD components, as well as both NS and UD components, are performed in the X-Z plane and Y-Z plane 2D models, respectively. The information of the original records from the Aizuwakamatsu earthquake and the Michoacán earthquake are shown in table 1 and Figure 2, respectively. Two levels (SL-1 and SL-2) of input peak bedrock accelerations (PBAs), including both horizontal and vertical components, are produced by scaling the original record PGAs.
To limit the dimensions of the computational model, only a part of the site most affected by the input excitation is mapped onto the computational domain, with the remainder captured by an artificial boundary condition. The 2D viscous-spring artificial side boundaries are used on the side boundary of the model to deal with the effect of the outgoing wave radiation toward infinity [12]. The bottom boundaries of the 2D models are considered to be rigid.

**Table 1.** Original seismic record information used as bedrock motions in this study

| Earthquake, Year | Moment magnitude | Station code | Epicenter distance (km) | Ds,95 (s) | Predominant period (EW/NS/UD) | Sampling frequency (Hz) |
|------------------|------------------|--------------|-------------------------|-----------|-------------------------------|------------------------|
| Aizuwakamatsu, 2016 | 7.4              | FKS023       | 146                     | 24.19     | 0.12s/0.32s/0.23s             | 100                    |
| Michoacán, 1985  | 8.1              | SUCHIL       | 226.4                   | 14.91     | 0.60s/0.35s/0.36s             | 100                    |

**Figure 2.** Acceleration time histories and Fourier spectra of the original seismic records

2.3. **Modeling of the AP1000 nuclear island structure**

A node to surface constraint method is used to connect the bottom of the 3D AP1000 nuclear island structure model (i.e., Node 500) to the top surface of the raft. Thus, the AP1000 nuclear island structure, the group-piles, and raft foundation, and the site can be formed as a whole 3D system [8]. The calculation scale of nonlinear seismic response analyses of the whole 3D system is enormous. For the sake of improving the calculation efficiency, the 3D model is simplified into two equivalent 2D models through vector decomposition of the 3D parts and their interactions, in the X-Z and the Y-Z planes, respectively. The detailed model is shown in Figure 3.

The 2D simplification of the 3D nuclear island structure model is mainly based on the vector decomposition of the 3D components and the 3D constraint association between the components and nodes in the X-Z plane and the Y-Z plane. Take the X-Z plane model, for example, the width of the site in the horizontal X direction is set as 400 m. Meanwhile, the relative difference between
coordinates of all the nodes in the 3D model in the X direction and the Z direction is kept unchanged. Besides, the vector decompositions of the 3D constraints, couplings, and other interactions between structural components and nodes are performed, the components in X and Z directions are reserved and the relative difference values of coordinates and constraint components in the Y direction are all set to zero. Then the simplified 2D plane model can be established and analyzed. It is similar to the simplification of the 2D model in the Y-Z plane [13-14]. Detailed magnification diagrams of the 2D nuclear island structure models are shown in Figures 3(e) and (g).

For validation of the 2D simplification of the 3D nuclear island structure model, a comparison of the PAs between the 2D and 3D models is carried out, in Figure 4. It can be noticed all the deviations between the PA responses of the 2D model and the 3D model are smaller than 10% and most of the deviations of the PAs are smaller than 5%. Therefore, the 2D simplified models are reliable.

Figure 3. Overview diagrams of the AP1000 nuclear island structure for the finite element model.
2.4. Modeling of pile-raft foundation and site
The group piles and the raft foundation are simulated with concrete C40 and regarded as an elastic material. The irregular-shaped raft is 3 m thick, and the long side size of the raft is 78.03 m and the short side is 54.478 m, as shown in Figure 3(b). There are 230 piles in total, the diameter of the pile is 1.5 m and the length is 36 m. Furthermore, the pile top is embedded into the raft with 0.15 m, and the pile bottom is embedded into basalt with 2 m. In the 2D model, the group piles are simplified into 20 and 9 equivalent piles in the X-Z plane and Y-Z plane, respectively. The pile is simulated by the B21 element in ABAQUS. The hypothesis that ignoring the slip between underground structures and surrounding soil is safe [15]. Therefore, the raft and surrounding soil are combined by the tie constraint in ABAQUS without considering relative slip and movement. Each pile is divided into two parts: one part embedded in the raft and the other part embedded in soil and rock. In this way, the 3D model of the nuclear island structure-pile-raft foundation is simplified, as shown in Figure 3(b). Two large-scale 2D refined finite-element models are established as shown in Figures 3(a), (c), and (d).

The mesh size with spatial varying in the horizontal and vertical directions should be smaller than approximately one-tenth to one-eighth of the wavelength associated with the highest cutoff frequency $f_{\text{max}}$ to avoid numerical damping [16], here, $f_{\text{max}} = 25 \text{ Hz}$. The CPE4 element in ABAQUS is mainly used in soil and raft simulation. To obtain a valid solution, the time step size $\Delta t$ estimated by ABAQUS/Explicit is set as $10^{-5} \text{ s}$.

2.5. Nonlinear constitutive model of soil and its parameters
A set of non-Masing rules for irregular loading conditions associated with earthquakes are used to model the hysteretic behavior of soil in Figure 5(a) [17-18]. The initial skeleton curve of the hysteresis model follows the Davidenkov equation:

$$
\tau = G_{\text{max}} \gamma \left[ 1 - H(\gamma) \right]
$$

(1)

$$
H(\gamma) = \left( \frac{\gamma / \gamma_r}{1 + (\gamma / \gamma_r)^A} \right)^B
$$

(2)

where $\tau$ is shear stress; $G_{\text{max}}$ is initial shear modulus; $\gamma$ is shear strain; $H(\gamma)$ is the function describing the shape of stress-strain relationship; $A$ and $B$ are non-dimensional constants, $\gamma_r$ is reference shear strain.

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**Figure 4.** Comparison of the peak accelerations between the 2D model and the 3D model for the AP1000 nuclear island structure under (a) FKS023 and (b) SUCHIL.
The constitutive model adopted in this analysis has been used repeatedly to conduct the 2D or 3D nonlinear analysis in a series of researches during the past three years [18-21]. The model parameters of soils are listed in Table 2, which are obtained based on the laboratory tests of undisturbed soil samples collected from the boreholes at the AP1000 nuclear island structure site.

### Table 2. Constitutive model parameters of soils used in this study.

| No. | Soil                                 | P-wave velocity (m/s) | S-wave velocity (m/s) | Density (kg/m³) | Parameter A | Parameter B | Parameter γr (×10⁻⁴) |
|-----|--------------------------------------|------------------------|------------------------|-----------------|-------------|-------------|---------------------|
| 1   | Silty clay①                          | 1485                   | 105                    | 1810            | 1.03        | 0.47        | 5.28                |
| 2   | Silty clay with silty sand interbed  | 1500                   | 102                    | 1900            | 1.01        | 0.45        | 6.04                |
| 3   | Mucky silty clay                     | 1509                   | 239                    | 1930            | 1.03        | 0.46        | 5.90                |
| 4   | Silty clay②                          | 1503                   | 237                    | 1890            | 1.03        | 0.45        | 6.01                |
| 5   | Silty clay③                          | 1530                   | 254                    | 1940            | 1.04        | 0.45        | 6.61                |
| 6   | Silty clay④                          | 1548                   | 325                    | 1960            | 1.06        | 0.44        | 7.41                |
| 7   | Silty sand                           | 1629                   | 346                    | 2010            | 1.08        | 0.44        | 8.29                |
| 8   | Vesicular basalt                     | 3020                   | 1360                   | 2620            | 1.20        | 0.401       | 10.50               |

3. The effect of soil secondary nonlinearity on the seismic responses of the nuclear island structure

To analyze and highlight the influence of SPSI-induced SSNE on the seismic response of the AP1000 nuclear island structure, the calculation cases are listed in Table 3.

3.1. Peak acceleration response

The peak accelerations of the containment vessel and the shield building with the height are shown in Figures 6 and 7. For the response of the 2D model in the X-Z plane subjected to the EW and UD components of bedrock motion FKS023, the variation of the horizontal peak accelerations of the containment vessel with the height is slightly different from those of the shield building. For the heights above 75 m, the horizontal peak accelerations in the Case 2 and Case 3 are very close, and in Case 1 are lowest, which indicates that the soil primary nonlinearity effect has little effect on the horizontal peak acceleration responses of the nuclear island structure. On the other hand, for with the heights below 75 m, the horizontal peak accelerations of the nuclear island structure in Case 2 are
largest, followed by Case 3, and lowest in Case 1, which indicates that the soil primary nonlinearity effect amplifies the horizontal peak acceleration responses at the lower part of the nuclear island structure, whereas the SSNE strongly decreases the horizontal peak acceleration responses. For the response of the 2D model in the X-Z plane subjected to the EW and UD components of bedrock motion SUCHIL, the variation of the horizontal peak accelerations of the nuclear island structure with the height is monotonic increasing. Furthermore, the difference of the peak accelerations of the nuclear island structure in Case 5 and Case 4 is almost irrelevant to the height, i.e., the influence of SSNE on the horizontal peak acceleration responses of the nuclear island structure is independent of the height. It seems that the SSNE is not susceptible to the horizontal peak acceleration responses of the nuclear island structure subjected to the bedrock motion with the dominant long period components.

### Table 3. Summary of calculation cases.

| Model                  | Input bedrock motion (components) & (PBA level) | Calculation case | Soil primary nonlinearity effect | Soil secondary nonlinearity effect |
|------------------------|-------------------------------------------------|------------------|---------------------------------|-----------------------------------|
| **2D Model in X-Z Plane** | FKS023 (EW+UD) & (SL-1 & SL-2)                  | 1 (One-step method) | √                               | √                                 |
|                        |                                                 | 2 (Two-step method)| √                               | ×                                 |
|                        |                                                 | 3 (Rigid ground)  | ×                               | ×                                 |
|                        | SUCHIL (EW+UD) & (SL-1 & SL-2)                  | 4 (One-step method)| √                               | √                                 |
|                        |                                                 | 5 (Two-step method)| √                               | ×                                 |
|                        |                                                 | 6 (Rigid ground)  | ×                               | ×                                 |
| **2D Model in Y-Z Plane** | FKS023 (NS+UD) & (SL-1 & SL-2)                  | 7 (One-step method)| √                               | √                                 |
|                        |                                                 | 8 (Two-step method)| √                               | ×                                 |
|                        |                                                 | 9 (Rigid ground)  | ×                               | ×                                 |
|                        | SUCHIL (NS+UD) & (SL-1 & SL-2)                  | 10 (One-step method)| √                              | √                                 |
|                        |                                                 | 11 (Two-step method) | √                              | ×                                 |
|                        |                                                 | 12 (Rigid ground)  | ×                               | ×                                 |

For the response of the 2D model in the Y-Z plane subjected to the NS and UD components of FKS023, the horizontal peak accelerations of the nuclear island structure increase monotonically with the height, the horizontal peak accelerations of the nuclear island structure in Case 8 are the largest, followed by Case 7, and lowest in Case 9. It is demonstrated that the soil primary nonlinearity effect can greatly amplify the horizontal peak acceleration responses of the nuclear island structure, but this amplification is significantly weakened due to the existence of SSNE. However, the influence of the soil primary and secondary nonlinearity effects on the PAs of the nuclear island structure are positively correlated with the bedrock motion levels and the height. Additionally, the SSNE plays a key role in magnifying the PAs for heights below 55 m, which is slightly different from those in the X-Z plane.

For the vertical peak acceleration responses of the 2D model in the X-Z plane, the soil primary nonlinearity effect can result in a moderate amplification. But this amplification can be slightly weakened if the SSNE is considered because the height of the nuclear island structure plays a minor role in the vertical peak acceleration responses.

3.2. Spectral acceleration response

As discussed above, the influence of the soil SSNE is more susceptible with increasing height. Here, the normalized spectral acceleration (SA) $\beta_s$ (5% damping) at the top of the shield building for the intensity of SL-2 level are shown in Figure 8.

For the 2D model in the X-Z plane, the $\beta_s$ values of horizontal spectrum accelerations at the periods of less than 0.1 s in Case 1 and Case 2 are smaller than those in Case 3. This indicates that the soil
primary nonlinearity effect weakens the high-frequency responses of the shield building. Moreover, the $\beta$ values in Case 1 are the lowest, which illustrates the SSNE can further weaken the high-frequency responses of the shield building. The $\beta$ values at the periods above 0.28 s in Case 1 are the largest, followed by Case 2, and are lowest in Case 3. Compared with the spectrum acceleration responses of shield building under the rigid foundation, the soil primary nonlinearity effect plays a key role in the spectrum acceleration amplifications at the middle-long periods, and the existence of SSNE can further increase such amplification. Moreover, the predominant period of the $\beta$ spectrum in Case 2 is consistent with that of the bedrock motion. The $\beta$ spectrum in Case 1 appears to be a bimodal phenomenon, and the main peak is shifted toward the long periods, indicating that the existence of the SSNE makes the soil-pile-raft foundation-nuclear island structure system more flexible.

Similarly, for the 2D model in the Y-Z plane, the $\beta$ values of horizontal spectrum accelerations at periods of less than 0.34 s in Case 9 are greater than those in Case 8, and the $\beta$ values in Case 7 are the lowest. This result indicates that, compared with the horizontal $\beta$ spectra of shield building under the rigid foundation, the soil primary nonlinearity effect weakens the $\beta$ values at periods of less than 0.34 s, and the SSNE further intensifies the weakening effect. At the periods of 0.34 s to 0.5 s, the $\beta$ values in Case 7 are almost identical to those in Case 9, whereas the $\beta$ values in Case 8 are much larger than those in Cases 7 and 8. This indicates that the influence of the soil primary and secondary nonlinearity effects on the $\beta$ spectra of shield building cancel out over this range of periods. However, the SSNE plays a key role in magnifying $\beta$ spectra at the middle-long periods of 0.5 s to 1.0 s. Additionally, the $\beta$ spectra response in Case 7 appears to be a bimodal phenomenon, and the predominant period is shifted toward the long periods.

![Variation of the peak accelerations of the nuclear island building with height subjected to earthquake motion FKS023.](image)

As shown in Figure 8(d), the predominant periods of the horizontal $\beta$ spectra in cases 4 to 6 are almost the same as that of the input bedrock motion, and the $\beta$ curves in Case 4 and Case 5 are almost consistent with each other. Compared with the $\beta$ curves in Cases 1 and Case 2, a marked phenomenon is observed that the soil primary and secondary nonlinearity effects strongly filter out these high-frequency components of bedrock motions. In Figure 8(e), the horizontal $\beta$ spectra at the periods of less than 0.28 s in Case 12 are highest, followed by Case 11 and are lowest in Case 10, i.e., the
coupling effects of soil primary and secondary nonlinearity strongly weaken the $\beta$ spectra of the shield building. In the periods of 0.28 s to 0.5 s, the $\beta$ values in Case 11 are larger than those in Case 10, which means that SSNE plays a key role in weakening the SA responses of shield building; whereas the soil primary nonlinearity effect plays a key role in the effect of weakening in the periods above 0.5 s. Compared with the horizontal $\beta$ spectra of the shield building, the predominant periods of the vertical $\beta$ spectra of the shield building are shifted toward the short periods. This confirms that the influence of the SSNE on the vertical $\beta$ spectra of shield building is significantly smaller than those of the horizontal $\beta$ spectra.

Figure 7. Peak acceleration at different elevations of the nuclear island structure subjected to earthquake motion SUCHIL.
3.3. Peak relative displacement response

Taking the horizontal peak displacement relative to the nuclear island structure bottom as an indicator of the magnitudes of horizontal seismic responses. Figure 9 depicts the variation of the absolute value of horizontal peak relative displacements (abbreviated as PRDs) of the containment vessel and the shield building subjected to the bedrock motions with the SL-2 level. The variations of the PRDs of the containment vessel and the shield building with height are almost identical, and the PRDs of the containment vessel are always slightly less than those of the shield building. The PRDs of the nuclear island structure calculated by the one-step method are always greater than those calculated by the two-step method, and the PRDs of the nuclear island structure considering the effect of site flexibility are always greater than those calculated by the rigid ground assumption. It indicates the SSNE makes the soil-pile-raft foundation-nuclear island structure system more flexible.

Figure 8. Normalized spectral acceleration $\beta$ (5% damping) at the top of the shield building (SL-2).
Figure 9. Absolute values of the PRD relative to the bottom (Node 500) of the nuclear island structure at different elevations.

In each subfigure of Figure 9, for each node of the nuclear island structure, there is a set of three PRDs at the same elevation, which can be compared for the differences between the one-step method, the two-step method, and the rigid foundation assumption. The magnitude of $\Delta N_{CV}$ for the containment vessel and $\Delta N_{SB}$ for the shield building in Figure 9 (a), in which the difference of PRD values calculated by the one-step method and by the rigid foundation assumption, is a proxy of the soil-pile-structure interaction (SPSI) nonlinear effect. Similarly, the magnitude of $\Delta S_{CV}$ for the containment vessel and $\Delta S_{SB}$ for the shield building in Figure 9 (a), in which the difference between the PRD values calculated by the one-step method and by the two-step method, is a proxy of the SSNE induced by the SPSI nonlinear effect. Therefore, $\Delta S_{CV}/\Delta N_{CV}$ and $\Delta S_{SB}/\Delta N_{SB}$ represent the proportion of SSNE in the SPSI nonlinear effect for the PRD responses of the containment vessel and shield building, respectively. As shown in Figure 9, the influences of the SSNE on the PRDs of the containment vessel and the shield building are very similar. In the X-Z plane, the SSNE induced by bedrock motion FKS023 is much larger than that induced by SUCHIL, and the $\Delta S/\Delta N$ induced by FKS023 is over 3 times larger than that for SUCHIL. The bedrock motion SUCHIL with a more abundant low-frequency component is quite sensitive to the existence of soft soil. The low-frequency components are amplified after passing through the soil layer, and this amplification effect is dominated by the soil primary nonlinearity effect while the $\Delta S/\Delta N$ appears smaller. Therefore, the SSNE has less influence on the PRDs for soft soil under earthquakes with more abundant low-frequency components. For the bedrock motion FKS023 with rich high-frequency components, the SSNE of the 2D model in the X-Z plane is slightly larger than that of the 2D model in the Y-Z plane;
whereas for the bedrock motion SUCHIL with rich long-period components, the SSNE of the 2D model in the Y-Z plane is much larger than that of the 2D model in the X-Z plane.

As discussed above, the results indicate that the magnitude of SSNE is closely related to the spectral characteristics and intensities of bedrock motions and the lumped-mass spatial distribution characteristics of the nuclear island structure.

4. Conclusions
In this study, a large-scale 2D refined numerical modeling of the nuclear island structure built on the group pile-raft foundation is conducted under different bedrock motions. The main conclusions are summarized as follows:

The soil primary nonlinearity effect plays a key role in the horizontal and the vertical peak acceleration responses of the nuclear island structure, and the SSNE always decreases the horizontal peak accelerations. For bedrock motions with rich high-frequency components, the influence of SSNE on the horizontal peak accelerations is strong, and this influence increases with the increase of bedrock motion levels. On the contrary, the SSNE has little influence on the vertical peak accelerations. The PA is a significant indicator in the seismic design of the nuclear island structure, when the SSNE is considered, the horizontal PA results could be more cost-effective for the seismic design.

Regarding the horizontal SA responses of the nuclear island structure, the influence of the SSNE is sensitive to the high-frequency components of bedrock motions. The SSNE significantly weakens the horizontal SAs at the short periods and amplifies the horizontal SAs at the middle-long periods, and makes the predominant period of the horizontal SAs significantly shift toward the long periods. However, the influence of the SSNE on the vertical SAs is quite moderate and makes the predominant period of the vertical SAs significantly shift to the short periods.

The SSNE significantly increases the flexibility of the soil-pile-raft foundation-nuclear island structure system, which would increase the horizontal PRDs of the nuclear island structure. Also, the SSNE induced by bedrock motions with rich high-frequency components is much larger than that induced by bedrock motions with rich long-period components. In summary, as the adverse effect cannot be neglected, when the proposed nuclear island structure needs to be supported and reinforced by the pile-raft foundation, the displacement responses for seismic design should be calculated considering SSNE using bedrock motions with abundant high-frequency components. It is necessary to discover the SSNE effect on the seismic response of the pile-foundation in further study.

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