ORIGINAL ARTICLE

Latin American Journal of Solids and Structures

www.lajss.org

Numerically study of SSSI effect on nuclear power plant on layered soil

Qun Chen[a], Mi Zhao[a], Junqi Zhang[a]*, Xiuli Du[a]

[a]Key Laboratory of Urban Security and Disaster Engineering of Ministry of Education, Beijing University of Technology, Beijing 100124, China. Email: chenq_ly@163.com, zhaomi@bjut.edu.cn, zhangjunqi@bjut.edu.cn, duxiuli@bjut.edu.cn

*Corresponding author

https://doi.org/10.1590/1679-78257508

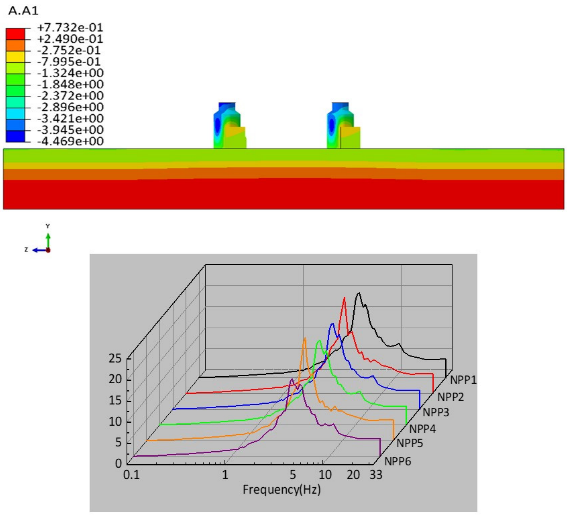
Abstract

In typical dynamic soil-structure interaction (SSI) problems, the dynamic response a structure can be affected by the existence of some nearby structures, which is sometimes referred to as the dynamic structure-soil-structure interaction (SSSI). This effect is especially important in the earthquake engineering design of adjacent nuclear power plants, as the safety risk is relatively high. However, the current understanding on the SSSI of nuclear power plants is still insufficient. In this work, we use the finite element method to investigate the SSSI of two nuclear power plants located at a specific distance under earthquake excitation. Four nuclear-power-plant-soil systems are designed to account for the SSI and SSSI respectively, where the soil properties are obtained from drilling data. The effect of the SSSI on the nuclear power plants is studied by comparing the dynamic responses of four nuclear power plants-soil systems in vertical and horizontal directions, in which both layered soils and local weak interlayer soils are considered. The results of numerical study show that the presence of one nuclear power plant has a favorable effect on the seismic response of an adjacent nuclear power plant, such as reducing the displacement response, but this effect is limited. In addition, the SSSI effect is related to not only the soil properties, but also the direction of ground motion. Furthermore, the existence of soft soil layers complicates the SSSI effect. The results provide important insights for the construction and expansion of nuclear power plants.

Keywords

Nuclear power plant, Seismic response, SSSI effect

Graphical Abstract



Received: February 10, 2023. In revised form: February 15, 2023. Accepted: March 03, 2023. Available online: March 06, 2023.
https://doi.org/10.1590/1679-78257508

1 INTRODUCTION

Soil-structure interaction (SSI) is one of the most important topics in earthquake engineering. The research on SSI shows that different soil can significantly change the dynamic response of the structure (Naserkhaki and Pourmohammad., 2012; Bolisetti et al., 2018; Jiang, et al.,2022). As one of the branches of SSI, Structure-soil-structure interaction (SSSI) mainly focuses on the influence of adjacent structures on one another in an SSI system by the scattering and reflection of seismic waves. It has been a research hot-spot in recent decades and is also known as foundation-soil-foundation interaction (FSFI) or dynamic cross interaction (DCI) (Lou et al., 2011), as the interaction effect is mainly dominated by the mechanical properties of the foundation of structures.

The commonly used methods to study the SSSI include the theoretical, experimental and numerical methods, which have all achieved fruitful results in the past few decades. Alexander et al. (2013) simplified the dynamic problem to an equation containing a set of four parameters by a 2-D SSSI formulation. Based on this work, Aldaikh et al. (2015;2016) further produced a theoretical formulation for three adjacent buildings based on the result of parametric numerical analysis and a series of shaking table tests. The physical modelling of the SSSI and its effect on the dynamics of adjacent structures are investigated. For the problem involving soil nonlinearity, Vicencio and Alexander (2018a, 2018b; 2021) presented a theoretical formulation for the 2-D SSSI, which considered a nonlinear phenomenological Bouc-Wen model for the soil. A numerically simplified reduced-order model is proposed to explore the influence of SSSI between multiple buildings in a three-dimensional arrangement. Recently, Lu et al. (2020) developed a simple but effective discrete model consisting of discrete mass and spring elements to model the static and dynamic interaction between multiple buildings. Although these theoretical methods are simple to implement and efficient to calculate, there are still many limitations. For instance, the structures are often overly simplified, and complex anisotropic material properties of soil are difficult to model. In addition to the theoretical methods, centrifuge experiment has also been frequently used in the research of SSSI. Mason et al. (2013) conducted two geotechnical centrifuge tests and pointed out the SSSI can be beneficial or detrimental depending on the earthquake motion and the structural system. The results of different centrifuge experiments show that SSSI effects are most significant for low-intensity earthquake shaking (Trombetta et al., 2014, 2015), and SSSI can significantly alter the response of proximally located urban structures (Jabary and Madabhushi, 2017). SSSI affected structure response in both time and frequency domains, especially the Fourier amplitudes and pseudo accelerations of structural base acceleration at the frequencies near the natural frequency of adjacent structure (Barrios et al., 2021; Ngo et al., 2019; Wang et al., 2022). In one word, these experiments can provide reliable result of the SSSI, however, the time and labor costs are relatively high. It is difficult to perform parametric study when considering different factors. Furthermore, in the experiments the model size has to be reduced, which poses additional challenge when interpreting the results.

With the rapid development of modern computers, numerical methods provide researchers with another alternative to investigate the effect of SSSI, among which the finite element method (FEM) is the most popular method. Padron (Padron et al., 2009) studied numerically the dynamic through–soil interaction between adjacent pile-supported structures in a viscoelastic half-space under incident S and Rayleigh waves. It was found that nearby buildings can significantly increase the seismic response of a structure. But other researchers also pointed out that the adjacent structures may also be beneficial to the dynamic responses of a structure considering SSSI condition in building design (Naserkhaki and Pourmohammad, 2012; Roy et al., 2015). Interaction between twin buildings with SSSI condition slightly mitigates the unfavorable effects comparing to one single building with SSI condition (Madani et al., 2015). The structural drift and co-seismic settlement could be influenced by the properties of the adjacent structure (Knappett et al., 2015). One of most salient effect of SSSI was to extend the buildings' natural period, therefore increasing the lateral displacement between the stories and decreasing the floor shears. (Ghandil et al., 2016). SSSI effect is enhanced by the soil layering, and is more pronounced for shallower layer and stiffer bedrock (Liang et al., 2017, 2018). Based on the beneficial effect of SSSI mechanism, a novel device was developed for seismic vibration control (Cacciola et al., 2015). Recent research shows that the structure seismic response of SSSI is mainly dependent on the structural characteristics, rather than the location of the structures (Gan et al., 2019). Bybordiani and Arici (2019) studied the effects of the prominent factors such as the distance between the structures, soil moduli, and the number of structures on the dynamic through-soil interaction of adjacent buildings using rigorous finite element models in the frequency domain in a two-dimensional setting. Bolisetti and Whittaker (2020) analyzed the influence of SSSI on low-to medium-rise buildings through numerical simulations. It is concluded that the dominant influence factors on the SSSI effect include the frequency spectrum characteristics of the input ground motion, the structure spacing and the number of adjacent structures (Long et al., 2021). Moreover, nearby structure has a significant effect on the floor response spectrum of base isolated building and superstructure (Cilsalar and Cadir, 2021; Bandyopadhyay et al., 2021). In addition to the study of SSSI effect on above-ground structures, the study on underground structures, such as subway stations (Miao et al., 2020;

Zhu et al., 2021; Qiu et al., 2021), has also attracted attention. The advantages of the FEM include its simplicity to implement and flexibility in modelling complex problems. Various different types of above-ground and underground structures can be accurately modelled, and both homogeneous and layered soil can be considered. Different seismic input can be implemented in the FEM framework. The cost is relatively low compared with the experiments, enabling efficient parametric study and sweeping.

The conventional SSI analysis on nuclear structures (Bolisetti et al., 2018) considering safety-related issues has been thoroughly conducted, however, the study of SSSI based on actual field data of nuclear power plant has not been reported to the best knowledge of authors. The SSSI effect turns out to be significant, especially for nuclear power plant. Due to the recent increase of demand of the capacity of power output, a lot of nuclear power plants are being expended, that is to say, new structures will be constructed near the existing ones, changing the mechanical properties of the system. What's more, the new constructed structures sometimes locate on different soil layers, further exacerbate the complexity of the problem. These adjacent nuclear power plants may have beneficial or harmful effects on other nuclear power plants. However, due to the large size and irregularity of the nuclear power plant, full-scale experiment is usually not possible, making small-scale model test and finite element method the main viable methods to study the dynamic response of nuclear power plant. In addition, the finite element model of nuclear power plant-soil system requires significant amount of computational resources, including both the CPU hours and the computer memory. The SSSI effect of full-scale nuclear power plants in layered sites and complex sites under both vertical and horizontal seismic waves has not been comprehensively studied. In this paper, we investigate the effect of SSSI on the nuclear power plant by comparing the dynamic responses of nuclear power plants under vertical and horizontal ground motions. Four nuclear power plants-soil systems are designed to consider the SSI and SSSI respectively according to the actual measured soil properties.

The remainder of this paper is organized as follow. Section 2 illustrates the nuclear power plant structures and four nuclear power plants-soil systems modelled by ABAQUS. Numerical studies are presented in Section 3, including dynamic response of the nuclear power plant model and floor response spectrum under vertical and horizontal ground motions. Finally, conclusions are drawn in Section 4.

2 NUMERICAL MODELING OF NUCLEAR POWER PLANT AND SEISMIC WAVE

2.1 Finite element model

A finite element model for a CAP1400 nuclear power plant is established using finite element software ABAQUS. The nuclear power plant considered in this study consists of three components, namely the concrete shield building (CSB), the concrete auxiliary building (CAB) and the raft foundation (RF). The steel vessel container and the internal equipment are ignored as they are not important in the seismic response. The wall thickness of the CSB is 1.1m, the outer diameter is 49.97m, and the top elevation is 87.739m. The roof elevations of the three parts of the CAB are 30.24m, 32.24m and 47.52m respectively. The height of RF is 6.4m. CSB and RF are modeled by solid trilinear hexahedron elements (C3D8), whereas CAB is modeled using four-node shell elements (CPS4). The mesh size for both the solid and shell elements is 2m. The total numbers of element and node are 18,681 and 22,832, respectively. Tie constraint is applied to connect the CSB, CAB and RF. Several reference points are selected to present the results. The reference points A and B are two points on the bottom and top surface of the RF, respectively. Reference points D, E and F are points located at places where section of the CSB changes. In addition, reference points C and F are vertices of CAB and CSB, respectively. The mesh and location of the reference points nuclear power plant are shown in the Figure 1(a). The Young's modulus of concrete material is 35.5 GPa, the density is 2500 kg/m^3, and the Poisson's ratio is 0.2. The mass of the whole model is 18.66×10^{7}kg.

The model containing both the nuclear power plant and the soil is shown in Figure 1 (b-e). Four different cases are modeled for comparison. In Case 1 and Case 2, one nuclear power plant is modeled, and the size of the soil is 1000×600m. In Case 3 and Case 4, two nuclear power plants are modeled to investigate their interaction, and the soil size is 1000×800m. The distance between the centers of the containment cylinders is 200m. Uniform hexahedron element is used to discretize the soil, the size of which is 2m. The soil in Case 1 and Case 3 is homogeneous layered soil, while in Case 2 and Case 4 a homogeneous layered soil with weak interlayer is considered. By comparing the dynamic responses of NPP1 and NPP2 modeled in Case 1 and Case 2, it can be found that the influence of weak interlayer on SSI. The effect of SSSI can be found by comparing the dynamic response of the nuclear power plant modeled in Case 1 and Case 3. Case 4 is established according to the actual situation that two nuclear power plants are located on different soil during the expansion. In Case 4, NPP6 has already established on site soil1, NPP5 will be built on Site 2. The effect on SSSI of local weak interlayer can be found by comparing the dynamic response of the nuclear power plant modeled in Case 3 and Case 4. The soil properties of the site soil are shown in Table 1, all soil properties data are from the actual site measurement provided by the Site Safety Analysis Report (SSAR) of Guangdong NPP Phase I Project.

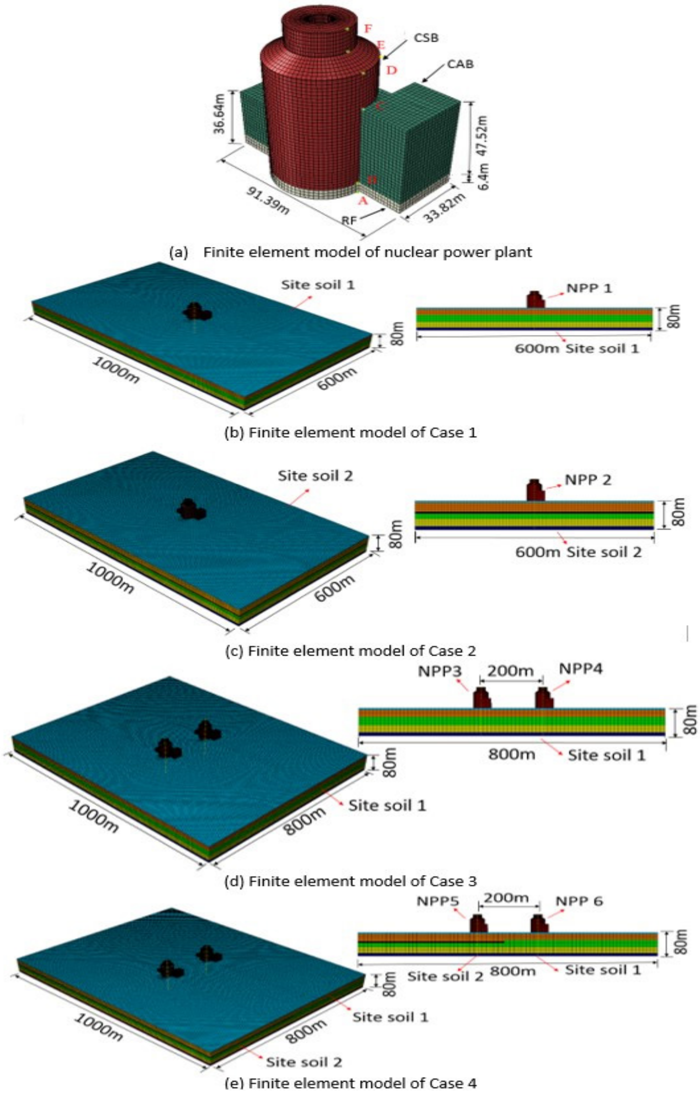


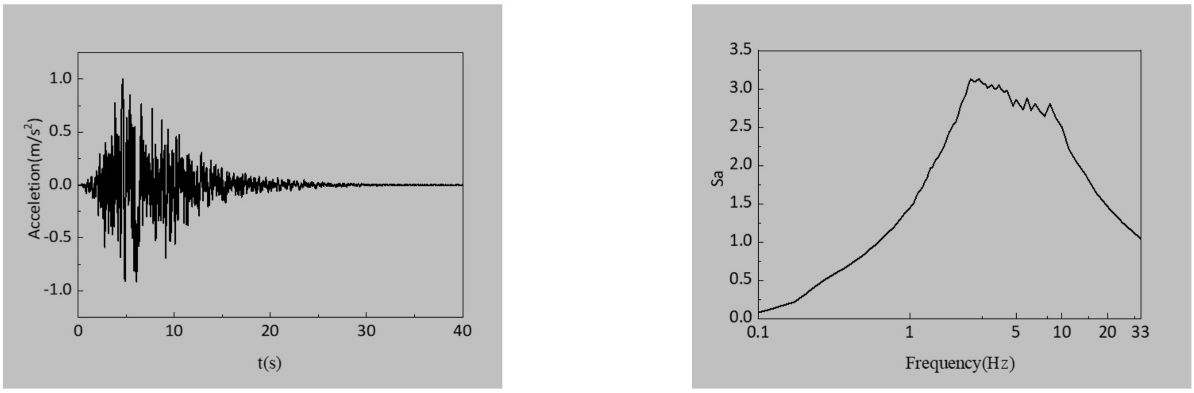
Figure 1. Finite element model of nuclear power plants and soil

Table 1 Material properties of site soil

soil	Layer thickness(m)	Mass density(kg/m^3)	S wave velocity(m/s)	Poisson ratio
site soil 1	5	2020	452	0.414
	20	2460	887	0.399
	25	2470	1162	0.328
	20	2460	1538	0.292
	10	2460	1832	0.232
site soil 2	5	2020	452	0.414
	25	2460	887	0.399
	5	1910	770	0.411
	15	2470	1162	0.328
	20	2460	1538	0.292
	10	2460	1832	0.232

2.2 Seismic waves

An artificial ground motion is generated using standard design response spectrum with 5% damping ratio, the duration of which is 40s. Ground motionamplitude is adjust to 0.1g and input from the bottom of the soil model considering the soil amplification effect and elastic material. The acceleration time history and the corresponding response spectra are shown in Figure 2.



(a) Acceleration time history (b) Response spectra

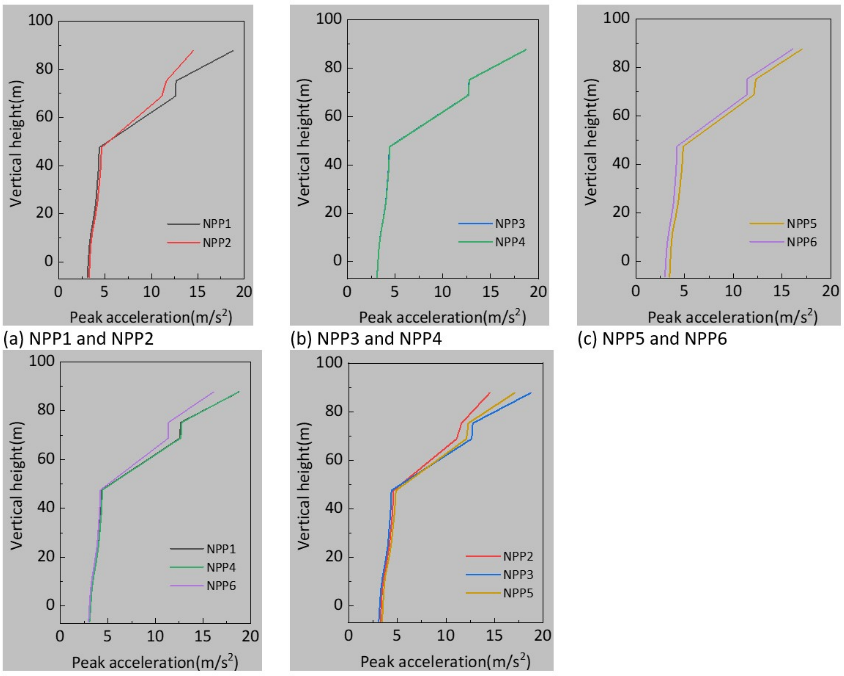
Figure 2. The artificial ground motion and response spectra

3 RESULTS AND DISCUSSION

3.1 Horizontal seismic response

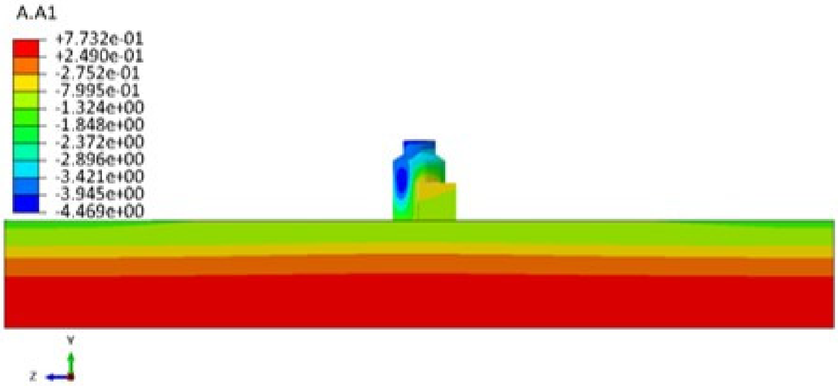
3.1.1 Horizontal acceleration

Peak acceleration curves in X direction are plotted in Figure 3 against the height of structure. The individual nuclear power plants are labeled as NPP1, NPP2, etc., as shown in Figure 1. In case 1 and case 2, we compare the acceleration in NPP1 and NPP2. The difference in acceleration at point A (bottom of the foundation) is relatively small, but there is a big difference at point F (top of the plant). The acceleration at point F of NPP2 is 22.8% smaller than that at point F of NPP1. Acceleration of case 1 and case 3 in X direction (t=5.42) are shown in Figure 4. In case 3, the peak accelerations curves of NPP3 and NPP4 are almost identical, from the bottom of the foundation to the top of the plant. On the other hand, in case 4 the peak acceleration of NPP5 is larger than that of NPP6 in the whole range along the structure height. The maximum difference is observed at point A, where the acceleration of NPP5 is 15.7% larger than that of NPP6. The minimum difference occurs at point F, and NPP5 is 5.9% larger than that of NPP6. For the nuclear power plants on site 1, the peak accelerations at the bottom of foundations of NPP1, NPP3, NPP4 and NPP6 are basically the same, but the peak accelerations at point F are different, especially for NPP6, the peak accelerations at point F is 14.2% smaller than that of NPP1. For the nuclear power plant on site 2, i.e. NPP2 and NPP5, the difference at the bottom of the foundation is negligible, but the peak acceleration of NPP2 at point F is 15% lower than that of NPP5.

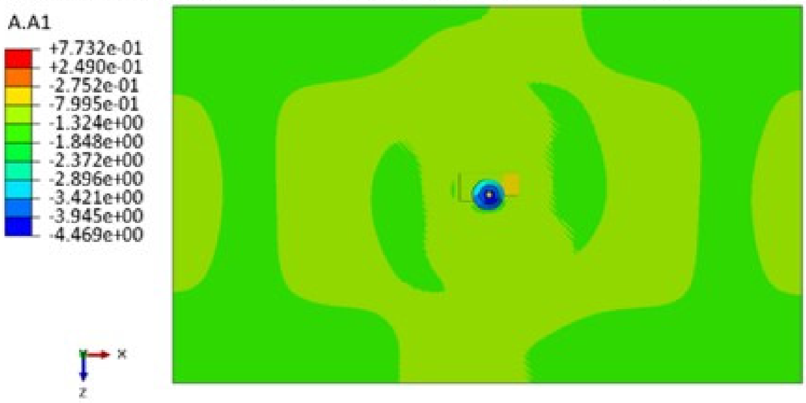


(a) NPP1 and NPP2 (b) NPP3 and NPP4 (c) NPP5 and NPP6
(d) NPP1, NPP4 and NPP6 (e) NPP2, NPP3 and NPP5

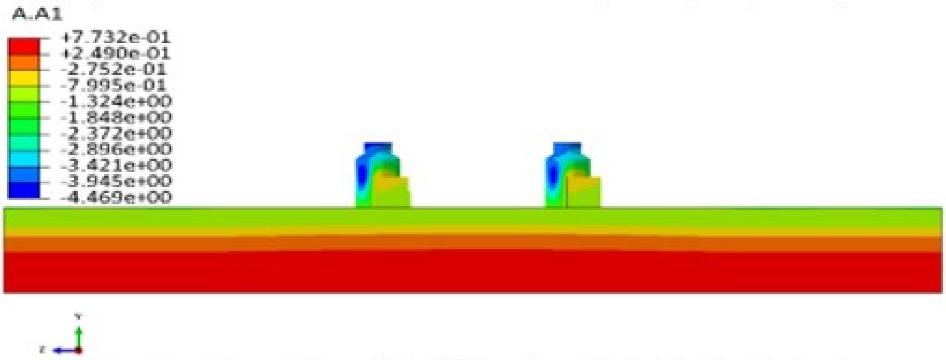
Figure 3. Peak acceleration along structural height in X direction



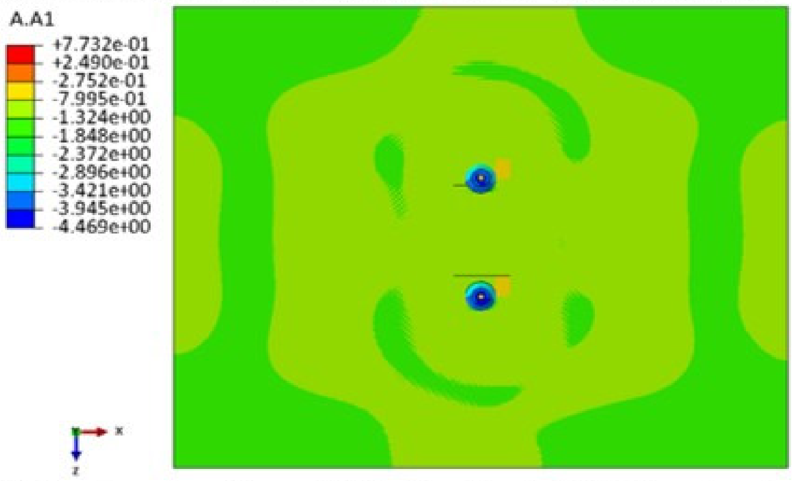
(a) Acceleration of Case 1 in X direction (t=5.42, Right view)



(b) Acceleration of case 1 in X direction (t=5.42, Top view)



(c) Acceleration of Case 3 in X direction (t=5.42, Right view)



(d) Acceleration of case 3 in X direction (t=5.42, Top view)

Figure 4. Acceleration of case 1 and case 3 in X direction (t=5.42)

For the ground motion in X direction, there is no significant difference between the results of case 1 and case 3 on a homogeneous layered site. The study shows that the influence of SSSI can be ignored at a spacing of 200m. For case 4 where two nuclear power plants are located in different site conditions, the existence of soft soil layer leads smaller peak acceleration of nuclear power structure, which has a favorable impact on structural seismic resistance, and SSSI effect leads to larger peak acceleration results of nuclear power structure.

Peak accelerations along structural height under Z direction are shown in Figure 5. The seismic responses in the Z direction of all nuclear power plants are significantly different from those in the X direction. The peak acceleration in the whole height of NPP2 structure is larger than that of NPP1, and the peak acceleration at point A of NPP2 is 4.6% higher than that at point A of NPP1. The peak acceleration at F of NPP2 is 3.5% higher than that at F of NPP1. For horizontal ground motion in Z direction, under the condition of homogeneous layered site, the peak acceleration curves along the structure height of NPP3 and NPP4 are almost identical, which is the same as the ground motion in the X direction. In case 4, The peak acceleration of NPP5 at all points along the structure height is larger than that of NPP6, and the maximum difference occurs at point F, where NPP5 is 31.4% higher than that of NPP6, and the peak acceleration of NPP5 at point A is 23.7% higher than that of NPP6. For nuclear power plants on site 1, the peak acceleration at each point of NPP6 model structure is the minimum, and the peak acceleration at each point of NPP1 model structure is the maximum. The peak acceleration at point F of NPP6 model is reduced by 12.1% and 19% compared with NPP4 and NPP1. For the nuclear power plants on site 2, the peak accelerations of NPP2 and NPP5 at the bottom of the foundation and at each point of the plant are similar, but the peak acceleration of point F at NPP3 is 12.5% lower than that at NPP5.

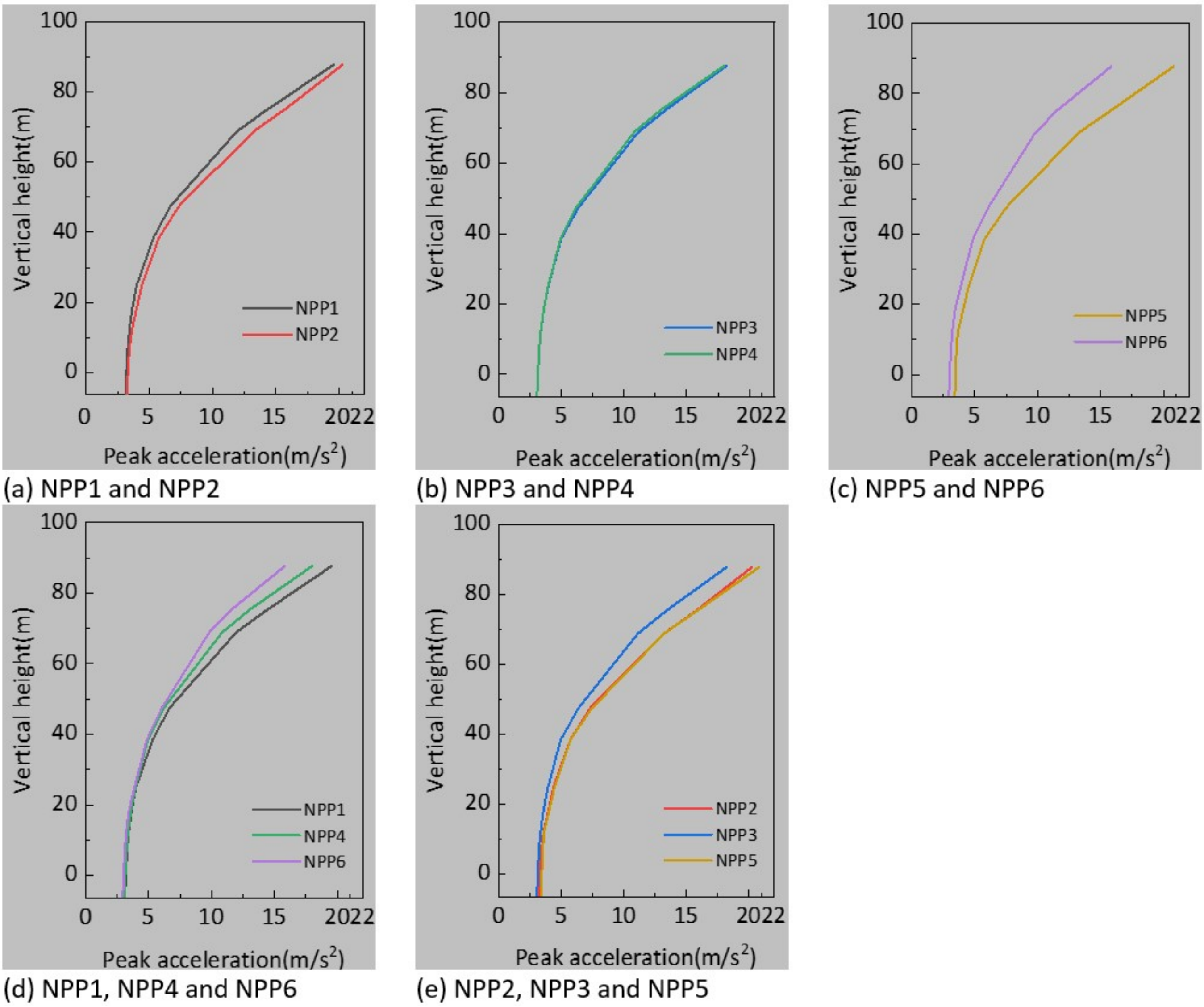


Figure 5. Peak acceleration along structural height in Z direction

From the result obtained above, we observe that the peak acceleration results in Z direction of case 3 are smaller than those of case 1 under the condition of homogeneous layered site, which indicates that the SSSI has a favorable effect on the adjacent structures. For case 4 under complex site field and two nuclear power plants located in different site conditions, the SSSI effect is beneficial for the nuclear power structure at site 1, but has little effect on the nuclear power plant at the site 2.

3.1.2 Horizontal displacement

Peak displacement along structural height in X direction are shown in Figure 6. For horizontal ground motion in X direction, the peak relative displacement of the X direction at each point of the structure shows the same law as the x- direction peak acceleration. For NPP1 and NPP2, there is little difference in the peak relative displacement at each point. The maximum difference point is at F, where the peak relative displacement of NPP2 is reduced by 11.1% compared with that of NPP1. The peak relative displacement of NPP5 at all points along the structure height is larger than that of NPP6, with the largest difference occurring at point C and 16.6% higher than that of NPP6, and the smallest difference occurring at point F and 10.2% higher than that of NPP6. For the nuclear power plant on site 1 condition, the peak relative displacement of each point in NPP6 is the smallest, and the peak relative displacement of point F in NPP6 is 7.4% lower than that in NPP1. For the nuclear power plants on site 2, the peak relative displacement of F point in NPP2 is reduced by 8.2% compared with NPP5.

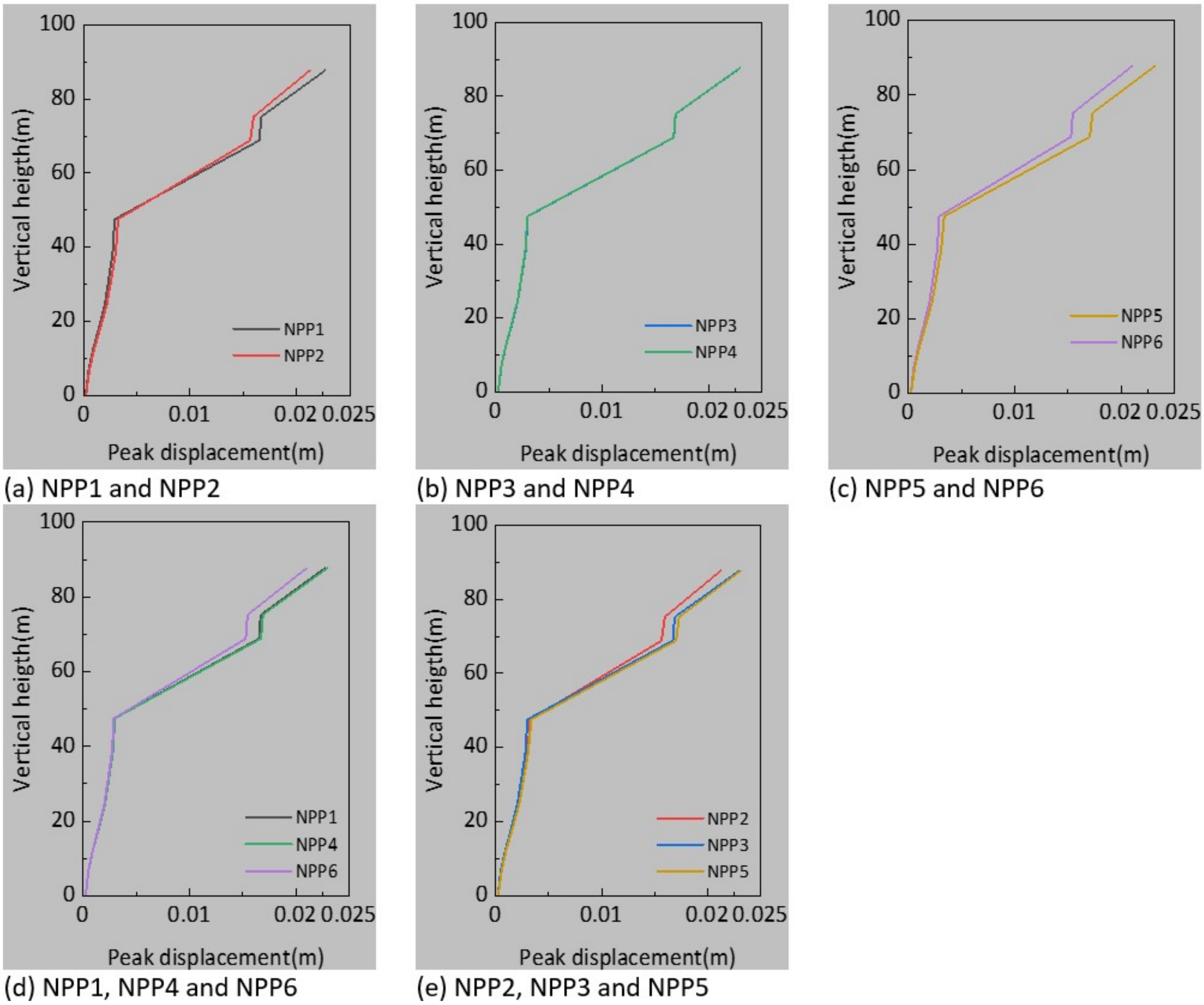


Figure 6. Peak displacement along structural height in X direction

Peak displacement along structural height in Z direction are shown in Figure 7. For horizontal ground motion in Z direction, the peak relative displacement of each point of NPP2 structure is larger than that of NPP1. The largest difference occurred at the bottom of the foundation, with the peak relative displacement of A point in NPP2 increased by 30.6% compared with that of NPP1, and the peak relative displacement of F point in NPP2 increased by 16.6% compared with that of NPP1. In case 3, the peak relative displacement of point F in NPP3 is 2.8% higher than that of NPP4. In case 4, the peak relative displacement of NPP5 is larger than that of NPP6 at all points along the structure height, and the maximum difference occurs at point F, which is 35.3% larger than that of NPP6. For nuclear power plants on site 1, the peak relative displacement results of NPP6 model are the smallest, and the peak relative displacement results of NPP1 model are the largest. The peak relative displacement of point F in NPP6 is 13.2% lower than that of NPP1. For the nuclear power plants on site 2 condition, there is little difference between the NPP2 and NPP5 in peak relative displacement.

SSSI effect has a favorable effect on structural seismic response on homogeneous layered site. In case 4, the presence of local weak interlayer has a favorable effect on NPP6, while the effect of SSSI on NPP5 is negligible.

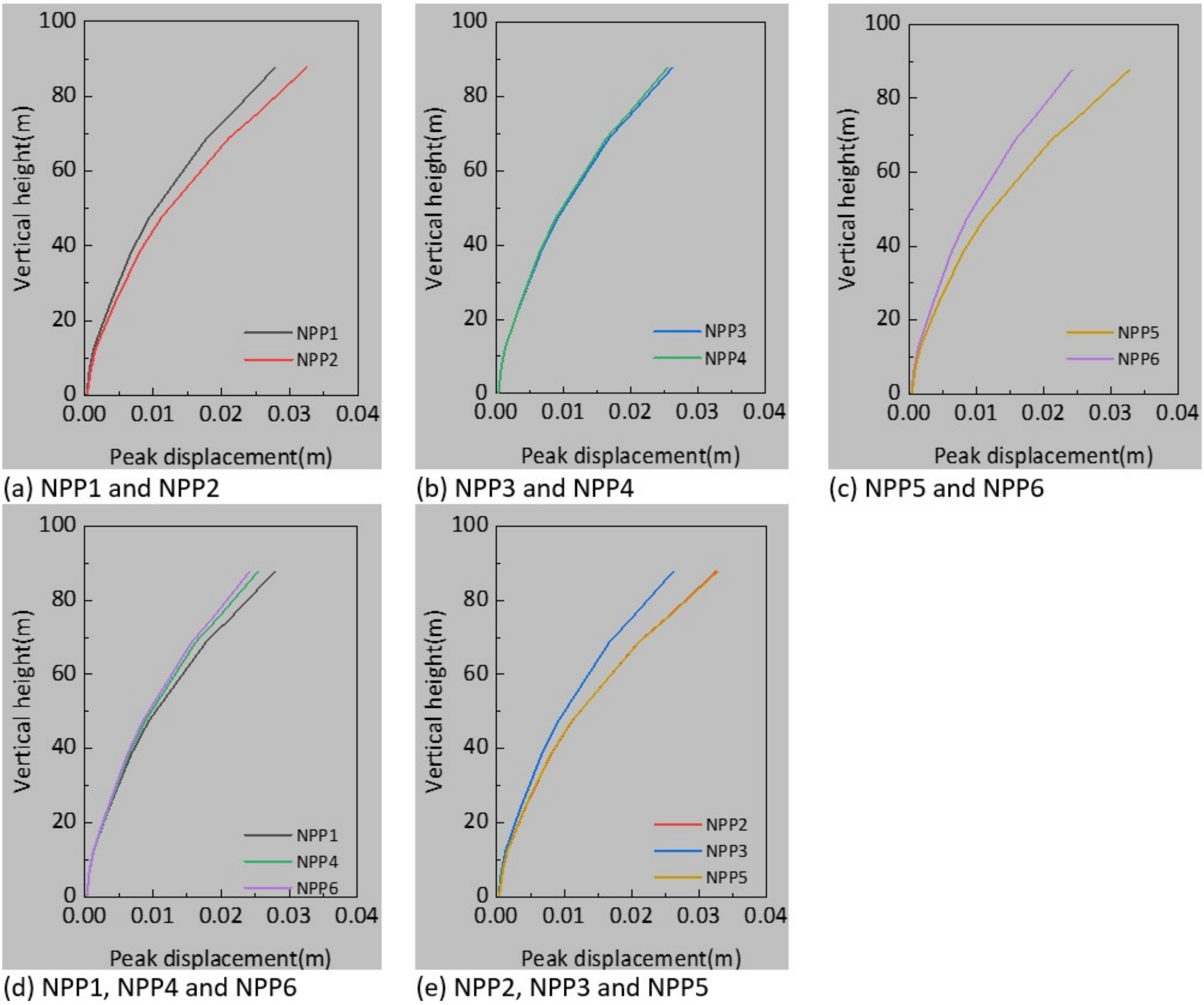
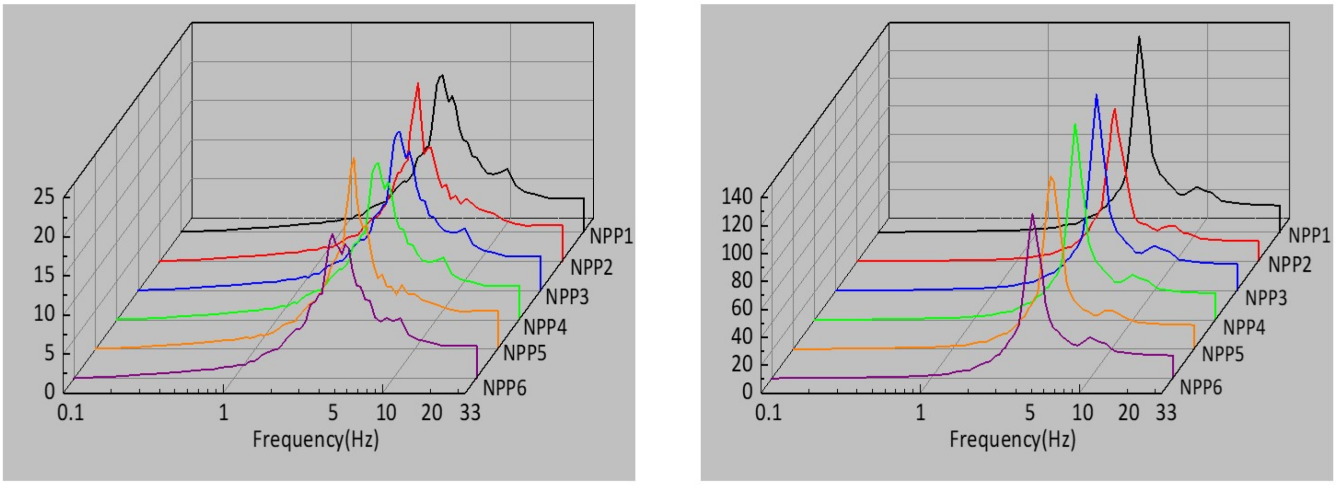


Figure 7. Peak displacement along structural height in Z direction

3.1.3 Horizontal floor response spectrum

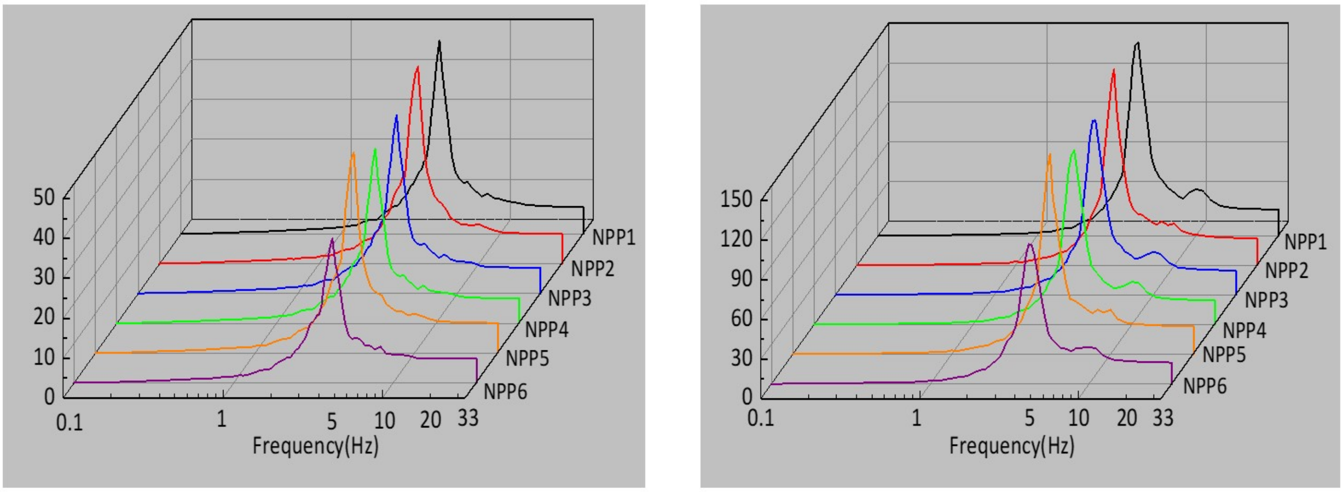
The floor response spectrums of point C and F in X direction considering 5% damping are shown in the Figure 8. Compared with NPP1, the peak value of floor response spectrum at point F is significantly reduced in NPP2 (Figure 7(b)), and the corresponding frequency of the peak value also moves to a lower frequency. The response spectra of NPP1, NPP3 and NPP4 at both points C and F are almost equal, indicating that the effect of SSSI on the response spectra of floors in the X direction of ground motion can be ignored on homogeneous layered site. In case 4, the peak value of the floor response spectrum of NPP2 is smaller than that of NPP5, but the corresponding frequencies of the peak value are not too different. The peak value of the response spectrum of NPP6 floors is smaller than that of NPP1, indicating that the presence of soft soil layer under complex site conditions leads to a decrease in the peak value of the floor response spectrum of an adjacent structure.



(a)The floor response spectrums of point C (b)The floor response spectrums of point F

Figure 8. The floor response spectrums of point C and F in X direction (5% damping)

The floor response spectrums of point C and F in Z direction considering 5% damping are shown in the Figure 9. Under the Z direction of ground motion, the floor response spectrum of NPP3 and NPP4 floors is smaller than that of NPP1. The peak value of the floor response spectrum at point C of NPP3 is 9.8% lower than that of NPP1, and the peak value of the floor response spectrum at point F of NPP4 is 9.9% lower than that of NPP1. The results show that the SSSI effect has a favorable effect on the adjacent structure under the condition of homogeneous layered site. The weak interlayer reduces the floor response spectrum of the NPP6, which plays the role of protecting the internal equipment. There is little difference between NPP2 and NPP5 on floor response spectra, indicating that the SSSI effect on NPP5 can be neglected.



(a)The floor response spectrums of point C (b)The floor response spectrums of point F

Figure 9. The floor response spectrums of point C and F in Z direction (5% damping)

3.2 Vertical seismic response

3.2.1 Vertical acceleration

Peak acceleration along structural height in Y direction are shown in Figure 10. The vertical peak acceleration at each point of the structure is obviously different from the horizontal peak acceleration. There is little difference in the vertical peak acceleration of each model, and the peak acceleration at the bottom of the foundation is almost the same. The peak acceleration of point F in NPP2 is 2.3% lower than that in NPP1, and the peak acceleration of point F in NPP5 is 1.6% lower than that in NPP6.

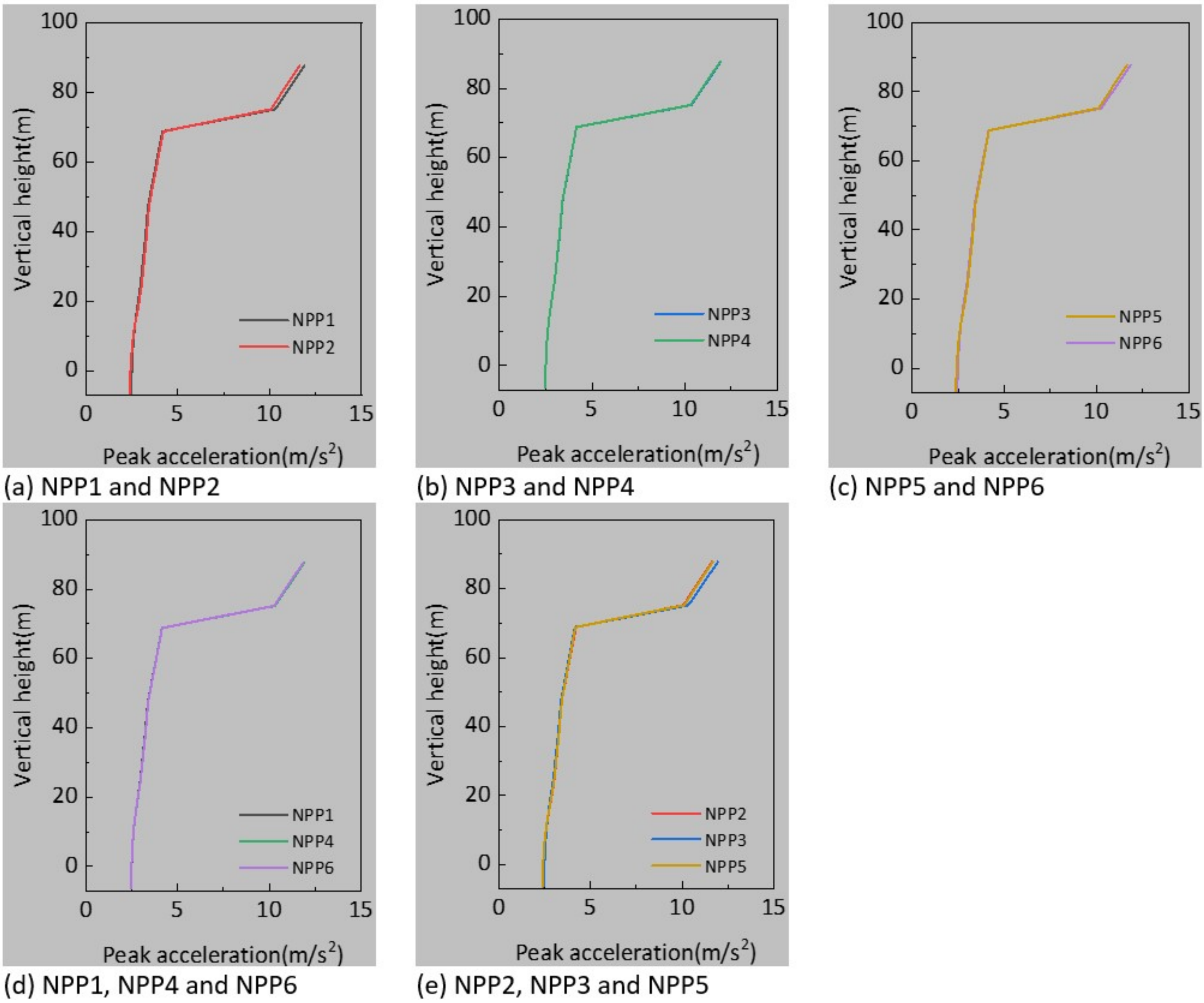
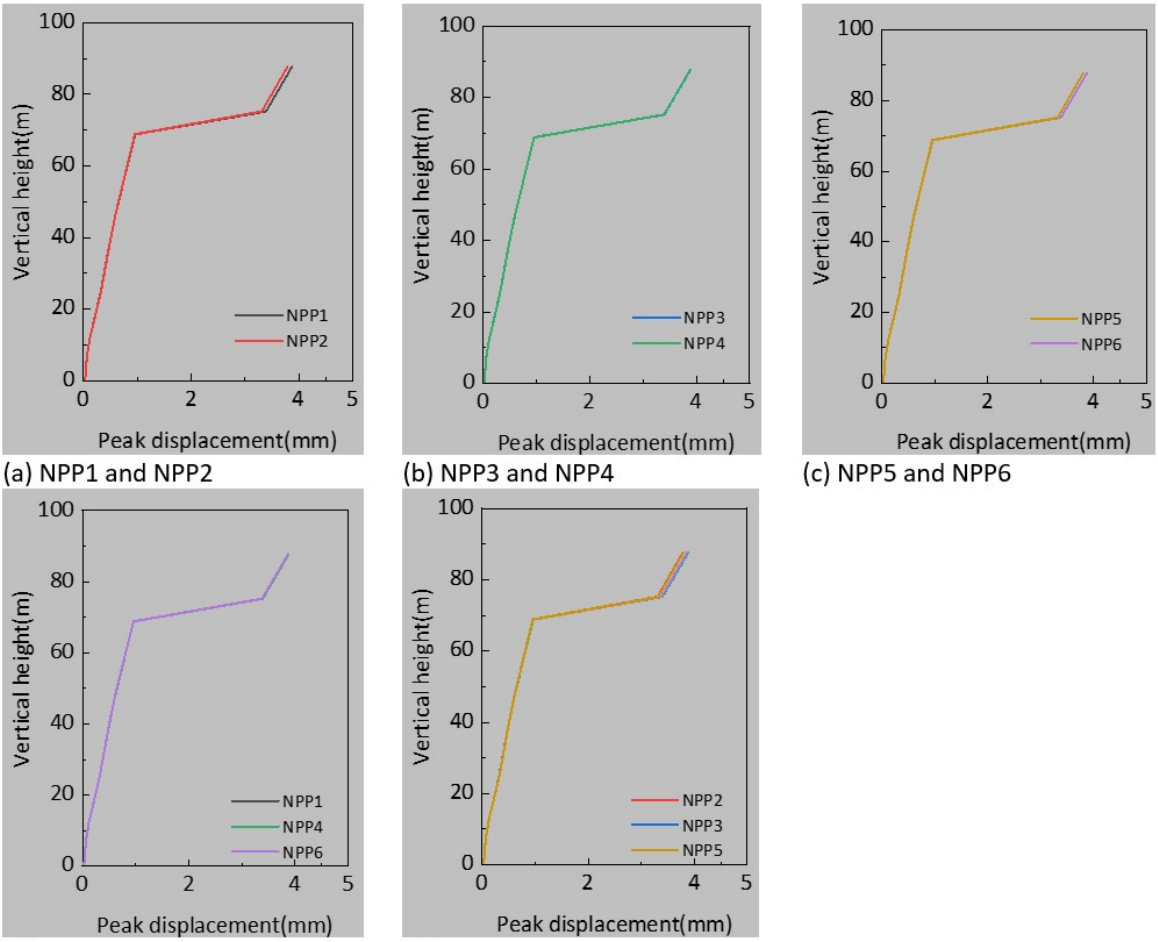


Figure 10. Peak acceleration along structural height in Y direction

3.2.2 Vertical displacement

Peak displacement along structural height in Y direction are shown in Figure 11. The vertical peak relative displacement and vertical peak acceleration at each point of the structure show the same law. For nuclear power plants located in different site conditions, the relative vertical peak displacements of containment and plant are not significantly different. The peak relative displacement of point F in NPP2 is just reduced by 2.2% compared with NPP1, and the peak relative displacement of point F in NPP5 is only reduced by 1.8% compared with NPP6.



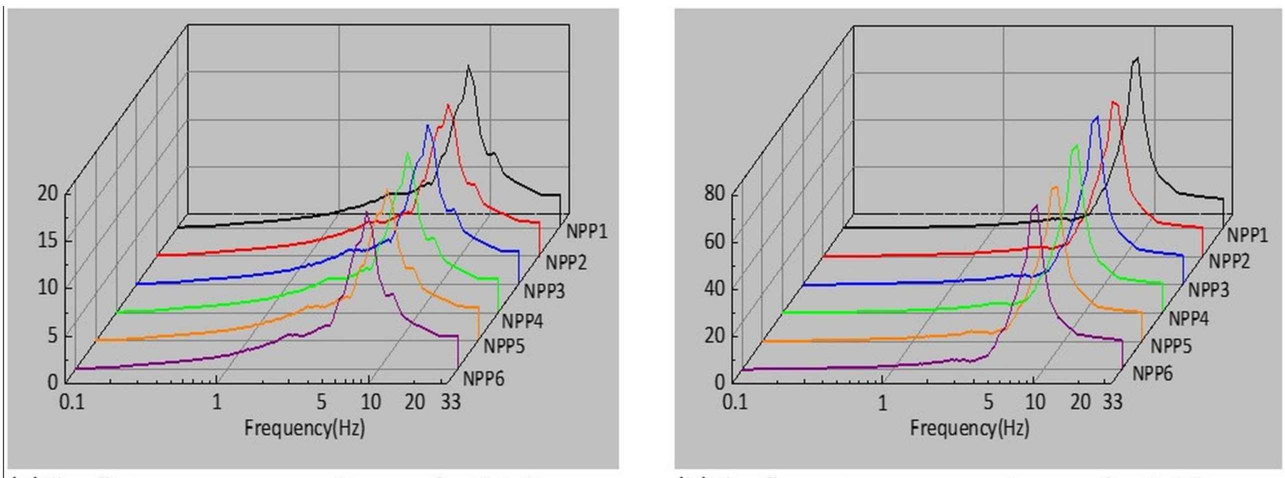
(a) NPP1 and NPP2 (b) NPP3 and NPP4 (c) NPP5 and NPP6

(d) NPP1, NPP4 and NPP6 (e) NPP2, NPP3 and NPP5

Figure 11. Peak displacement along structural height in Y direction

3.2.3 Vertical floor response spectrum

The floor response spectrum of point C and F in Z direction considering 5% damping are shown in the Figure 12. The peak value of the floor response spectra at each point of NPP3 and NPP4 are smaller than those at each point of NPP1. In NPP4, the peak value of the floor response spectrum at point F is 1.5% lower than that in NPP2, and the peak value of the floor response spectrum at point C decreased by 1.7%. The reduction of peak value of the floor response spectrum in the vertical action of ground motion is smaller than that in the horizontal Z direction action of ground motion, indicating that SSSI plays a beneficial role in the vertical seismic response of the structure, but the beneficial effect is limited.



(a)The floor response spectrums of point C (b)The floor response spectrums of point F

Figure 12. The floor response spectrums of point C and F in Y direction (5% damping)

4 CONCLUSIONS

In this paper, four numerical models of nuclear power plant-soil system are designed to investigate the dynamic SSSI interaction between nuclear power plants and layered soil. These models include two different types of layered soil and six nuclear power plants. The dynamic responses of the structures in homogeneous layered soil and soil with weak layer are compared in both vertical and horizontal directions. We draw the following conclusions:

1. The SSSI effect on the seismic response is favorable of adjacent nuclear power plants located on homogeneous layered soil at specific distances, i.e., SSSI can reduce the acceleration and displacement in horizontal direction comparing with a stand-alone nuclear power plant.
2. The SSSI effect is closely related to the direction of ground motion. The SSSI effect is limited in reducing the vertical seismic response of adjacent nuclear power plants.
3. The existence of local weak layer in soil further complicates the SSSI effect. Whether this effect is beneficial or detrimental needs to be evaluated carefully on a case-by-case basis.

Acknowledgements

This research was supported by the National Natural Science Foundation of China (51738001). The support is gratefully acknowledged.

Author's Contribuitions: Methodology, Formal analysis, Validation, Writing–original draft, Visualization, Q Chen; Conceptualization, Investigation, Data curation, Supervision, Writing – review & editing, M Zhao; Visualization, Data curation, Supervision, Writing – review & editing, J Zhang; Writing – review & editing, X Du.

Editor: Marcílio Alves

References

Aldaikh, H., Alexander, N.A., Ibraim, E., Knappett, J. (2016). Shake table testing of the dynamic interaction between two and three adjacent buildings (SSSI). Soil Dynamics and Earthquake Engineering 89:219–232.

Aldaikh, H., Alexander, N.A., Ibraim, E., Oddbjornsson, O. (2015). Two dimensional numerical and experimental models for the study of structure-soil-structure interaction involving three buildings. Computers and Structures 150:79-91.

Alexander, N.A., Ibraim, E., Aldaikh, H. (2013). A simple discrete model for interaction of adjacent buildings during Earthquakes. Computers and Structures124:1-10.

Bandyopadhyay, S., Parulekar, Y.M., Sengupta, A., Chattopadhyay, J. (2021). Structure soil structure interaction of conventional and base-isolated building subjected to real earthquake. Structures 32: 474–493.

Barrios, G., Uemura, K., Kikkawa, N., Itoh, K., Larkin, T., Orense, R., Chouw, N. (2021). Dynamic response of stand-alone and adjacent footing on saturated sand. Soil Dynamics and Earthquake Engineering 143:106584.

Bolisetti, C., Whittaker, A.S. (2020). Numerical investigations of structure-soil-structure interaction in buildings. Engineering Structures 215: 110709.

Bolisetti, C., Whittaker, A.S., Coleman, J.L. (2018). Linear and nonlinear soil-structure interaction analysis of buildings and safety-related nuclear structures. Soil Dynamics and Earthquake Engineering 107: 218–233.

Bybordiani, M., Arici, Y. (2019). Structure-soil-structure interaction of adjacent buildings subjected to seismic loading. Earthquake Engineering and Structure Dynamics 48:731–748.

Cacciola, P., Espinosa, M.G., Tombari, A. (2015). Vibration control of piled-structures through structure-soil-structure-interaction. Soil Dynamics and Earthquake Engineering 77:47-57.

Cilsalar, H., Cadir, C.C. (2021). Seismic performance evaluation of adjacent buildings with consideration of improved soil conditions. Soil Dynamics and Earthquake Engineering 140: 106464.

Gan, J., Li, P., Liu, Q. (2019). Study on Dynamic Structure-Soil-Structure Interaction of Three Adjacent Tall Buildings Subjected to Seismic Loading. Sustainability 12, 336.

Ghandil, M., Behnamfar, F., Vafaeian, M. (2016). Dynamic responses of structure-soil-structure systems with an extension of the equivalent linear soil modeling. Soil Dynamics and Earthquake Engineering 80:149–162.

Jabary, R.N., Madabhushi, S.P.G. (2017). Structure-soil-structure interaction effects on structures retrofitted with tuned mass dampers. Soil Dynamics and Earthquake Engineering 100:301-315.

Jiang, J., El Naggar, M. H., Huang, W., Xu, C., Zhao, K., & Du, X. (2022). Seismic vulnerability analysis for shallow-buried underground frame structure considering 18 existing subway stations. Soil Dynamics and Earthquake Engineering 162, 107479.

Knappett, J.A., Madden, P., Caucis, K. (2015). Seismic structure-soil-structure interaction between pairs of adjacent building structures. Geotechnique 65(5):429-441.

Liang, J., Han, B., Todorovska, M.I, Trifunac, M.D. (2017). 2D dynamic structure-soil-structure interaction for twin buildings in layered half-space I: Incident SH-waves. Soil Dynamics and Earthquake Engineering102: 172–194.

Liang, J., Han, B., Todorovska, M.I., Trifunac, M.D. (2018). 2D dynamic structure-soil-structure interaction for twin buildings in layered half-space II: Incident SV-waves. Soil Dynamics and Earthquake Engineering113: 356–390

Long, H., Wang, Z., Zhang, C., Zhuang, H., Chen, W., Peng, C. (2021). Nonlinear study on the structure-soil-structure interaction of seismic response among high-rise buildings. Engineering Structures 242: 112550.

Lou, M., Wang, H., Chen, X., Zhai, Y. (2011). Structure-soil-structure interaction: Literature review. Soil Dynamics and Earthquake Engineering31:1724-1731.

Lu, Y., Li, B., Xiong, F., Ge, Q., Zhao, P., Liu, Y. (2020). Simple discrete models for dynamic structure-soil-structure interaction analysis. Engineering Structures 206: 110188.

Madani, B., Behnamfar, F., Riahi, H.T. (2015). Dynamic response of structures subjected to pounding and structure–soil–structure interaction. Soil Dynamics and Earthquake Engineering78:46–60.

Mason, H.B., Trombetta, N.W., Chen, Z., Bray, J.D., Hutchinson, T.C., Kutter, B.L. (2013). Seismic soil–foundation–structure interaction observed in geotechnical centrifuge experiments. Soil Dynamics and Earthquake Engineering 48:162-174.

Miao, Yu., Zhong, Y., Ruan, B., Cheng, K., Wang, G. (2020). Seismic response of a subway station in soft soil considering the structure-soil-structure interaction. Tunnelling and Underground Space Technology 106: 103629.

Naserkhaki, S., Pourmohammad, H. (2012). SSI and SSSI effects in seismic analysis of twin buildings: discrete model concept. Journal of Civil Engineering and Management 18(6): 890–898.

Ngo, V.L., Kim, J.M., Chang, S.H., Lee, C. (2019). Effect of Height Ratio and Mass Ratio on Structure-Soil-Structure Interaction of Two Structures Using Centrifugal Experiment. Applied Sciences 9(3), 526.

Padron, L.A., Aznarez, J.J., Maeso, O. (2009). Dynamic structure-soil-structure interaction between nearby piled buildings under seismic excitation by BEM-FEM model. Soil Dynamics and Earthquake Engineering 29:1084–1096.

Qiu, Y.J., Zhang, H.R., Yu, Z.Y., Zhang, J.K. (2021). A modified simplified analysis method to evaluate seismic responses of subway stations considering the inertial interaction effect of adjacent buildings. Soil Dynamics and Earthquake Engineering 150:106896.

Roy, C., Bolourchi, S., Eggers, D. (2015). Significance of structure–soil–structure interaction for closely spaced structures. Nuclear Engineering and Design 295:680-687.

Trombetta, N.W., Mason, H.B., Hutchinson, T.C., Zupan, J.D., Bray, J.D., Kutter, B.L. (2015). Nonlinear Soil-Foundation-Structure and Structure-Soil-Structure Interaction: Engineering Demands. Journal of Structure. Engineering 141(7):04014177.

Trombetta, N.W., Mason, H.B., Hutchinson, T.C., Zupan, J.D., Bray, J.D., Kutter, B.L. (2014). Nonlinear Soil–Foundation–Structure and Structure–Soil–Structure Interaction: Centrifuge Test Observations. Journal of Geotechnical and Geoenvironmental Engineering 140(5):04013057

Vicencio, F., Alexander, N.A. (2018a). Dynamic interaction between adjacent buildings through nonlinear soil during earthquakes. Soil Dynamics and Earthquake Engineering108:130-141.

Vicencio, F., Alexander, N.A. (2018b). Higher mode seismic structure-soil-structure interaction between adjacent building during earthquakes. Engineering Structures 174: 322–337.

Vicencio, F., Alexander, N.A. (2021). Method to evaluate the dynamic structure-soil-structure interaction of 3-D buildings arrangement due to seismic excitation. Soil Dynamics and Earthquake Engineering 141: 106494.

Wang, J., Guo, T., Du, Z. (2022). Experimental and numerical study on the influence of dynamic structure-soil-structure interaction on the responses of two adjacent idealized structural systems. Journal of Building Engineering 52: 104454.

Zhu, T., Wang, R., Zhang, J.M. (2021). Effect of nearby ground structures on the seismic response of underground structures in saturated sand. Soil Dynamics and Earthquake Engineering146: 106756.