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ENERGY DISSIPATION OF A BULGED FOUNDATION UNDER A NUCLEAR POWER PLANT MODEL CONSIDERING EARTHQUAKE SOIL STRUCTURE INTERACTION

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Abstract

Considering the interaction between a foundation of a building and the underneath soil can ensure more accurate response of a building during earthquakes, and also the interaction can form plastic zones in soil and thus dissipate energy. To understand the dynamic behavior of different components better and figure out the way of optimizing the aseismic structure of nuclear power plant, this paper discusses the influence of changing the shape of the foundation on energy dissipation.

Physics discovery shaking table test of a Nuclear Power Plant (NPP) model including Earthquake Soil Structure Interaction (ESSI) was performed to study the seismic behavior of the NPP model. A glass model with a scale ratio of 1/40 was used as the test model for AP1000. Tongji 6D shaking table capabilities were fully used to better explore the influence of surface waves on energy dissipation of different foundations. A flexible soil box was applied which can better eliminate the boundary effect on the seismic response of the soil and prepare the test conditions for exploring the interaction between soil and structure. Flat and bulged foundations were set as controls: flat foundation tests were used to observe physics phenomena of ESSI, while new tests, with modified foundation (bulging foundation), were used to better understand physics energy dissipation under an NPP model during ESSI behavior. Besides, the tests used 3D excitation as input motions for NPP model with and without isolation. For test purpose, the frequency similarity constant S_f, which is the ratio of the prototype fundamental frequency to the design fundamental frequency of the main parts of the model such as the soil, the isolation system and the superstructure, was designed equal to 3.3, also as the main control parameter for this experiment design. In addition, Shanghai silty clay which with 1890kg/m^3 density and 88.4m/s shear wave velocity was selected to satisfy the soft soil test condition.

The test results are used to state dynamic behavior under an NPP (model in this case) during ESSI behavior. The seismic response of the NPP model including acceleration response spectra of different elevations in horizontal and vertical directions, peak acceleration values along the increasing height, and soil pressure time histories on flat foundation and bulged foundation are compared for different cases. For the non-isolated model, compared with flat foundation, it was found the bulged foundation would not show better ability to dissipate energy. On the contrary, the bulged foundation would produce more obvious rocking effect in the main frequency ranges, which was the main reason for the amplification of structural response. On the other hand, for the isolated model, using a bulged foundation can increase the energy dissipation of isolation bearings to a small extent, which could better transfer the seismic energy in the horizontal directions, but the response of the superstructure shows different characteristics in the two horizontal directions need to be further studied.

Keywords: Nuclear Power Plants, Earthquake Soil Structure Interaction (ESSI), Bulged Foundation, Energy Dissipation; Isolation

1. Introduction

For traditional non-isolated nuclear power plants, the ESSI effect cannot be ignored because of the large mass, stiffness and high-security requirement of nuclear power plants, so ESSI analysis is an important link in seismic design and safety analysis of nuclear power plants. As for isolated structures, studies by M. Constantinou [1] and Zou [2] et al. believe that ESSI has a certain influence, but its influence is much smaller than that of non-isolated structures, so it cannot be considered in the general design of isolated structures. However, a growing number of studies, like by Song [3] and Spyrakos et al. [4] believe that it is necessary to consider the influence of ESSI when analyzing isolated nuclear power plant structures. The design of isolated NPP structure based on rigid foundation assumption is not inclined to safety. Therefore, the influence of ESSI on isolated NPP structure needs to be further studied. In the study of the performance of structural isolation systems for NPP, the rigid ground assumption was subjected to greater errors due to the flexibility and non-boundary characteristics of the soil foundation as shown in the work by H. Gavin et al. To ensure more accurate ground motion input and the overall model of soil and structure, the interaction between soil and structure was be considered shown in the work by Sayed and S. Mahmoud et al. [5], which was different from the assumption of the traditional seismic theory of rigid foundation.

To date, many studies have been conducted on the seismic isolation of nuclear power plants to isolation performance and soil-structure interaction. Huang [6] based on the performance design of nuclear power plants, and pointed out that isolation can improve the seismic performance of the structure and reduce the damage for secondary components. G.P. Warn [7] analyzed the performance of lead-rubber bearings focused on vertical stiffness. Jenna [8] used a two-dimensional isolator model to perform a spectral analysis of the seismic response in a base isolated NPP structure. Annie Kammerer et al. [9] analyzed the regulatory gaps and challenges for licensing advanced reactors using seismic isolation. Besides, a development of three-dimensional (3D) isolation systems for advanced reactor systems in Japan, studied by Takahashi [10], has also received extensive attention. Wang [11] conducted theoretical and experimental research on the three-dimensional seismic isolation technology of nuclear power plants and showed that the three-dimensional seismic isolation system can reduce the vertical seismic response of nuclear equipment. Zhou [12] performed a series of case study analyses of a modern NPP model to examine the benefits and challenges associated with 3D isolation compared with horizontal isolation. M. Sayed and D. Kim et al. [13] worked on the performance of the rigidly fixed base isolated NPP reactor building compared to the one considering nonlinear pile-soil interaction. The results indicate under the short-period inputs that the base isolated NPP model considering pile foundation show higher responses than the rigidly fixed base isolated NPP, while they are less under the long-period ground motions. Whittaker [14], Tabatabaie [15] and Wang [16] et al. studied the seismic responses of nuclear power plants using frequency domain analysis method. Moreover, soil characteristics were also considered as an important factor by Liu [17], Gao [18], and Zhuang [19].

However, the foundation, which participates in the energy dissipation by changing the degree of soil plasticity during the dynamic soil-structure interaction should be considered. This paper explores how changes in the shape of the NPP foundation affect the energy dissipation during earthquakes. In this paper, physics discovery shaking table test of an NPP model including ESSI was performed to study the seismic behavior of the NPP model on a soil site. Flat foundation test data were used to better understand physical phenomena. A new test, with bulged foundation, was used to better understand physics energy dissipation under an NPP model in this case during ESSI behavior. Concretely, the seismic behaviors of the NPP model on a soil site with without modified (bulged) foundation shape were compared in this study. Aspects include isolation and non-isolation conditions with 3D excitation, and the results were organized to compare the peaks of acceleration, soil pressure time histories, and floor response spectrums of each test and to analyze the energy dissipation during ESSI behavior.

2. Experimental design

2.1 Designing for model similarity

The model similarity is a crucial factor in structural model test designing, it determines the similarity indices of all physical properties. Considering that multiple materials (soil, concrete, rubber, and so on) were included in the soil-structure system, the frequency similarity ratio S_f was selected as the main control parameter to make the model test results reflect the actual dynamic interaction characteristics to the maximum extent. S_f, in this model test, is equal to 3.3, and the first order frequencies of the three main components for the prototype and the test model are shown in Table 1.

Table 1 Frequency of the model and the prototype (unit: Hz)

System components	Prototype	Model
Superstructure	3.27	10.80
Isolation system	0.61	2.00
Soil	2.39	7.89

2.2 Main components of the soil-structure system

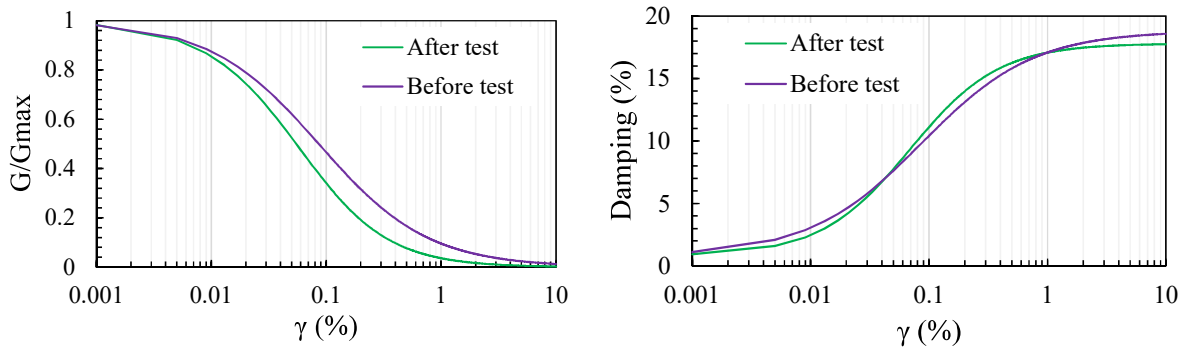
For the study of shaking table test considering SSI, the model soil was usually loaded in a finite size container due to the limitations of the shaking table size and load capacity, which often make errors because of the "model box effect" (different dynamic results caused by the reflection of waves at the soil boundary and the changes of the systematic vibration mode) [20]. To reduce the model box effect, a flexible soil box, supported by Tongji University in Shanghai, was applied to this study, as shown in Fig. 1. The soil box was in a shape of a cylinder with a diameter of 3000 mm, the side wall was made of rubber film (thickness 5 mm) with reinforced in a circular manner, which providing radial stiffness and allowing the soil to undergo layered horizontal shear deformation. Moreover, a layer of gravel was attached to the bottom steel plate of the soil box with epoxy resin to form a rough surface to reduce the relative slip between the soil and the container. During the tests, shear deformation could be seen obviously.

Fig. 1 – The flexible soil box

The prototype site chosen for this test is from the third of nine soil profiles provided by KEPCO [21], with a fundamental frequency of 2.39 Hz. Shanghai silty clay was used as the model soil with a height of 1.18 m, the density and measured shear wave velocity were 1890 kg/m^3 and 88.4 m/s, respectively. The dynamic properties of the model soil before and after the test are shown in Fig. 2. Besides, when structural isolation is considered, the isolation system was arranged between the foundation and the superstructure and consists of four identical lead rubber bearings (LRBs). The diameter of each isolator was 100mm, and the diameter of the inner lead core was 13mm. Every single LRB comprised 15 steel plates with a thickness of 2mm and 16 rubber layers with a thickness of 3mm for each. Mechanical properties of the model LRB are shown in Table 2.

As the main research object, AP1000 containment model was manufactured using plexiglass by the length similar ratio S_l (1/40). Comparison of physical parameters between the prototype and the model are shown in Table 3. Plexiglas model of AP1000 containment was used to guarantee the superstructure to keep

in an elastic state as much as possible during the shaking tests. In Fig. 3, to satisfy the similarity ratio of frequency, a steel plate with supplemental mass blocks (total 1524 kg) was placed in the bottom of the superstructure, counterweights of 75 kg, 150 kg, 115 kg can be seen distributed at three floors on the superstructure.



(a) $G/G_{max} \sim \gamma$ (b) Damping ~ γ

Fig. 2 – Dynamic properties of Shanghai silty clay used to make the model soil foundation

Table 2 Mechanical properties of the model LRB

Name	Initial stiffness K_1 (kN/m)	Post-yield stiffness K_2 (kN/m)	Vertical stiffness K_v (kN/m)	Effective stiffness K_{eff} (kN/m)	Yield force F_y (kN)
LRB	972	61.8	51000	89	1.46

Table 3 Overview of the model and the prototype (unit: m)

Parameter	Prototype	Model
Height	71.10	1.78
Diameter	44.20	1.10
Thickness	0.92	0.01 (not to scale)
Material	Steel	Plexiglass

2.3 Sensor arrangement and foundations

Fig. 4 shows the layout sketch of the measuring points in the test model system. In the model soil, three rows of three-directional accelerometers were distributed in two directions. Similarly, the accelerometers were also arranged along two directions at some critical heights of the superstructure. Fig. 5 (a) and (b) show the cross sections of two foundations and the arrangement of the soil pressure gauges at the base of the foundation between the model soil and the structure, respectively. To obtain the relative deformation and shear force of the isolators, pull-line displacement gauges and force transducers were positioned at the isolation layer as shown in Fig. 5 (c). In addition, two pull-line displacement gauges were also positioned on the top of the structure for measuring the absolute displacement.

2.4 Seismic inputs and test groups

RG1.60 earthquake wave, El Centro earthquake wave, and Kobe earthquake wave were selected as the test input motions. The AP1000 design spectrum was appropriately adjusted at special frequencies based on the RG1.60 standard spectrum of the United States [22]. As an artificial seismic motion executed in the experiment, the RG1.60 wave was synthesized from the AP1000 design spectrum, which has good adaptability in China since it can completely envelop the spectrum of potential sites with large margins [23]. Response spectra of the seismic inputs and the design spectra with 5% damping in three directions can be seen in Fig. 6, all spectra were scaled by PGA 0.30g. As specified in the AP1000 standard design, the peak

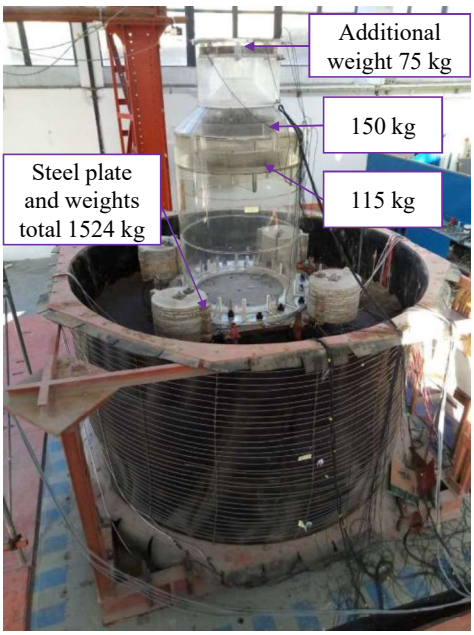


Fig. 3 – The soil-structure test model

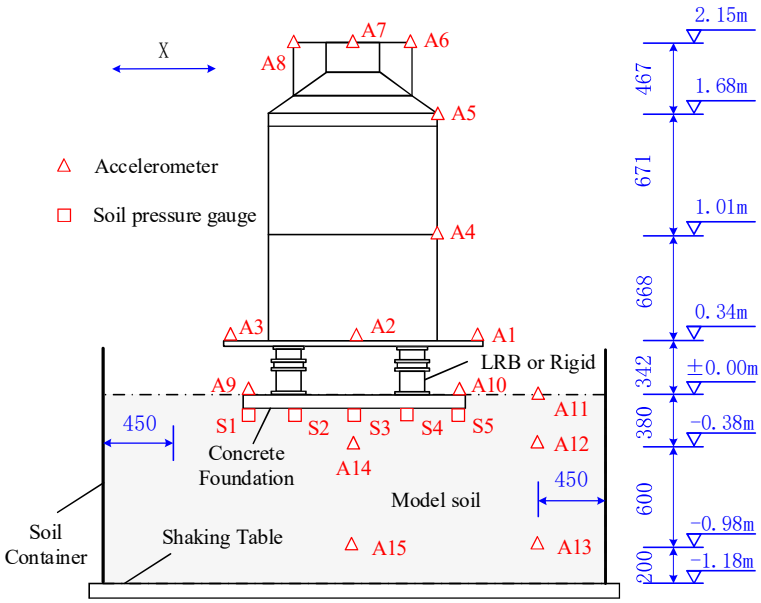
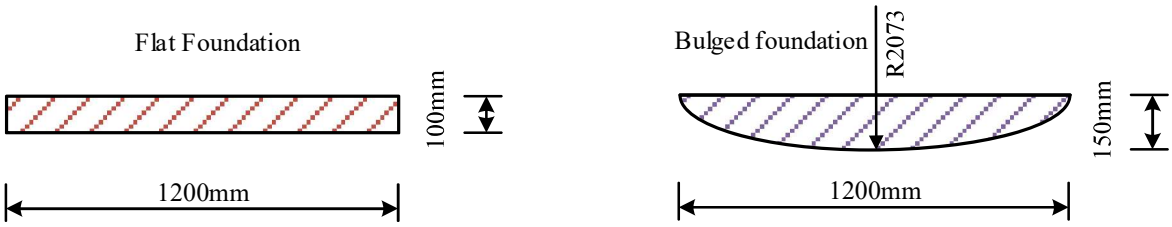
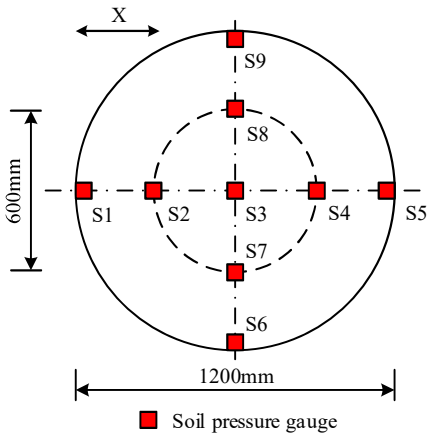


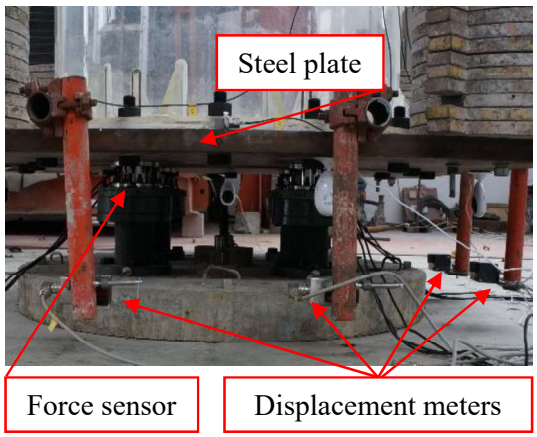
Fig. 4 – Accelerometers and soil pressure gauges in the soil-structure system



(a) Two foundation cross sections



(b) Arrangement of soil pressure gauges

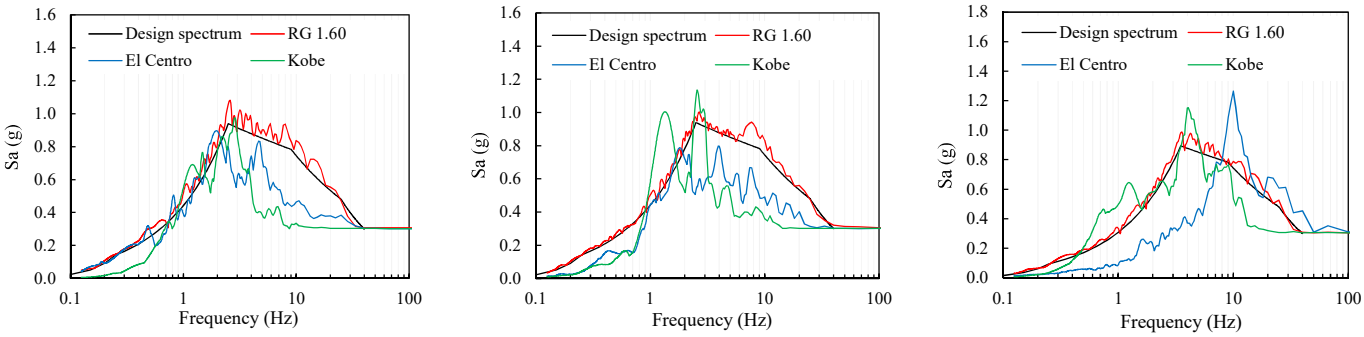


(c) Isolation layer

Fig. 5 – Arrangement of sensors in foundation and isolation layer

acceleration for a Safe-Shutdown Earthquake (SSE) is 0.30g. Besides, this model test also includes the seismic input levels of Operating Basis Earthquake (OBE) and Seismic-Margin Earthquake (SME), which have a PGA of 0.15g and 0.50g, respectively. For artificial seismic wave, the PGA ratio of RG1.60 earthquake in three directions (two horizontal and one vertical) was 1:1:0.67, and for natural earthquakes were uniformly based on recordings. Besides, white noise was adopted as an excitation to identify the dynamic characteristic parameters of the system with a peak acceleration 0.07g.

In this study, five test groups, shown in Table 5, have been set up to explore the changes of seismic response for the soil-structure system affected by isolated condition and the shape of the foundation.



(a) X-direction (b) Y-direction (c) Z-direction

Fig. 6 – Response spectra curves of seismic inputs to AP1000 spectra

Table 5 Test group set-ups

Test	Abbreviation	Foundation	Isolation condition
1	FI	Flat	Isolation
2	FN	Flat	Non-isolation
3	FF	Soil	--
4	BN	Bulged	Non-isolation
5	BI	Bulged	Isolation

Note: FF means free field.

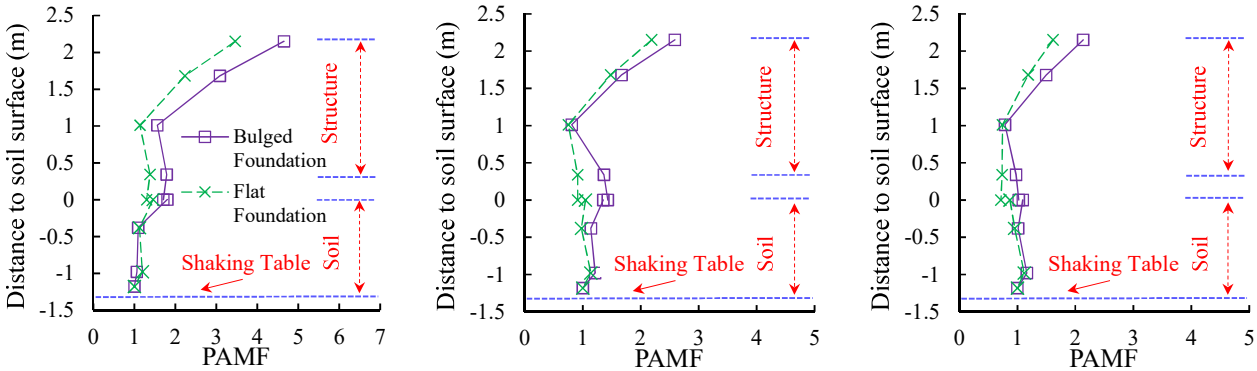
3. Test results

3.1 Peak acceleration responses in the model system

The peak acceleration is an important indicator in the seismic design of nuclear power plants, the peak acceleration amplification factor (PAMF) can clearly express the maximum acceleration response characteristics of the site and structure under the ground motions. Fig. 7 and 8 show the comparison of normalized PAMFs for different foundation model systems with and without seismic isolation bearings, respectively. The selected observation points including points in the model soil (A13, A12 and A11) and points along X direction (A10, A1, A4, A5 and A6) in the model structure, the seismic excitation is RG1.60 waves at OBE, SSE and SME levels.

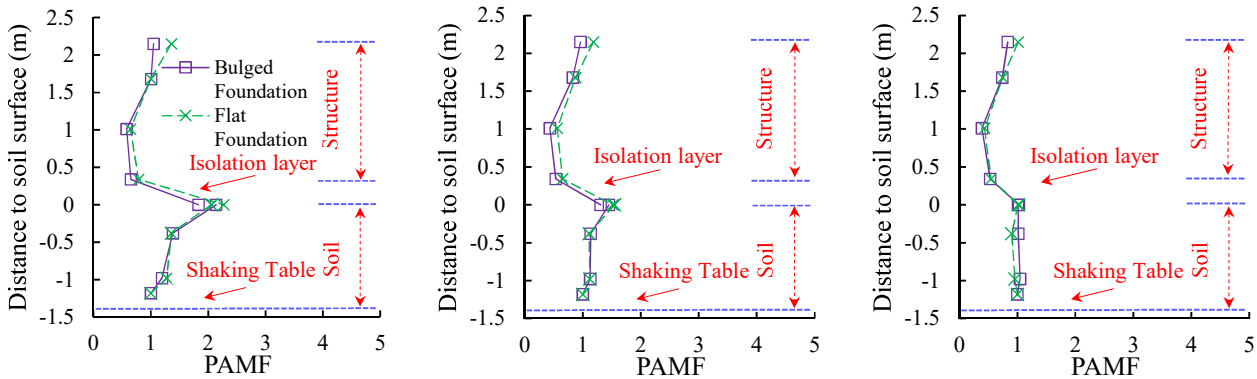
In Fig. 7, it can be seen that the increase of seismic input level caused the PAMFs of the non-isolated model system to decrease gradually. At OBE input level, the PAMF values in the model soil increase with decrease of depth. The PMAF values from A11 (near the soil surface) significantly exceed 1.0, which indicates the model soil has an amplification effect on the response acceleration. While at SME input level, the PMAF value of A11 for BN and FN are 1.09 and 0.87, respectively. The reason is that with the increase of the seismic input level, the nonlinear development of the model soil increases. However, the shape of the foundation affects the dissipative effect of the system on the seismic energy. For the model structure, the

bulged foundation shows a significant amplification on the response acceleration. Compared with FN, the amplification of the PAMF value for BN is most obvious at the top of the model structure. As the seismic intensity increases, the amplification of PAMFs at the top of the structure are 34.3%, 18.3%, and 32.3%, respectively. In addition, PMAFs at the bottom and top of the structure are greater than that at the middle, the non-isolated nuclear power structure model exhibits a rocking effect during ground shaking, which is a cause for concern.



(a) OBE input level (b) SSE input level (c) SME input level

Fig. 7 – Normalized PAMFs in non-isolated model (RG1.60 wave)



(a) OBE input level (b) SSE input level (c) SME input level

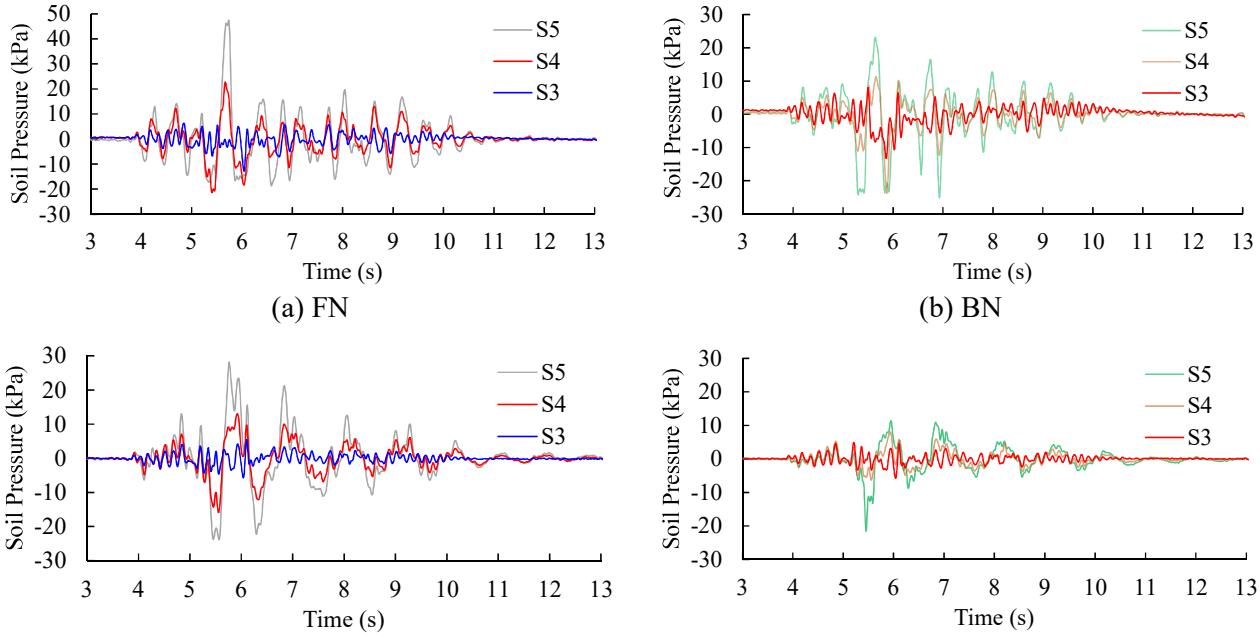
Fig. 8 – Normalized PAMFs in isolated model (RG1.60 wave)

Fig. 8 shows similar acceleration responses for the two structural systems with seismic isolation, and likewise, the overall PAMF values decrease with increasing input intensity levels. Compared with the non-isolated system, the dynamic response of the isolated model system changes significantly: the response acceleration amplification effect of the model soil is more obviously, the PAMF value of each floor is smaller, and the energy dissipation of the model system mainly relies on the relative deformation of the isolation layer. Compared with FI, the PAMF values of the BI model are slightly smaller, indicating that the energy dissipation effect of the bulged foundation is not significant in this horizontal direction.

3.2 Soil pressure responses between soil and foundation

Soil pressure can directly reflect the interaction force between the foundation and the structure and is an important reference for experimental studies considering the SSI effect. Fig. 9 represents the variation of soil pressure at measurement points S5, S4 and S3 for different model systems under the SME input level. The pressure data was obtained by subtracting an initial static pressure value, which was then processed by noise reduction and the filtering interval was 0.1-30Hz.

It can be seen from Fig. 9 that the foundation is subjected to a gradual increase in dynamic soil pressure from the center to the edge during ground shaking. In Fig. 9 (a) and (b), the maximum soil pressure of S5 is 47.47 kPa and 23.17 kPa respectively, the bulged foundation reduces the maximum soil pressure at point S5 by 51.2%. In Figs. 9 (c) and (d), the peak soil pressures of S5 are 28.17 kPa and 11.44 kPa, respectively, the maximum soil pressure reduces by 59.4%. This indicates that for both isolated and non-isolated systems, the use of bulged foundation can reduce the interaction forces between soil and structure under ground shaking to a considerable extent. Therefore, under the site condition in this test, the bulged foundation cannot play an energy-dissipation role by increasing the nonlinear development of the soil model.



(a) FN (b) BN (c) FI (d) BI

Fig. 9 – Soil pressure time histories at SME input level (RG1.60 wave)

In addition, comparing Fig. 9 (a) and (c), it can be seen that the use of seismic isolation bearings is also an important factor in reducing the interaction force between the soil and the model structure. With reference to the frequency similarity ratio design, the seismic isolation layer reduces the fundamental frequency of the model structure to about 2 Hz. This frequency is less than the soil model fundamental frequency of 8 Hz, the dynamic behavior of the structural system is dominated by the relative motion of the seismic isolation layer, thus reducing the interaction force between the foundation and the soil, which in turn reduces the plastic energy dissipation of the model soil.

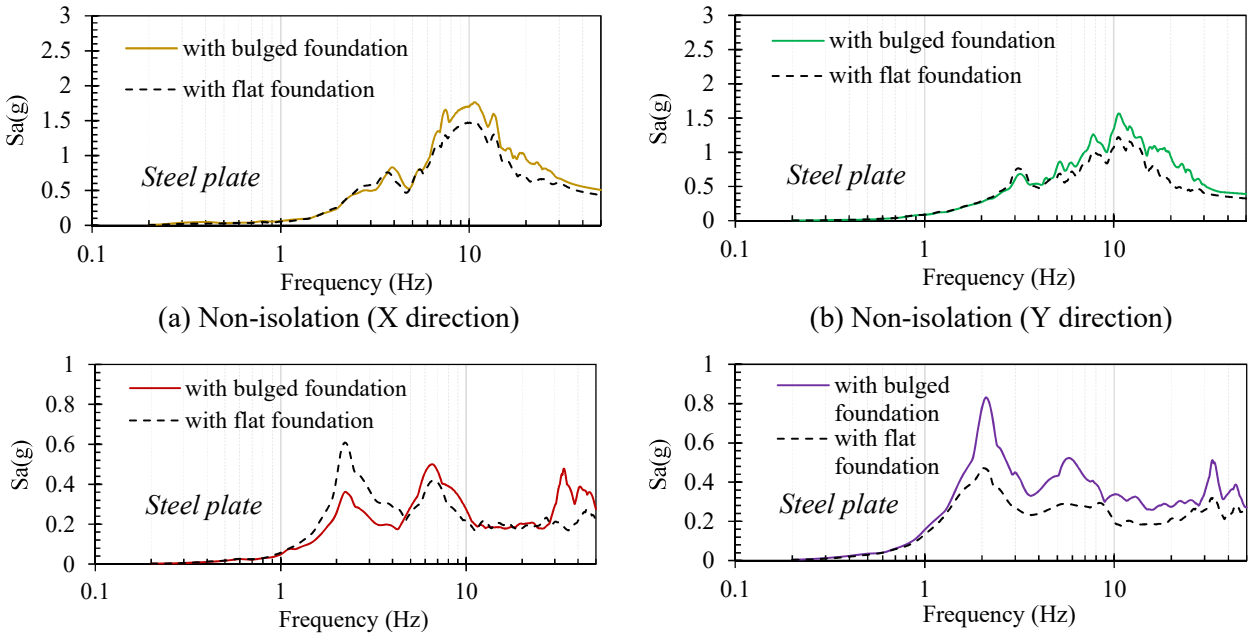
3.3 Spectral acceleration responses and hysteresis curves

The bottom of the nuclear power structure is the floor where the important nuclear equipment is concentrated, thus it is especially important to perform a spectral analysis for the seismic responses at the bottom floor of the nuclear power structure. Floor response spectral accelerations for the bottom of the model structure with different foundations under El Centro wave at SME input level are shown in Fig. 10.

In Fig. 10 (a) and (b), the floor response spectrum at the bottom of the BN structure has a larger amplitude mainly in the 7-30 Hz band compared to the FN structure, which is similar to the analytical result from the acceleration responses. The peak spectral accelerations are near the design fundamental frequency of the model structure (10.80 Hz). For isolated model structure, an interesting analytical result appears in Fig. 10 (c) and (d). In the X direction, the peak amplitudes of the floor response spectra near 2Hz are 0.61 g and 0.36 g for FI and BI, respectively, while in the Y direction, the peak amplitudes of the floor response spectra are 0.47 g and 0.83 g, respectively. This indicates that the floor response of the BI structure under three-

dimensional ground shaking excitations is inconsistent in the horizontal directions, compared with that of the FI. Besides, the response spectral amplitude for BI is obviously larger in the 30-50 Hz frequency band. The reason for this phenomenon may be that, compared with the flat foundation, the bulged foundation under the dynamic behavior of horizontal shear waves is subjected to larger vertical and oblique force components, and the complex interaction forces lead to different dynamic responses of the model structure in the X and Y directions as well as the generation of high-frequency vibrations. More investigations are pending for further numerical analyses.

Fig. 11 shows the hysteresis curves of a typical bearing at SME seismic input level. In the figures, the shape of the hysteresis curve varies due to the different characteristics of the input motion spectrum. Combined with more experimental results, it can be found that the hysteresis curves of the bearing in the BI system are slightly fuller. This indicates that the use of bulged foundation in this soil-structure interaction model system allows the seismic isolation bearings perform more energy dissipation functions, but the overall difference is not significant.



(a) Non-isolation (X direction) (b) Non-isolation (Y direction)

(c) Isolation (X direction) (d) Isolation (Y direction)

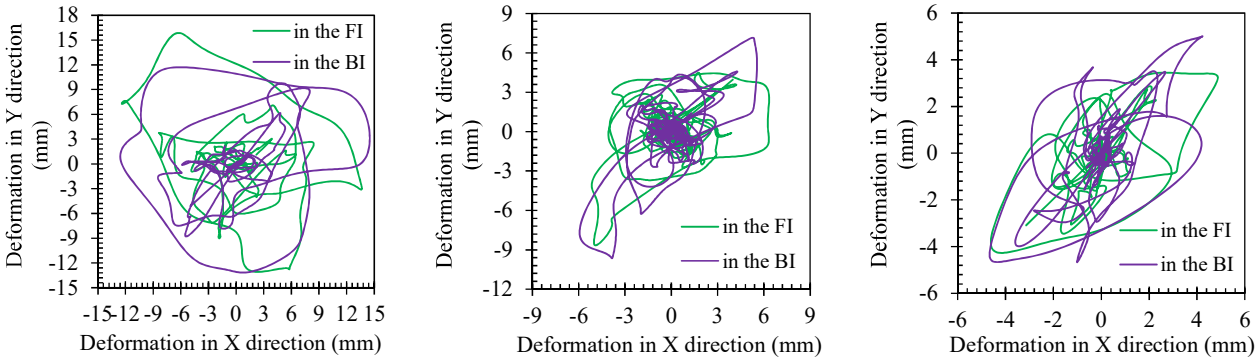
Fig. 10 – Floor response spectral accelerations for the bottom of the NPP model with different foundations at SME input level (El Centro wave)

3.4 Rocking effect analysis

Referring to Fig. 4, measurement points A1 and A3 were set along the X-direction at the top edge of the foundation, and the comparison of the vertical acceleration time histories provided by A1 and A3 is shown in Fig. 12. From the figures, it can be seen that the acceleration timescale has a phase difference of about 180 degrees in some time periods, indicating that the non-isolated structure has a rocking effect under ground shaking [24]. To investigate the extent to which the shape of the foundation affects the rocking effect for the model structure, a spectral analysis of the vertical acceleration response was performed in this section.

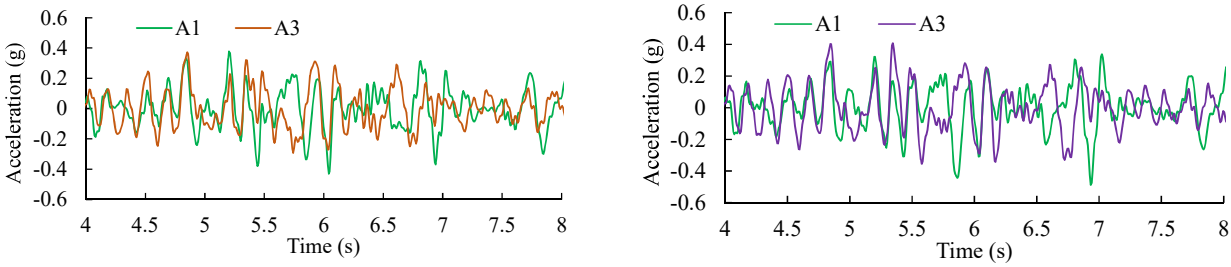
Fig. 13 shows the ratio spectra of acceleration responses for the foundation, the amplitudes were calculated by the ratio of the vertical acceleration response spectra of the foundation for BN and FN, which represents the amplification of the rocking behavior in the frequency domain. In Fig. 13, the ratio spectrum is influenced by the seismic spectral characteristics and intensity. As the input intensity increases, the response amplification of the rocking effect by bulged foundation is mainly concentrated near the fundamental frequency of the model soil and the structure, with the amplification coefficients ranging from about 1.00-

1.46 and distributed in the 5-30 Hz frequency band. It is shown that the amplification of the horizontal acceleration responses of the non-isolated model structure partly originates from the amplification of the rocking effect by the bulged foundation, which has no better energy dissipation effect in this model soil condition.



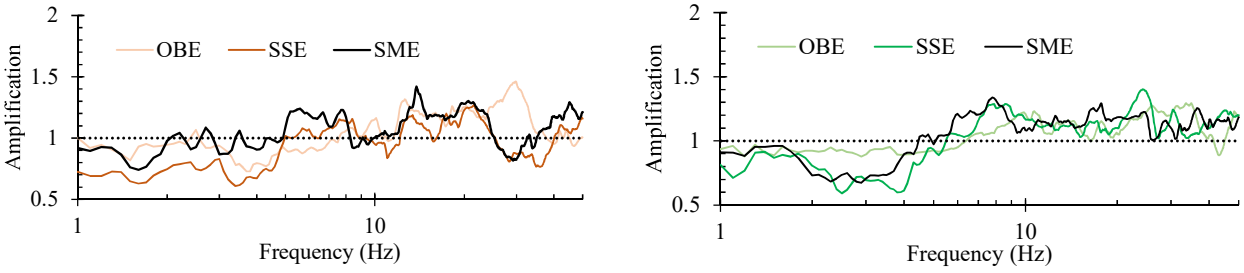
(a) RG1.60 (b) El Centro (c) Kobe

Fig. 11 – Hysteresis curves for a typical isolation bearing at SME input level

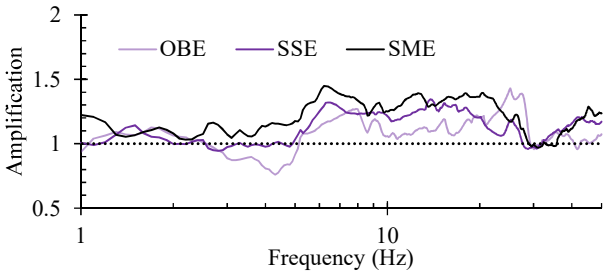


(a) FN (b) BN

Fig. 12 – Comparison of vertical acceleration time histories between point A1 and A2 (RG1.60 wave)



(a) RG1.60 wave (b) El Centro wave



(c) Kobe wave

Fig.13 – Vertical acceleration ratio spectra

4. Conclusions

The effects of NPP foundation shape on seismic energy dissipation were explored by model tests in this paper and the main conclusions are as follows:

(1) In this model test, the model soil has an amplifying effect on the acceleration responses of the nuclear power structure. As the input intensity increases, the nonlinear development of the model soil increases and the peak acceleration magnification factor at the soil surface decreases. At the same input intensity, the amplification effect of acceleration responses of isolated structure is more significant than that of the non-isolated structure due to the decrease of soil-structure interaction force.

(2) With reference to the soil pressure results, the interaction force between the bulged foundation and the model soil is smaller compared to the flat foundation, resulting in a smaller degree of nonlinear development of the model soil during ground shaking and a lower energy dissipation effect. Therefore, using a bulged foundation to increase energy dissipation is not appropriate in this site condition, the adaptability of the site is also worthy of attention.

(3) For the isolated model structure, using a bulged foundation complicates the dynamic responses of the structural system: on the one hand, the bulged foundation is better able to make the LRBs play an energy-dissipating role, whose hysteresis curves are slightly fuller; on the other hand, the horizontal seismic responses of the model structure are not consistent with that of the structure using a flat foundation. More comprehensive analyses of the seismic responses for nuclear power structure using a bulged foundation need to be further performed.

(4) For the non-isolated structure, the bulged foundation increases the horizontal acceleration responses with a more pronounced rocking response. The analysis of the vertical acceleration responses of the foundation shows that the frequency distribution of the bulged foundation amplifies the rocking behavior in the 5-30 Hz band and the response spectral ratio ranges from 1.00 to 1.46 compared with that using flat foundation.

5. Acknowledgements

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