DYNAMIC CHARACTERISTICS OF A LARGE HORIZONTAL ROTATING MACHINE FOUNDATION CONSIDERING SOIL-STRUCTURE INTERACTION

Qi HU[1], Kai ZHANG[2], Jianwen SHAO[3], Yun CHEN[4], Huajian FANG[5,*], Shaoqi LU[6]

For a large horizontal rotating machine foundation in layered soils, the finite element and infinite element (FE-IFE) coupled method in ABAQUS is used to simulate the vibration of the structure and the surrounding soil caused by the horizontal excitation force of the machine. A simplified analytical model is also proposed by considering homogeneous soil to study the dynamic characteristics. Five cases are designed, and the results are compared. The results show that the soil-structure interaction (SSI) should be considered during the analysis, with the maximum response displacement amplitude of the structure reduced by 80% after considering SSI, and the corresponding frequency dropping from 4.72 Hz in the fixed-base case (case 2 without SSI) to 2.71 Hz in the FE-IFE coupled model (case 4, with SSI).

Keywords: Dynamic; Soil-structure interaction; Foundation; Finite element-infinite element coupled analysis; Analytical model

1. Introduction

For the analysis of dynamic characteristics of dynamic machine foundation, the basic theoretical methods can be sorted as the elastic half space system and the mass-spring-damping system. According to these two basic systems, there are many simplified calculation methods for engineering application. Gazetas [1] presented a complete set of algebraic formulas and dimensionless charts for readily computing the dynamic sti and damping coefficients of foundations harmonically oscillating

[1] Associate professor, College of Civil Engineering and Architecture, Zhejiang University of Technology, China, e-mail: huqi@zju.edu.cn
[2] Master, Zhejiang University of Technology, China, e-mail: 1309789542@qq.com
[3] Senior engineer, Architectural Design and Research Institute of Zhejiang University, China, e-mail: shaojw@ gmail.com
[4] Senior engineer, Architectural Design and Research Institute of Zhejiang University, China, e-mail: 727681168@qq.com
[5] Engineer, Zhejiang Zhefeng Engineering Consulting Co., Ltd., China, e-mail: akuang@live.cn
[6] Master, Dongtong Geotechnical Technology Limited Co., Ltd., China, e-mail: 504328241@qq.com
*Corresponding Author

on/in a homogeneous half space. These simplified equivalent springs and dashpots for both surface and embedded foundations of arbitrary shapes were discussed in detail [2-4]. But for complicated dynamic machine foundations in layered soils, the elastic half space theory is not applicable. It is also difficult to consider the energy radiation problem of the foundation vibration source in soil when applying the mass-spring-damping system. Therefore, the soil-foundation-structure system modelled by numerical methods is generally used for the dynamic response analysis of complicated dynamic machine foundations.

The dynamic behaviors of the dynamic machine foundation involve the structure-soil interaction (SSI). When the direct method is used for the SSI analysis, the key is to simulate the semi-infinite space characteristics of soils. Generally, the numerical method and the semi-analytical method are applied and the artificial boundary conditions are introduced to simulate the effect of radiation damping in infinite soil. The research of literature [5] provided an insight into the numerical simulation of SSI phenomena in a shaking table facility, and the results showed the fundamental frequency of the soil-foundation-structure system with a fixed base dropping from 22.5 Hz to 12 Hz after considering the SSI effect. Bhowmik et al. [6] developed a FE-IFE coupled model, and studied the nonlinear characteristics of a single pile in layered soil under different horizontal dynamic loads. Wen et al. [7] established three-dimensional finite element models of an underground substation with FE-IFE coupled method to study the SSI effect.

A large horizontal rotating machine foundation is planned to be designed and constructed in soft soils located in Hangzhou, China. A large excitation force will be generated by the machine during its operation. This paper aims at studying the dynamic characteristics of the above dynamic machine foundation, in order to avoid resonance or excessive response displacement of the structure and foundation under the excitation force when the machine works. The FE-IFE coupled method and a simplified analytical model are applied in the dynamic analysis. Five cases are designed through which the effects of SSI and material damping on the dynamic responses of the structure and soils are studied.

2. Basic theories

The horizontal excitation force induced by the horizontal rotating machine can be considered as harmonic excitation as the machine generally works in a state of uniform rotation. The basic theories of the steady-state dynamic analysis in this study are introduced as follows.

The governing equation of motion for a SSI system can be expressed as:

$$[M]\{\ddot{r}\}+[C]\{\dot{r}\}+[K]\{r\}=\{R\} \tag{1}$$

where [M] is the mass matrix, [C] is the damping matrix, [K] is the stiffness matrix, {r} is the response displacement, {$\dot{r}$} is the response velocity, {$\ddot{r}$} is the response acceleration, {R} is the excitation force.

For the harmonic excitation force with a frequency of ω, there is:

$$\{R(\omega,t)\} = \{F\} e^{i\omega t} \tag{2}$$

Its steady-state response displacement can be expressed as according to equation (1):

$$\{r\} = \{u\} e^{i\omega t} \tag{3}$$

where {F} is the amplitude of the excitation force, {u} is the amplitude of the displacement, i is the imaginary unit, and t is the time.

In the frequency domain, the governing equation of motion can be expressed as [8, 9]:

$$[S]\{u\} = [F] \tag{4}$$

where [S] is the dynamic stiffness matrix which is:

$$[S] = [K] + i\omega[C] - \omega^2 [M] \tag{5}$$

Therefore, {u} can be obtained through equations (4)-(5).

3. Case design

3.1 Soil properties

The building structure and the foundation for the horizontal rotating machine is planned to be designed and constructed in soft soils in Hangzhou. The engineering properties of soils are determined by the data from an adjacent engineering project. The calculation parameters of layered soils are shown in table 1. The pile foundation is in S4, S5, S6, S10-1 and S10-3. S10-1 and S10-3 are selected as the bearing layers and the soils below S10-3 are considered as rigid bedrock. The relative positions of the structure, pile foundation and layered soils are shown in Fig. 1.

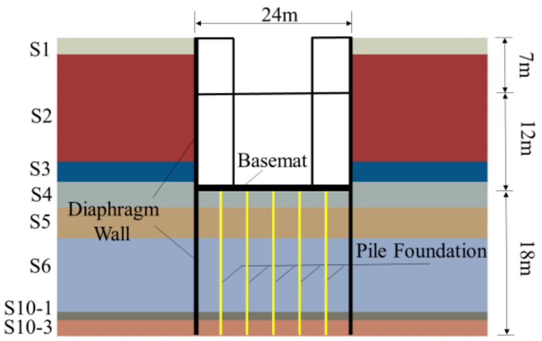


Fig. 1. Schematic diagram of the structure and the layered soils

Table 1

Table of calculation parameters of soil

Soil layer	Description	Thickness /m	Natural density /kg·m^{-3}	Poisson 's ratio	Shear wave velocity /m·s^{-1}	Shear modulus /MPa	Elastic modulus /MPa
S1	Filling soil	2.05	1800	0.35	75	9.93	26.8
S2	Mucky clay	13.3	1720	0.48	125	26.88	53.1
S3	Clay	2.5	1830	0.45	155	43.97	125.8
S4	Silty sand	3.2	1850	0.4	220	89.54	218.5
S5	Silty clay	3.8	1830	0.4	170	52.88	150.7
S6	Round gravel	9.15	1950	0.35	300	175.5	363.7
S10-1	Completely weathered argillaceous siltstone	1	2000	0.3	1240	3077	8000
S10-3	Moderately weathered argillaceous sandstone	2	2100	0.25	1950	8000	20000

For the layered soils shown in figure 1, the bedrock is idealized as a rigid half space, the vertical shear beam model can be adopted to analyze the dynamic characteristics of the soils [10, 11]. In the vertical shear beam model, considering the transverse vibration of layered soils column with unit width, one can get the natural frequencies of layered soils.

The vertical shear beam model is used to calculate the first natural frequency (fundamental frequency) and the third order natural frequency of the layered soils in this study, which are about 1.26 Hz and 5.10 Hz (ω_{n1}=7.92 rad·s^{-1}, ω_{n3}=32.04 rad·s^{-1}).

Rayleigh damping is adopted for the layered soils, which can be expressed as [12]:

$$[C]=\alpha[M]+\beta[K] \tag{6}$$

$$\alpha=2\zeta\,\omega_1\omega_2/(\omega_1+\omega_2) \tag{7}$$

$$\beta=2\zeta/(\omega_1+\omega_2) \tag{8}$$

where α and β are Rayleigh damping coefficients, ω_1 is the fundamental frequency, ω_2 is the high order natural frequency which has great impact on the system and is set as the third order natural frequency [13,14], and ζ is material damping ratio.

ζ_s is the material damping ratio of soil and is determined by mechanical properties of soil [15]:

$$\zeta_s = V_s a_0 / 2\pi \tag{9}$$

where V_S is the shear wave velocity and the specific value of each soil layer used in this paper is given in table 1. a_0 is the frequency-independent attenuation coefficient.

The damping of each soil layer calculated by the formula above is shown in table 2.

Table 2

Damping of soil in each layer

Soil layer	a_0 / s·m^{-1}	α / s^{-1}	β / s
S1	1.25E-03	0.3157	0.00124
S2	1.25E-03	0.3157	0.00124
S3	1.00E-03	0.3132	0.00123
S4	1.35E-03	0.6002	0.00237
S5	1.00E-03	0.3435	0.00135
S6	1.00E-03	0.6062	0.00239
S10-1	3.85E-04	0.6224	0.00245
S10-3	7.75E-04	0.6348	0.00250

3.2 Structure properties

The building for the machine is designed as a two-story concrete structure underground. The diaphragm wall (1.2 m thick, 37 m deep) serves as the retaining wall during the excavation of the basement (i.e., the two-story concrete structure) and the exterior wall of the basement. The thickness of the inner concrete wall of the -1 story and -2 story are 1.8 m and 3.1 m, respectively. The height of the -1 and -2 stories are 7 m and 10 m, respectively. The height of -1 and -2 stories are 7 m and 10 m, respectively. The basemat (bottom plate of the basement) is 2 m thick, 24 m wide and 24 m long. There is a 1.8 m diameter hole set on the floor slab of -1 story (the central zone, 3 m thick) for the installation of the machine. The thickness of other floor slabs are all 1 m thick. The self-weight of the machine is 2×10^5 kg. The maximum rotation speed of the machine is 600 rot/min (10.0 Hz), and the maximum horizontal excitation force is 750 kN.

The 5×5 group pile foundation is designed. The concrete piles are 18 m long with 1m diameter and 4 m spacing. Both the piles and diaphragm wall have an embedment depth of 2 m in the bearing layer S10-3.

For the concrete material in this study, the elastic modulus is 30 GPa, the Poisson's ratio is 0.25, and the density is 2500 kg·m^{-3}. Through numerical simulation (see case 1 in the following section), the fundamental frequency and the third order natural frequency of the structure (with piles and diaphragm wall) are

5.03 Hz (31.6 rad·s^{-1}) and 9.26 Hz (58.18 rad·s^{-1}), respectively. The Rayleigh damping of the concrete material is set to be α=2.048 s^{-1} and β=0.00111 s (the material damping ratio ζ_c = 0.05) for the later analysis.

3.3 Numerical model and analytical model

The FE-IFE coupled model in ABAQUS R2016x (Dassault Systemes Simulia Corp.) is used to study the dynamic behaviors of the SSI system shown in figure 2 numerically. The linear elastic model is adopted for the soils and the concrete material. According to the literature [6, 7], the FE-IFE coupled analysis method is used for the soil boundary condition in the overall system analysis.

For the numerical analysis in the FE-IFE coupled model, the following basic assumptions are adopted [16, 17].

(1) Each layer of soil is homogeneous and extends infinitely in the horizontal direction. There are no normal or shear stresses on the free surface of S1, and there are no displacements at the bottom of S10-3.

(2) The soil is linearly elastic, homogeneous and isotropic with frequency-independent material damping of the hysteretic type. There is no relative sliding among different layers of soil, and the soil overlies the rigid bedrock below S10-3.

(3) The contact between the diaphragm wall and soil is complete and perfect, without sliding or separation.

(4) There is no relative displacement among the piles and the surrounding soils.

Table 3

Elements, boundary conditions and coupling conditions used in the FE-IFE analysis

Item	Condition	Note
Model dimension	Length × width × depth =200m×200m×37m	Finite element only
Layered soils	C3D8R,C3D10 solid elements	
Concrete wall, floor slabs and basemat	S4R shell elements	
Piles	B31 beam elements	
Horizontal boundary conditions	CIN3D8 infinite solid elements	
Bottom boundary conditions of the bottom soils	Fixed	
Contact between layered soils and the diaphragm wall	Nodes coupling	Perfect contact
Contact between piles and layered soils	Nodes coupling	Perfect contact

Based on the above assumptions, the elements, boundary conditions and coupling conditions used in the FE-IFE coupled model are set as table 3. Shell elements (S4R) are used for floor slabs, concrete walls, and beam elements (B31) are used for the pile foundation. Solid elements (C3D8R and C3D10) are used for the soils. The self-weight of the machine is evenly distributed to the nodes of the -

1 story floor slab supporting the machine by using the inertia mass. The horizontal excitation force is set at the central of the -1 story floor slab.

The dimension of elements of the structure is 2 m×2 m. The dimensions of soil elements range from 1 m×1 m to 5 m×5 m with increasing distance from the structure. Meshed model and output points of the structure and soils are shown in Fig. 2.

A simplified analytical method is also proposed to study the dynamic characteristics of the SSI system shown in Fig. 2. Generally, the foundation is treated as a rigid block in the simplified model for foundation dynamic problems, and the soil is analyzed as a homogeneous elastic half space. If the simplified homogeneous elastic half space model is used in this project, although the result is not accurate enough, it can still be regarded as a reference for the analysis.

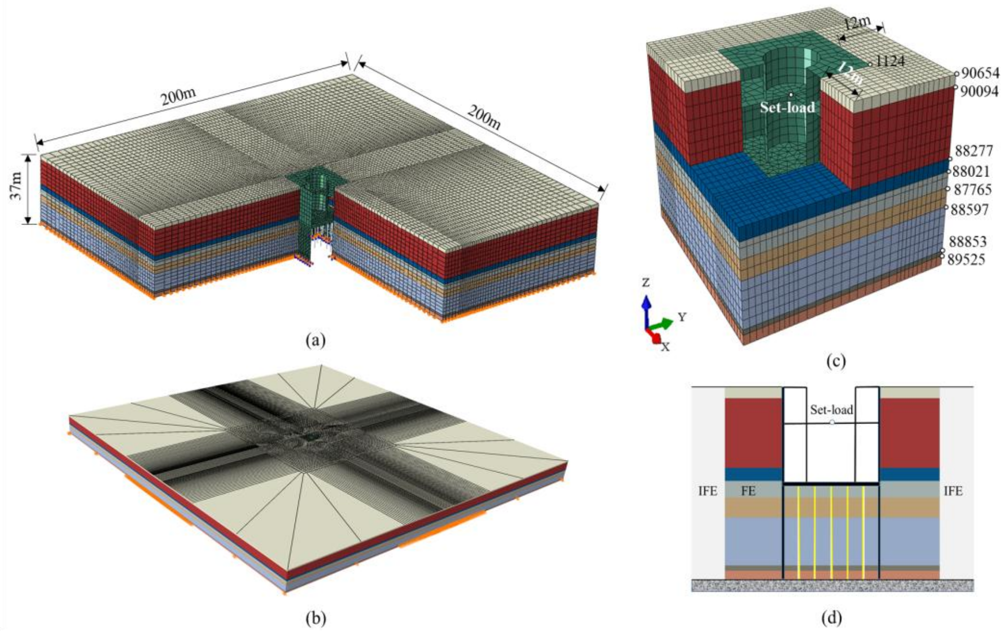


Fig. 2. The FE-IFE model. (a) structure, pile foundation and layered soils (FE-region) (b) the total model. (c) corner point and loading point of structure, and output points of soils, (d) cross-sectional view

In the project analyzed in this paper, the most mass of the structure is concentrated on the part above the basemat which is mainly embedded in soil layer S2 and is influenced by layer S2 mostly. Therefore, the layered soils are simplified as a homogenous elastic half space with same values of the parameters of S2. The shear modulus, Poisson's ratio and density of the homogenous elastic half space are G_h=26.88 MPa, $\nu_{h,}$=0.48 and ρ_h=1720 kg·m^{-3}, and the material damping ratio of the homogenous elastic half space is ζ_h=0.05. The structure underground can be simplified as a rigid block without considering the diaphragm below the basemat or the pile foundation. As shown in figure.3, the soil-foundation-structure system researched in the project can be simplified as a homogenous elastic half space model. The half-length *L* and half-width *B* of the basemat are both 12 m, the embedded depth of the basemat *D* is 19 m, the height of complete sidewall (the exterior of the basement) soil contact in the vertical direction *d* is 19 m, and the distance from the centroid of the sidewall to ground surface *h* is 9.5 m.

According to Gazetas and Tassoulas [1, 2], the equations (10)-(18) for calculating the equivalent dynamic stiffness (spring constant) and the equivalent damping (dashpot coefficient) are proposed for the square (*L*=*B*) foundation embedded in the homogenous elastic half space.

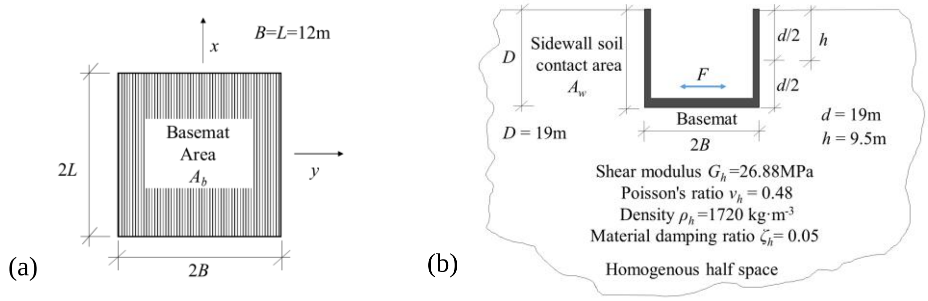


Fig. 3. Simplified homogenous elastic half space model.(a) plan view; (b) cross-sectional view

For the dynamic stiffness:

$$K_{y,\mathrm{suf}} = [2G_h L/(2-\nu_h)]\cdot[2+2.5(A_b/4L^2)^{0.85}] \tag{10}$$

$$K_{y,\mathrm{suf}} = [2G_h L/(2-\nu_h)]\cdot[2+2.5(A_b/4L^2)^{0.85}] \tag{11}$$

$$\bar{K}_y = k_y \cdot K_{y,\mathrm{emb}} \tag{12}$$

where $K_{y,\mathrm{suf}}$ is the static stiffness for the foundation on the surface of the homogenous elastic half space. A_b is the area of basemat. A_w is the area of the vertical sidewall surface in contact with the surrounding soil. $K_{y,\mathrm{emb}}$ is the static stiffness for the foundation embedded in the homogenous elastic half space. $\bar{K}_y$ is the dynamic stiffness, the dynamic stiffness coefficient k_y is 1 (regardless of the slight decrease of dynamic stiffness coefficient with the increase of excitation frequency).

For the damping, *C* is the damping coefficient which reflects the radiation and material damping generated in the simplified system (due to energy carried by waves spreading away from the foundation and energy dissipated in the soil by hysteretic action, respectively).

The radiation damping:

$$C_{y,\mathrm{suf}} = \rho_h V_s A_b \tag{13}$$

$$C_{y,\mathrm{emb}} = C_{y,\mathrm{suf}} + 4\rho_h (V_s + V_{La}) Bd \tag{14}$$

where $C_{y,\mathrm{suf}}$ is the radiation damping coefficient for the foundation on the surface of the homogenous elastic half space. $C_{y,\mathrm{emb}}$ is the radiation damping coefficient for the foundation embedded in the homogenous elastic half space. V_s and V_{La} are the shear wave velocity and Lysmer's analog wave velocity of the homogenous elastic half space and can be expressed as:

$$V_s = \sqrt{G_h / \rho_h} \tag{15}$$

$$V_{La} = 3.4 V_s / [\pi(1-\nu_h)] \tag{16}$$

The total damping C_{Total} of the simplified system can be expressed as:

$$C_{\mathrm{Total}} = C_{y,\mathrm{emb}} + 2\bar{K}_y \zeta_h / \omega \tag{17}$$

The equivalent damping ratio of the simplified system is:

$$\zeta_{\mathrm{equ}} = C_{\mathrm{Total}} \Big/ 2\sqrt{\bar{K}_y m} \tag{18}$$

where the equivalent mass (the mass of the basement) m is 1.67 ×10^7 kg.

The response displacement amplitude for the centroid of the basemat-soil interface can be obtained by the equation calculated for the steady-state dynamic response of a single-freedom system which can be expressed as:

$$u = \frac{F}{\bar{K}_y} \frac{1}{\sqrt{\left[1-\left(\omega \Big/ \sqrt{\frac{\bar{K}_y}{m}}\right)\right]^2 + 4\zeta_{\mathrm{equ}}^2 \left(\omega \Big/ \sqrt{\frac{\bar{K}_y}{m}}\right)}} \tag{19}$$

For the simplified model, the frequency-independent dynamic stiffness $\bar{K}_y$, and the equivalent damping ratio ζ_{equ} can be get through equations (10)-(18). The response displacement amplitude curve for the centroid of the basemat-soil interface can be obtained by equation (19). The main parameters of the simplified model are shown in table 4.

Table 4

Parameters of the simpilifed model

B / m	L / m	D / m	d / m	h / m	A_b / m^2	A_w / m^2	$K_{y,\mathrm{sur}}$ / N·m^{-1}	$K_{y,\mathrm{emb}}$ / N·m^{-1}	$C_{y,\mathrm{sur}}$ / N·s·m^{-1}	$C_{y,\mathrm{emb}}$ / N·s·m^{-1}
12	12	19	19	9.5	576	456	1.9×10^{10}	3.98×10^{10}	1.24×10^8	7.28×10^8

In order to calculate the maximum response displacement amplitude of the structure and the frequency corresponding to the maximum amplitude under the excitation force from the machine operation, the dynamic characteristics of the SSI system with a fixed amplitude of harmonic excitation force (750 kN) is studied under a range of frequency (0-20 Hz). As shown in table 5, five cases in three moels are designed in this study. Case 1 and case 2 in model 1 represent the model of the structure with diaphragm wall and pile foundation resting on rigid bedrock without layered soils which is established by FE method in Abaqus. The composition of model 1 and the division of the grid are the same as the settings of the structure in the FE-FEM model described above. Therefore, model 1 can be used to calculate the response displacement of the structure without SSI. The material damping is not considered in case 1, and Rayleigh damping is considered in case 2. Case 3 and case 4 in model 2 represent the FE-IFE coupled model considering SSI. Similarly, the material damping is not considered in case 3, and Rayleigh damping is considered in case 4. Case 5 in model 3 represents the simplified homogenous elastic half space model mentioned above. Considering the most unfavourable load condition, the excitation force is applied along both x and y axis simultaneously in cases 1-4. The excitation force is applied in a single horizontal direction in case 5. The location of the loading point in case 5 is set at the centroid of the basemat, and the location in other cases is shown in figure 2.

Table 5

Case design chart

Model		Excitation amplitude / kN	Frequncy range / Hz	Damping setting	Rigid bedrock	Layered soils
Model 1	Case1	750, both x and y axis	0-20	/	√	/
	Case2	750, both x and y axis	0-20	Rayleigh damping	√	/
Model 2	Case3	750, both x and y axis	0-20	/	√	√
	Case4	750, both x and y axis	0-20	Rayleigh damping	√	√
Model 3	Case5*	750, single direction	0-20	Equivalent damping	×	×

Note: *Case 5 is a simplified system with only the horizontal single direction in the steady-state analysis.

4. Results and Discussion

Due to the symmetry of the overall system , the response displacements of the SSI system in two horizontal directions are basically the same, the calculation results along y axis represent the response in horizontal direction, and the calculation results along z axis represent the response in vertical direction. For the structure, the response displacement in horizontal direction is much larger than that in vertical direction. Therefore, the results are compared only along y axis for the strucutre.

The response displacement amplitude curves in case 4-5 for the centroid of the basemat-soil interface are drawn in figure 4. The maximum amplitude and the corresponding frequency are summarized in table 6. For case 5, the frequency corresponding to the maximum amplitude (25.64 μm) is at the excitation frequnency (3.90 Hz). Case 4 has a lower value of the maximum amplitude (23.02 μm) at the excitation frequency (2.71 Hz).

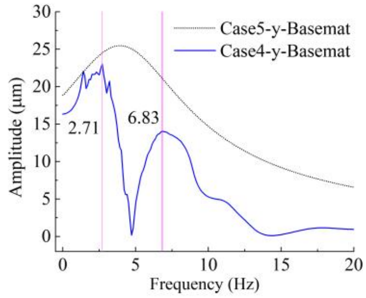


Fig. 4. Response displacement amplitude versus excitation frequency for the centroid of the basemat-soil interface in case 4-5

As compared to case 5, case 4 has lower amplitudes in all the excitation frequencies which shows that the stiffness in the basemat-soil interface of the FE-IFE coupled model is greater than that of the simplified model. The reasons can be that the radiation damping is underestimated, and the pile foundation and part of the diaphragm wall are not considering in the simplified model. Compared to the simplified model in case 5, the second peak at the excitation frequency (6.83 Hz) in case 4 shows the influence of the layered soils on the basemat-soil interface. The result of the FE-IFE coupled model is more accurate to reflect the actual situation compared with the simplified model.

Table 6

The maximum displacement amplitude and corresponding frequency for the centroid of the basemat-soil interface in case 4-5

Model	Maximum amplitude /μm		Corresponding frequency / Hz
Case 5	25.46		3.90
Case 4	First peak	23.02	2.71
	Second peak	14.05	6.83

The response displacement amplitude curves along y axis for the loading point in cases 1-4 are shown in figure 5, and the maximum amplitude and corresponding frequency are summarized in table 7. As compared to case 2, case 1 without considering the material damping needs a higher frequency to get the maximum amplitude. For case 1, the frequency (5.02 Hz) corresponding to the maximum amplitude is exactly the fundamental frequency of the structure. Case 2 has a much lower value of the maximum amplitude (281 μm) than that of case 1 (14962 μm) accordingly.

After considering SSI in the FE-IFE model, case 3 and case 4 have the same value of frequency (2.71 Hz) corresponding to the maximum amplitude. As compared to case 3, case 4 also has a lower value of the maximum amplitude due to the material damping. Through comparison between case 2 and case 4, the maximum amplitude and corresponding frequency are significantly reduced from 281 μm to 55.78 μm and 4.72 Hz to 2.71 Hz, respectively, after considering SSI.

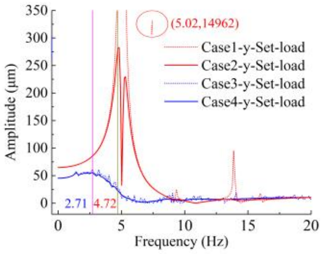


Fig. 5. Response displacement amplitude versus excitation frequency of the loading point in case 1-4

Table 7

The maximum displacement amplitude and corresponding frequency for the loading point in case 1-4

Model	Maximum amplitude /μm	Corresponding frequency / Hz
Case 1	14962	5.02
Case 2	281	4.72
Case 3	61.67	2.71
Case 4	55.78	2.71

The response displacement amplitude curves for the corner point in case 3-4 are shown in figure 6, and the maximum amplitude and corresponding frequency are summarized in table 8. It can be obtained that the maximum amplitudes of the corner point in case 3-4 are both at excitation frequency (2.71 Hz) along y axis, and the maximum amplitude is reduced by 12 % due to the material damping, from 56.28 μm (case 3) to 49.28 μm (case 4).

Through comparison among the curves in figure 4, 5 and 6 for the three points in case 4, it can be obtained that the maximum amplitude for each point is at the same excitation frequency (2.71 Hz), and the maximum response displacement amplitude in the structure is at the loading point along y axis.

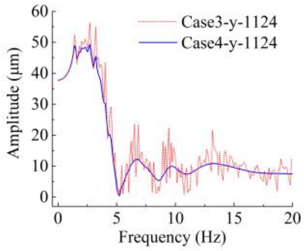


Fig. 6. Response displacement amplitude versus excitation frequency for the corner point in case 3-4.

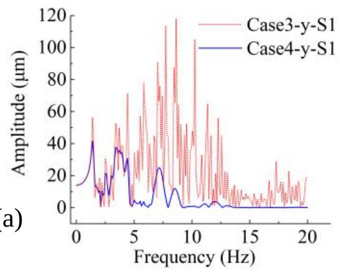
Table 8

Maximum response displacement amplitude and corresponding frequency for the corner point in case 3-4

Model	Maximum amplitude /μm	Corresponding frequency / Hz
Case 3	56.28	2.71
Case 4	49.28	2.71

For the layered soils in the FE-IFE coupled model, Fig. 7 describes the response displacement amplitude of the topsoil S1 in case 3-4 along y axis and z axis. Due to the free surface of the topsoil and the interaction among the different layers of soil, case 3 has more peaks than case 4 in high excitation frequency band (above 5 Hz) both along y axis and z axis when neglecting the material damping in case 3. As compared with case 3, the material damping in case 4 has great influence on the response displacement amplitudes in high excitation frequency band, and smaller influence in low excitation frequency band (below 5 Hz). It is necessary to consider the material damping in the SSI system.

The maximum response displacement amplitude of each layer of the soils along y and z axis in case 4 are summarized in table 9. It can be concluded that the maximum amplitude of the layered soils is in S1 (57.70 μm) in vertical direction, and the maximum amplitude of each soil layer decreases progressively from S1 to S10-3 in case 4, as the elastic modulus of soil increases with the depth increasing.



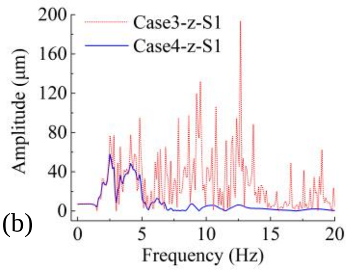


Fig. 7. Response displacement amplitude versus excitation frequency for output point in S1 along.in case 3-4 (a) y axis; (b) z axis

Table 9

Maximum response displacement amplitudes for output points of the layered soils in case 4

	Soil layer	S1	S2	S3	S4	S5	S6
y axis	Maximum amplitude / μm	41.55	40.77	18.16	19.02	17.45	9.80
z axis	Maximum amplitude / μm	57.70	53.70	26.24	21.33	16.34	8.58

5. Conclusion

For the underground structure designed for the horizontal rotating machine, the soil surrounding the structure has great influence on the overall vibration. It is necessary to consider SSI effect in the soil-foundation-structure system. The SSI effect can decrease the maximum response displacement amplitude of the structure by 80% from 281 μm (case 2, without SSI) to 55.78 μm (case 4, with SSI), and can also reduce the frequency corresponding to the maximum amplitude from 4.72 Hz to 2.71 Hz. Compared with the simplified model (case 5), the result of the FE-IFE coupled model (case 4) is more accurate and reasonable.

For the layered soils, the maximum response displacement amplitude of the layered soils is in S1 considering SSI (case 4). Material damping has great influence on the response displacement amplitude of the soils, especially in high excitation frequency band (case 4).

The analysis of the SSI effect on the soil-foundation-structure system can provide a reference for similar projects of complicated dynamic machine foundations.

REFERENCES

[1]. *G. Gazetas*, "Formulas and Charts for Impedances of Surface and Embedded Foundations", J. Geotech. Eng., **vol. 117**, 1991, pp. 1363-1381.

[2]. *G. Gazetas and J.L. Tassoulas*. "Horizontal Stiffness of Arbitrarily Shaped Embedded Foundations", J. Geotech. Eng., **vol. 113**, 1987, pp. 440-457.

[3]. *R. Dobry, and G. Gazetas,* "Dynamic response of arbitrarily shaped foundations", J. Geotech. Eng., **vol.112**, 1986, pp. 109-135.

[4]. *R. Dobry*, "Simplified methods in Soil Dynamics", Soil Dyn. Earthq. Eng., **vol. 61-62**, 2014, pp. 246-268.

[5]. *D. Pitilakis, M. Dietz, D. M. Wood, D. Clouteau and A. Modaressi,* "Numerical simulation of dynamic soil–structure interaction in shaking table testing", Soil Dyn. Earthq. Eng., **vol. 28**, 2008, pp. 453-467.

[6]. *D. Bhowmik, D.K. Baidya and S.P. Dasgupta*, "A numerical and experimental study of hollow steel pile in layered soil subjected to lateral dynamic loading", Soil Dyn. Earthq. Eng., **vol. 53**, 2013, pp. 119-129.

[7]. *B. Wen, L. Zhang, D. Niu and M. Zhang,* "Soil-Structure-Equipment Interaction and Influence Factors in an Underground Electrical Substation under Seismic Loads", Applied Sciences.-Basel, **vol. 7**, 2017, pp. 23.

[8]. *W. D. Smith*, "The Application of Finite Element Analysis to Body Wave Propagation Problems", Geophys. J. R. astr. Soc., **vol. 42**, 1975, pp, 747-768.

[9]. *J. P. Wolf.* "Dynamic soil-structure interaction", Prentice Hall, Englewood Cliffs, New Jersey, 1985.

[10]. *Y. Deng, J. Peng, P. Xu and X. Li*, "Research on spring-shear beam method for natural frequency of layered soils", Engineering Mechanics, **vol. 31**, 2014, pp. 144-151 (in Chinese).

[11]. *Y. Deng, J. Peng, W Fan, Z. Sun and J. Xue*, "Comparisons of computing method for natural frequency of horizontal layered soils on half space", Journal of Henan University (Natural Science), **vol. 45**, 2015, pp. 113-116 (in Chinese).

[12]. *M. Hudson, I. Idriss and M. Beikae.* "User manual for Quad4m: a computer program to evaluate the seismic response of soil structures using finite element procedures and incorporating a compliant base", University of California, California, 1994.

[13]. *A.O.L. Kwok, J. P. Stewart, Y. M. A. Hashash, N. Matasovic, R. Pyke, Z. Wang and Z. Yang*, "Use of Exact Solutions of Wave Propagation Problems to Guide Implementation of Nonlinear Seismic Ground Response Analysis Procedures", J. Geotech. Geoenviron. Eng., **vol. 133**, 2007, pp, 1385-1398.

[14]. *Q. Sun, J. Bo, D. Peng, and X. Jiang*, "Effect of Rayleigh damping matrix on seismic response analysis of deep soft soil", China Earthquake Engineering Journal, **vol. 39**, 2017, pp, 713-718 (in Chinese).

[15]. *H.R. Nejati, M. Ahmadi and H. Hashemolhosseini*, "Numerical analysis of ground surface vibration induced by underground train movement", Tunn. Undergr. Sp. Tech., **vol. 29**, 2012, pp. 1-9.

[16]. *W. Wu, K. Wang, Z. Zhang and C.J. Leo*, "Soil-pile interaction in the pile vertical vibration considering true three-dimensional wave effect of soil", Int. J. Numer. Anal. Meth. Geomech., **vol. 37**, 2013, pp. 2860-2876.

[17]. *G. Chen, S. Chen, X. Zuo, X. Du, C. Qi and Z. Wang*, "Shaking-table tests and numerical simulations on a subway structure in soft soil", Soil Dyn. Earthq. Eng., **vol.76**, 2015, pp. 13-28.