Simple Method for Dynamic Responses of Soil-Pile-Isolated Structure Interaction System

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Abstract: To investigate the effect of soil-pile-structure interaction (SPSI effect) on the dynamic response of a base-isolated structure with buried footings on a pile foundation, certain shake table tests are previously conducted. Based on the test results and the existing related studies, an efficient simplified model and a corresponding calculation method are verified for estimating the dynamic characteristics of a base-isolated structure with buried footings on a pile foundation with the SSI effect. In this method, the solutions by Veletsos and co-workers for a non-isolated structure with the SSI effect are verified and advanced for a base-isolated structure, and the solutions by Maravas and co-workers for a non-isolated structure on a pile foundation are introduced to consider the effect of the piles. By comparison with the shake table test, this work proves that the simplified method can efficiently estimate the dynamic responses of a base-isolated structure with buried footings on a pile foundation. Using parameter analysis, this work also shows that the dynamic characteristics of a non-isolated structure are quite similar to those of the base-isolated structure when the soil foundation is sufficiently soft, which means that the isolation layer gradually loses its isolation function as the soil foundation softens.

Key words: soil-structure interaction (SSI); base-isolated structure; seismic response; shake table test; simplified method

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0 Introduction

Base-isolated structures have been widely used to reduce earthquake damage in many types of structures. However, the effect of soil-structure interaction (SSI) is often neglected in the existing design methods. Previous research has proven that the SSI effect has a significant influence on the dynamic characteristics of a base-isolated structure, which further affects the dynamic responses of an isolated structure and the isolation efficiency of the isolation layer, e. g., Mahmoud[1] and Li[2]. Therefore, the SSI effect should be efficiently considered in the seismic design of an isolated structure.

Generally, the main methods for analysis of soil-foundation-structure interaction can be classified as follows: (1) analytical methods, which primarily refer to a simple foundation lying on an elastic half-space, e. g., Triantafyllidis[3] and Luco[4]; (2) numerical methods, i. e., the finite element method (FEM), the boundary element method (BEM), etc., that simulate the nonlinear characteristics of media, the contacts between the soil and foundation, and complicated foundations, e. g., Karabalis[5] and Politopoulos[6]; (3) simplified discrete methods, which allow rapid calculation of the soil-foundation-structure interaction system properties, e. g., Andreas[7]; (4) model testing, which primarily refers to investigation of the effect of soil-foundation-structure interaction on the seismic responses of the ground structure, e. g., Zhuang[8] and Li[2].

To estimate the SSI effect on the dynamic re-

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sponses of an isolated structure, Constantinou et al.[9] used the fundamental frequency of the interaction system to value the effect of the SSI on the isolated structure and studied the dynamic responses of a base-isolated structure in terms of a single degree of freedom. Novak et al.[10] studied the rotational effect of an isolator on the modal characteristics of an isolated system using a multilayer shear structure with fixed dynamic stiffness. The influence of the SSI effect was examined by investigating the modal properties, and certain important simplifications for the analysis were also suggested. Pender[11] also analyzed the seismic response of a non-isolated structure built on a nonlinear soil foundation by treating the upper structure as a rigid block and concluded that the nonlinear soil foundation can be viewed as a natural base isolation system. Pérez et al.[12] also investigated the SSI effect on the seismic responses of a base-isolated structure using elastic springs and viscous dampers to replace the soil, which proved that the SSI effects on the shear force were relatively more important than on the displacement, especially in the superior floors. Luco et al.[13] examined the SSI effects on the performance of a nonlinear seismic base isolation system for a simple elastic structure and developed a simple analytical expressions for the deformation of the base isolation system and of the superstructure at resonance in terms of an effective replacement oscillator characterized by amplitude-dependent frequency. Spyrakos et al.[14] investigated the effects of SSI on the response of base isolated multistory buildings founded on an elastic soil layer overlying rigid bedrock and subjected to a harmonic ground motion, and an extensive parametric study demonstratd that SSI effects were significant, primarily for squat, light structures, founded on soil-stratum of low stiffness.

In this work, the main aim is to develop a simplified model for estimating the dynamic characteristics of a base-isolated structure resting on a pile foundation in an elastic half-space. In this method, the fundamental period and damping of a base-isolated structure with buried footings on a pile foundation are compared and verified via shake table tests. Next, for a certain model structure in this paper, we analyze how the main parameters of the soil foundation affect the dynamic characteristics of the SSI system and present selected new findings and conclusions.

1 Simplified Method for Dynamic Characteristics of Base-Isolated Structure

According to the study by Liu[15], the model shown in Fig. 1(a) can be simplified to the model shown in Fig. 1(b). In Fig. 1, K is the equivalent horizontal stiffness of the upper structure, K_0 and C_0 the equivalent horizontal impedances of the isolation layer, K_x and C_x the horizontal impedances of the soil foundation, K_θ and C_θ the rotational impedances of the soil foundation, h the distance from the center of gravity of the foundation to the point of action of the entire inertia force of the isolated structure for the first-order vibration mode, u the horizontal displacement of the isolated structure relative to the foundation, u_θ the horizontal displacement caused by the rotation θ of the footing, u_g the horizontal displacement of the soil foundation at the ground surface, and M the total mass of the isolated layer and upper structure, excluding the mass of foundation.

Using the simplified model shown in Fig. 1(b) and neglecting the mass of the foundation, the dynamic equilibrium equation of interaction system can be expressed as

$$M(\ddot{u}+h\ddot{\theta}+\ddot{u}_f)+C_0'\dot{u}+K_0'u=-M\ddot{u}_g \tag{1}$$

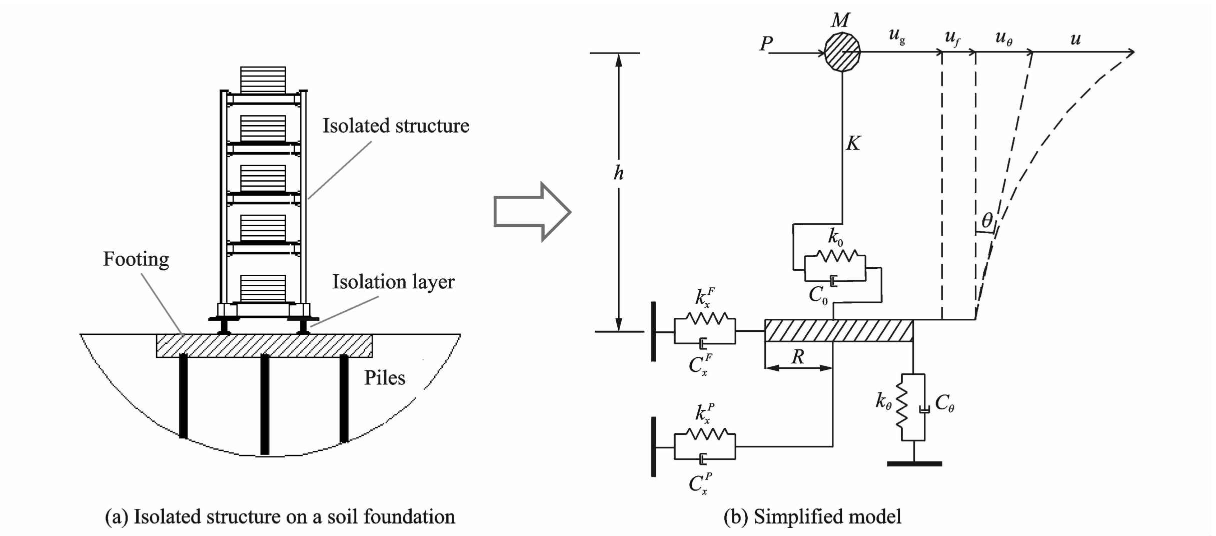
$$M(\ddot{u}+h\ddot{\theta}+\ddot{u}_f)+C_x\dot{u}_f+K_xu_f=-M\ddot{u}_g \tag{2}$$

$$M(\ddot{u}+h\ddot{\theta}+\ddot{u}_f)h+C_\theta\dot{\theta}+K_\theta\theta=-M\ddot{u}_gh \tag{3}$$

where K_0' and C_0' are the equivalent horizontal stiffness and damping factor of base-isolated structure, respectively, and are given as

$$\frac{1}{K_0'}=\frac{1}{K}+\frac{1}{K_0},\quad C_0'\approx C_0 \tag{4}$$

For the isolated structure, if the horizontal stiffness of the non-isolated structure is sufficiently larger than that of the isolation layer, K_0



(a) Isolated structure on a soil foundation (b) Simplified model

Fig. 1 Simplified model for the soil-isolated structure dynamic interaction system

and C_0 can be viewed as the total effective horizontal stiffness and damping factor of the isolated structure, respectively.

K_0 and C_0 can be calculated according to the effective stiffness and damping factor of isolation layer, i. e.,

$$K_0=\sum K_{ri}\tag{5}$$

$$C_0=2M\xi_0\sqrt{\frac{K_0}{M}}\tag{6}$$

$$\xi_0=\frac{\sum K_{ri}\xi_{ri}}{K_0}\tag{7}$$

where K_{ri} and ξ_{ri} are the horizontal stiffness and damping ratio of one isolator, respectively.

According to the solutions by Jennings and Bielak et al.[16], the dynamic properties of the SSI system ($\widetilde{T}$ and $\tilde{\xi}$) can be corrected by the dynamic properties of fixed-base structure (T_c and ξ_c), shown as

$$\widetilde{T}=T\sqrt{1+\frac{K}{K_x}\left(1+\frac{K_xh^2}{K_\theta}\right)}\quad\text{(Non-isolated)}\tag{8-a}$$

$$\widetilde{T}=T\sqrt{1+\frac{K'_0}{K_x}\left(1+\frac{K_xh^2}{K_\theta}\right)}\quad\text{(Base-isolated)}\tag{8-b}$$

$$\tilde{\xi}=\left(\frac{\widetilde{\omega}}{\omega_c}\right)^2\xi+\left[1-\left(\frac{\widetilde{\omega}}{\omega_c}\right)^2\right]\xi_s+\left(\frac{\widetilde{\omega}}{\omega_x}\right)^2\xi_x+\left(\frac{\widetilde{\omega}}{\omega_\theta}\right)^2\xi_\theta\tag{9}$$

where $\widetilde{T}$ and $\tilde{\xi}$ are the fundamental vibration period and damping ratio of interaction system, respectively; T, ξ the fundamental vibration period and damping ratio of the fix-base isolated structure, respectively; ξ_s the soil hysteretic damping; $\tilde{\xi}_0$ the damping ratio of the foundation; ω_c, ξ_c the fundamental circular vibration frequency and damping ratio of the base-isolated structure on a rigid foundation; ω_x, ξ_x the horizontal circular vibration frequency and damping ratio of the soil foundation, respectively; and ω_θ, ξ_θ the rotational circular vibration frequency and damping ratio of soil foundation, respectively, which can be given by

$$\omega_c=\sqrt{K'_0/M}=\sqrt{K'_0/\sum m_i},\ \omega_x=\sqrt{K_x/M}\tag{10-a}$$

$$\omega_\theta=\sqrt{K_\theta/Mh^2}\tag{10-b}$$

$$T_c=2\pi\sqrt{M/K'_0}=2\pi\sqrt{\sum m_i/K'_0}\tag{11}$$

$$\xi_c=\frac{C_0}{2\sqrt{K'_0M}},\ \xi_x=\frac{C_x}{2\sqrt{K_xM}}\tag{12-a}$$

$$\xi_\theta=\frac{C_\theta}{2\sqrt{K_\theta Mh^2}}\tag{12-b}$$

where C_x and C_θ are the horizontal and rotational damping factor of the soil foundation, respectively; and K_x, K_θ the horizontal and rotational stiffnesses of the soil foundation, respectively.

For a base-isolated structure built on a pile foundation, the stiffness of foundation should be mainly formed by the soils around the pile cap and the soils around the piles, respectively. In theory, the stiffness of soil foundation with the piles should be the sum of the stiffness of the soils around the pile cap and the soils around the piles.

However, it has been proved that the existing piles should weak the stiffness of the soils around the pile cap, but it is difficult to decide its contributions to the total stiffness of soil foundation accurately. Accordingly, in this paper, the stiffness of foundation with the piles are corrected by an approximate method as

$$K_x=\sqrt{(K_x^F)^2+(K_x^P)^2}, \quad K_\theta=K_\theta^F+K_\theta^P \tag{13}$$

where K_x^F and K_θ^F are the horizontal stiffness and rotational stiffness of soil foundation without piles, respectively; and K_x^P, K_θ^P are those of the pile foundation, respectively.

(1) K_x^F and K_θ^F

For an isolated structure on the ground without piles, the horizontal stiffness and rotational stiffness of the foundation can be determined by the following expressions given by Veletsos and the co-workers.

$$K_x^F=k_x^F K_s,\ K_\theta^F=k_\theta^F K_{s\theta} \tag{14}$$

$$C_x=c_x\frac{K_s R}{v_s},\ C_\theta=c_\theta\frac{K_{s\theta}R}{v_s} \tag{15}$$

where K_s and $K_{s\theta}$ are the static stiffnesses of foundation, which can be calculated by

$$K_s=\frac{8GR}{2-\upsilon}, K_{s\theta}=\frac{8GR^3}{3(1-\upsilon)} \tag{16}$$

where G is the soil shear modulus, R the radius of the surface footing, υ the soil Poisson's ratio, and v_s the propagation velocity of the shear waves in the half-space. In Eq. (14), k_x^F, k_θ^F, c_x, and c_θ are the frequency-dependent dynamic stiffness modifiers that describe the variation of the impedance terms with frequency, which are given by

$$k_x^F=1,\ k_\theta^F=1-\beta_1\frac{(\beta_2 a_0)^2}{1+(\beta_2 a_0)^2}-\beta_3 a_0^2 \tag{17}$$

$$c_x=\alpha_1,\ c_\theta=\beta_1\beta_2\frac{(\beta_2 a_0)^2}{1+(\beta_2 a_0)^2} \tag{18}$$

where α_1, β_1, β_2, and β_3 are the fitting parameters related to the soil Poisson's ratio, as shown in Table 1, and a_0 is a dimensionless frequency parameter defined as

$$a_0=\frac{\omega R}{v_s} \tag{19}$$

where v_s is the propagation velocity of shear waves in the half-space and ω the circular excitation frequency.

In practical engineering, the distribution of the soil layer and the embedded depth of foundation have effect on the impedance function (K_x^F and K_θ^F). K_x^F and K_θ^F should be modified by the method proposed by Bielak et al.[16] if the distribution of the soil layer and the embedded depth of foundation are considered in the estimation of impedance function.

Table 1 Values for fitting parameters of α_1, β_1, β_2, β_3

Parameter	$\upsilon=0$	$\upsilon=1/3$	$\upsilon=0.45$	$\upsilon=0.5$
α_1	0.775	0.65	0.6	0.6
β_1	0.8	0.8	0.8	0.8
β_2	0.525	0.5	0.45	0.4
β_3	0	0	0.023	0.027

(2) K_x^P and K_θ^P

With the pile effect on the dynamic impedance of the foundation, the following impedance functions derived by Marvas et al.[17] are used to determine K_x^P and K_θ^P

$$K_x^P=(4E_pI_p)^{1/4}\left[(k_x^p-m_p\omega^2)^2+(\omega c_x^p)^2\right]^{3/8}\cos\left(\frac{3}{4}\phi\right) \tag{20}$$

$$K_\theta^P=(4E_pI_p)^{3/4}\left[(k_x^p-m_p\omega^2)^2+(\omega c_x^p)^2\right]^{1/8}\cos\left(\frac{1}{4}\phi\right) \tag{21}$$

where E_pI_p is the bending stiffness of the pile cross-section, m_p the linear mass of pile. k_x^p and c_x^p are the moduli of distributed springs and dashpots along the pile according to the Winkler assumption, which are given as

$$k_x^p=\delta E_s,\ c_x^p=6(a_0^p)^{-1/4}\rho_s V_s d+2\frac{\xi_s k_x^p}{\omega} \tag{22}$$

where E_s is the soil elastic modulus, ρ_s the soil mass density, V_s the soil shear wave propagation velocity, d the pile diameter, ξ_s the soil hysteretic damping, a_0^p the dimensionless frequency parameter for a pile, which can be written as

$$a_0^p=\frac{\omega d}{V_s} \tag{23}$$

where δ is the dimensionless Winkler factor, which is given as

$$\delta = 1.67\left(\frac{E_{\mathrm{p}}}{E_{\mathrm{s}}}\right)^{-0.053} \tag{24}$$

where ϕ is a phase angle, which is given as

$$\phi = \arctan\left(\frac{\omega c_x^p}{k_x^p - m_{\mathrm{p}}\omega^2}\right) \tag{25}$$

2 Simplified Method for Seismic Responses of Base-Isolated Structure

Generally, the structure can be simulated using the lumped mass model to estimate the seismic responses of a base-isolated structure, as shown in Fig. 2. To consider the SSI effect, the dynamic characteristics of the isolated structure can be determined from Eqs. (8), (9), and the equivalent base shear method suggested in the earthquake resistant design code of China can be used to calculate the dynamic responses of an isolated structure with the rigid foundation assumption. Accordingly, the total horizontal seismic excitation is given by

$$F_{ek} = \alpha_1 M g \tag{26}$$

where α_1 is the seismic influence coefficient, which should be determined based on the fundamental vibration period and damping ratio of the isolated structure as calculated by Eqs. (8), (9). Next, the seismic excitation F_i for each floor of the isolated structure is given by

$$F_i = \frac{m_i g h_i}{\sum m_j g h_j} F_{ek} \tag{27}$$

where m_i, m_j are the respective lumped masses for the ith and jth floors of the isolated structure; and h_i, h_j are the respective heights for the ith and jth lamped mass to the bottom of the structure. The seismic interlayer shear force V_i can be expressed as

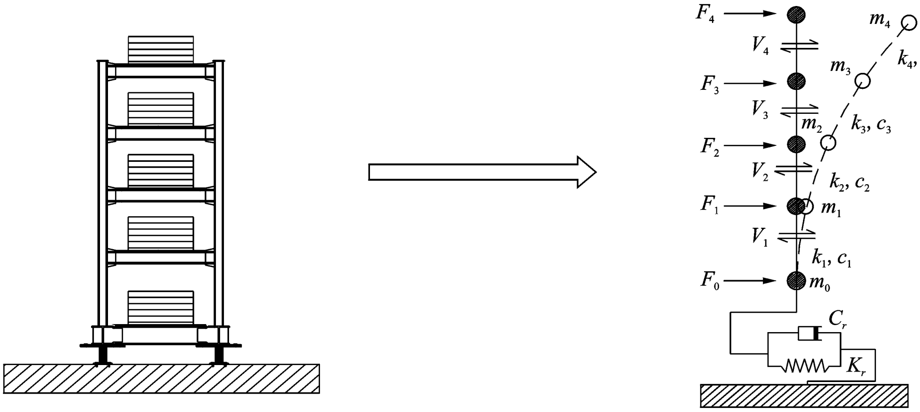
$$V_i = \sum_{i=1}^{n} F_i \tag{28}$$

The interlayer deformation of the isolated structure Δ is given by

$$\Delta = \frac{V_i}{K_i} \tag{29}$$

and the interlayer deformation of the isolation layer $\Delta_{\max}$ can be expressed as

$$\Delta_{\max} = \frac{F_{ek}}{K_0} \tag{30}$$



(a) Isolated structure on a rigid foundation

(b) Simplified lumped mass model

Fig. 2 Simplified model for isolated structure on a rigid foundation

3 Shake Model Tests

Four shake table tests were designed to model the seismic responses of a four-story structure under four different conditions: a non-isolated structure on a rigid foundation (Test I), a base-isolated structure on a rigid foundation (Test Ⅱ), a non-isolated structure on a soil foundation (Test III) and a base-isolated structure on a soil foundation (Test IV). The four tests are illustrated in Fig. 3.

A four-layer steel frame structure is constructed using square steel tubes for the columns and H-shaped steel for the beams. The main di-

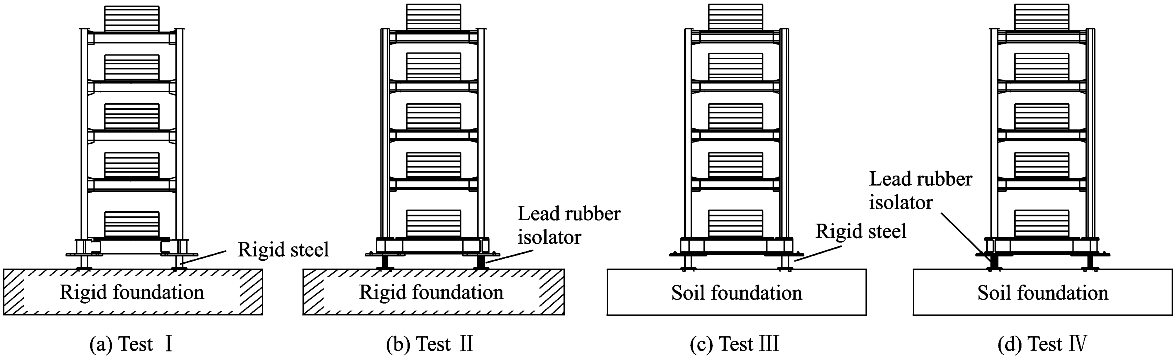


Fig. 3 Shake table tests designed for the four different conditions

mensions of the model steel structure are shown in reference by Zhuang[8]. Accordingly, the aspect ratio of the model structure in the vibration direction is 2.625. The weight of the model structure is 0.32 t. To consider the effect of the model weight on the response of the structure as soon as possible, an additional weight of 0.736 t is added to each floor. The total weight of the model structure plus the additional weight is approximately 4.0 t. Using the equivalent lumped mass method shown in Fig. 1, the total equivalent horizontal stiffness of the non-isolated structure is approximately 7.0 kN/mm, its viscous damping parameter is approximately 10.5 kN·s/m, and the effective height of the model structure is approximately 1.108 m.

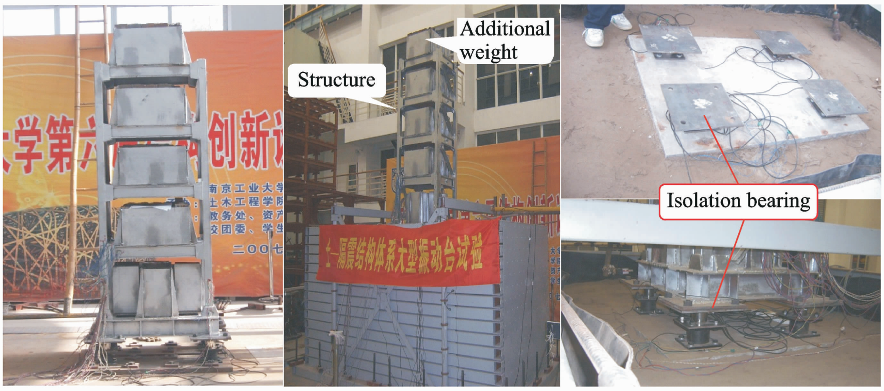
Four lead rubber bearings are used in the isolation layer of the structure. According to the stress similitude ratio of the isolator and the upper weight on them, the model isolators are designed with a diameter of transection of 100 mm, and the average compressive stress is 1.3 N/mm^2. Their shapes and salient quantities are shown in reference by Zhuang[8]. To determine the mechanical properties of the model isolators, dynamic loading tests are carried out for six lead rubber bearings. Next, four model isolators with similar mechanical properties are selected and used in the test. The equivalent horizontal stiffness of model rubber bearing is determined as 0.21 kN/mm when the horizontal shear strain γ is close to 50%, and the total horizontal stiffness of the isolators K_0 is approximately 0.84 kN/mm, for which the equivalent damping factor C_0 is approximately 10.93 kN·s/m.

The pile foundation is designed as the reinforced foundation of an isolated structure in the model. The pile bearing is designed as a rigid block of dimensions 1.2 m (vibration direction) × 1.0 m (vertical to the vibration direction) × 0.1 m (thickness). The pile foundations contain six piles, each with a cross-section of 0.035 m × 0.035 m. Micro-concrete and zinc-coated steel wires are used to build the pile foundation, and the dimensions of the model and the distribution of reinforced rebar are shown in reference by Zhuang[8]. Accordingly, the equivalent radius of the footing is approximately 0.618 m. The total bending stiffness of the pile cross-section (E_pI_p) is approximately 6.0 kN·m^2. The equivalent diameter of the pile cross-section d is approximately 3.95 cm, and the mass of simple pile m_p is approximately 2.45 kg.

To reflect the influence of the SSI effect on the dynamic characteristics and seismic response of the isolated structures, fine sand is used to build the model soil foundation; the Poisson's ratio υ is approximately 0.41, the hysteretic damping ξ_s is approximately 2%—5%, and the static and dynamic properties are tested before and after the shake test. The static physical quantities of the soil are shown in Table 2. According to another model test performed by author, the shear velocity of the model soil foundation is approximately 35 m/s. Finally, Fig. 4 displays selected photos from the test.

Table 2 Physical quantities of the soil used for model soil foundation

Test sample No.	Type of soil		Density/ (kg · m^{-3})	Shear modulus/ MPa	Specific gravity	Saturation/ %	Void ratio
1	Fine sand	Before test	1.826	7.01	2.68	76.5	0.742
2	Fine sand	After test	1.875	7.65	2.68	76.2	0.716



(a) Fixed on rigid foundation (b) Fixed on soil foundation (c) Lead rubber isolator

Fig. 4 Photos of tests for an isolated structure on different foundations

4 Simplified Method Verification Using Shake Table Tests

4.1 Dynamic properties of the structure

According to the equations given in Section 1, the main parameters of SSI system used to determine the dynamic characteristics of the model structure are calculated and given in Table 3. Similarly, the dynamic characteristics of different model test systems are compared in Table 4.

From Table 4, for the non-isolated structure on rigid or soil foundations, the dynamic properties calculated using the simplified method are all quite similar to those from the model tests. However, for the base-isolated structure on any one foundation, the dynamic properties determined by the simplified method are all rather different from those in the model tests. It is possible that this type of difference could be caused by the wrong dynamic parameters in the isolation layer. To

Table 3 Parameters used to calculate $\tilde{T}$ and $\tilde{\xi}$ of model isolated structure

SSI system		Parameters	Values
Structure		Horizontal stiffness $K/(\mathrm{kN\cdot mm^{-1}})$	7.01
		Damping factor $C/(\mathrm{kN\cdot s\cdot m^{-1}})$	10.52
Isolators		Horizontal stiffness $K_0/(\mathrm{kN\cdot mm^{-1}})$	0.84(1.30)
		Damping factor $C_0/(\mathrm{kN\cdot s\cdot m^{-1}})$	10.93
Foundation	Footing	Horizontal stiffness $K_x^F/(\mathrm{kN\cdot mm^{-1}})$	11.19
		Rotational stiffness $K_\theta^F/(\mathrm{kN\cdot m})$	3 840
		Horizontal damping factor $C_x/(\mathrm{kN\cdot s\cdot m^{-1}})$	120.56
		Rotational damping factor $C_\theta/(\mathrm{kN\cdot s\cdot m^{-1}})$	0.027
	Piles	Horizontal stiffness $K_x^p/(\mathrm{kN\cdot mm^{-1}})$	1.61
		Rotational stiffness $K_\theta^P/(\mathrm{kN\cdot m})$	7.39

Table 4 Dynamic properties of the structure in different conditions

	Type of foundation							
	Rigid foundation				Soil foundation			
	Frequency/Hz		Damping ratio/%		Frequency/Hz		Damping ratio/%	
	Test Ⅰ	Test Ⅱ	Test Ⅰ	Test Ⅱ	Test Ⅲ	Test Ⅳ	Test Ⅲ	Test Ⅳ
Model test(STWN1)	6.72	2.65	3.00	8.30	4.36	2.38	9.7	15.4
Simplified method	6.66	2.31 (2.64)	3.09	9.43 (8.24)	4.32	2.14 (2.39)	8.8	9.91 (9.06)
Relative difference/%	0.9	12.8 (0.3)	3.0	13.6 (0.7)	0.92	10 (0.4)	9.27	35.6 (41.16)

prove this doubt, the horizontal stiffness of the isolation layer should be about 1.3 kN/mm by the theory method. Accordingly, by the corrected stiffness, the dynamic properties of the isolated structure predicted by the developed simplified method are given in Table 4 in braces and are quite similar to those from the model tests except for the damping of the base-isolated structure on a soil foundation. For the base-isolated structure on soil foundation, the damping in the model test may be incorrectly caused by an out-of-order accelerometer or the effect of surrounding noise, which should be studied or verified in future work.

These results prove that the simplified method for the dynamic characteristics of a base-isolated structure on a soil foundation offers a verified and effective method that could be used in the seismic design of a base-isolated structure with the SSI effect.

4.2 Seismic responses of the isolated structure

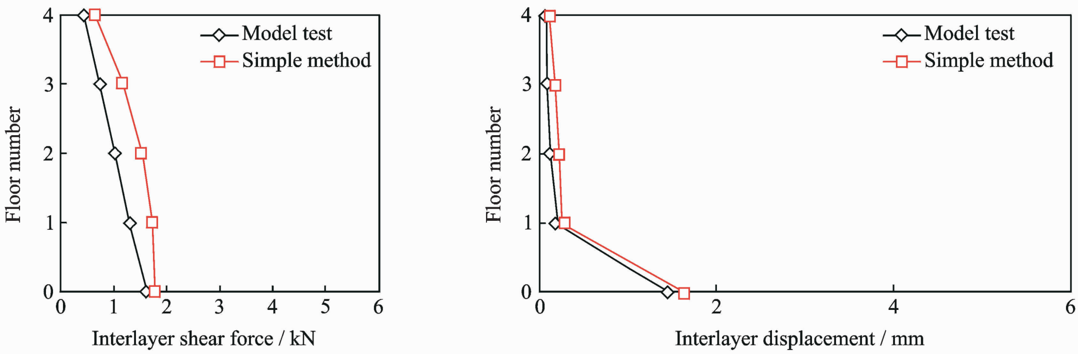
To verify the efficiency of the simple method for the seismic responses of a base-isolated structure with the SSI effect, the interlayer shear forces and deformations of the isolated structure are compared with those in the model tests. In the model tests, when the Kobe wave is inputted from bedrock with PGA = 0.1, 0.2 and 0.3g, the PGAs of the acceleration response at the bottom of the isolation layer are approximately 0.076, 0.136, and 0.19g, respectively. According to the dynamic parameters of the isolated structure determined by the simple method in Section 1 of this paper, the seismic influence coefficient α_1 is found to be 0.061, 0.105 and 0.153, as shown in Fig. 5.1.5 of the earthquake resistant design code of China. Using the simple method described in Section 2 of this paper, the interlayer shear forces and deformations are estimated and compared with the test results and are shown in Fig. 5.

From Fig. 5, when the input PGA from the bedrock increases, the interlayer shear forces from the simple method are similar to those in the model tests except for that of the first floor, where the input PGA is 0.3g. If the input PGA values are 0.1g and 0.2g, the interlayer shear forces and deformations are all larger than those in the model tests, especially for floors near to the middle height of the base-isolated structure. If the input PGA increases to 0.3g, the interlayer shear forces of the isolated structure are all similar to those in the model tests except for the isolation layer.

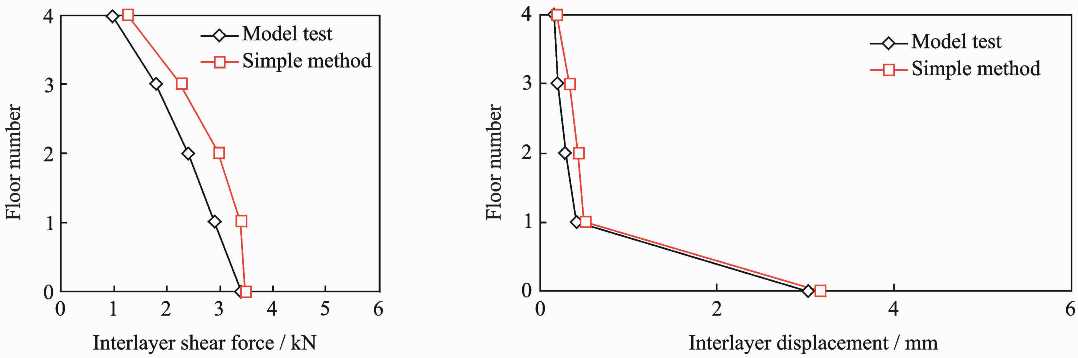
Additionally, with the increase in the input PGA, the interlayer displacement of the isolation layer from the simple method shifts from larger to smaller than that of the model test. The main reason for this result is that the initial horizontal stiffness is used for the full duration of the earthquake in the simple method, which should be weakened in the large shear deformation state of the rubber lead bearing, as shown in Table 3. In the model test, the maximal shear strain is approximately 15% if the input PGA is 0.3g. As a result, the horizontal stiffness of the isolation layer corrected by the interpolation method should be 0.92 kN/mm with an input PGA of

0. 3g, and thus, the corrected interlayer displacement should be 5. 78 mm, which is closer to 5. 98 mm in the model test than the 5. 31 mm value without the horizontal stiffness corrected by the shear strain.

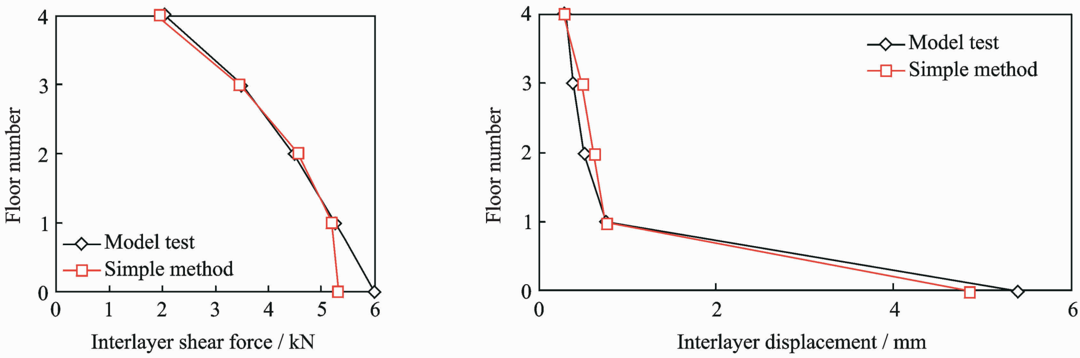
Generally, compared with the results in the model tests, the interlayer shear forces or displacements calculated by the developed simple method are safe for the base-isolated structure on a pile foundation.



(a) Kobe wave inputted from bedrock with PGA=0.1g



(b) Kobe wave inputted from bedrock with PGA=0.2g



(c) Kobe wave inputted from bedrock with PGA=0.3g

Fig. 5 Interlayer shear forces and displacements of the isolated structure on soil foundation

5 Parametric Analysis

To investigate the effects of the soil foundation on the dynamic characteristics of the soil-structure system, comparative graphs for the variation of the ratio $\widetilde{T}/T$ and the effective damping of the SSI system $\tilde{\xi}$ are presented in Figs. 6—9 for the different parameters of soil foundation considered. In Fig. 6, the wave parameter ($1/\sigma$) is

$$\frac{1}{\sigma}=\frac{h\sqrt{K/M}}{2\pi v_s} \tag{31}$$

In Fig. 6, the wave parameter ($1/\sigma$) has a great effect on the dynamic characteristics of the

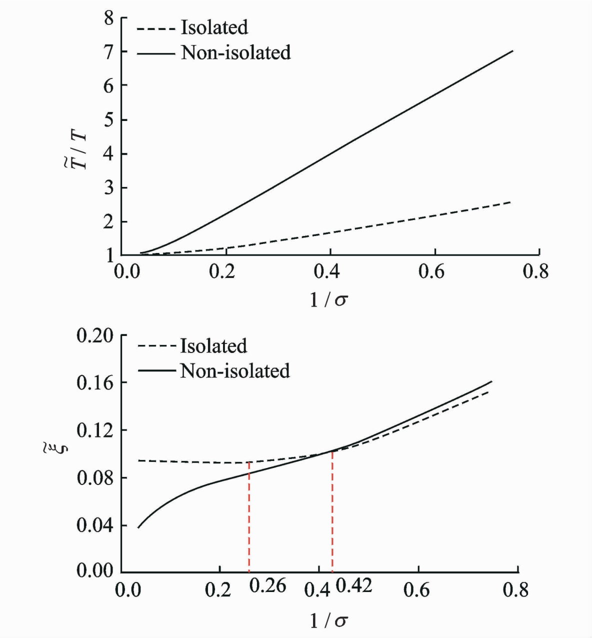


Fig. 6 Natural period and damping of the SSI system as a function of wave parameter ($1/\sigma$): $\omega=2\pi$, $\upsilon=0.41$, $\xi_s=0.05$, $K_x^F/K_x^P=1.33$

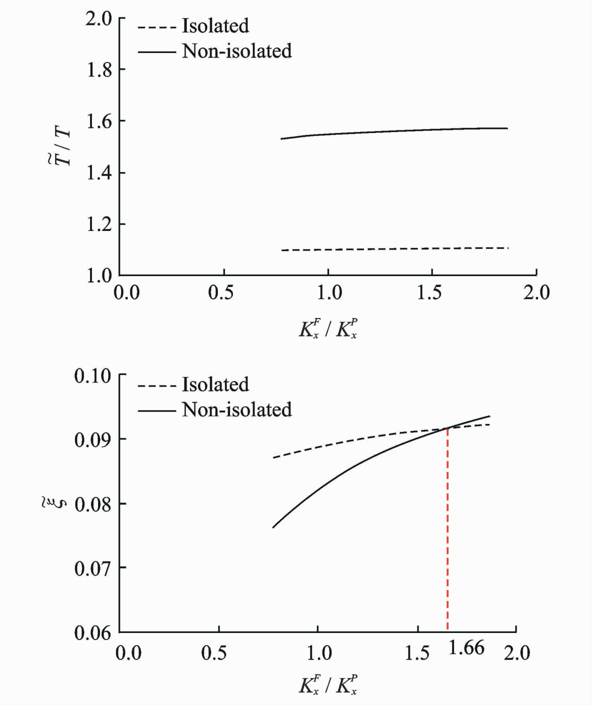


Fig. 7 Natural period and damping of the SSI system as a function of the stiffness ratio of the soil foundation to the piles (K_x^F/K_x^P): $\omega=2\pi$, $\upsilon=0.41$, $\xi_s=0.05$, $1/\sigma=0.214$

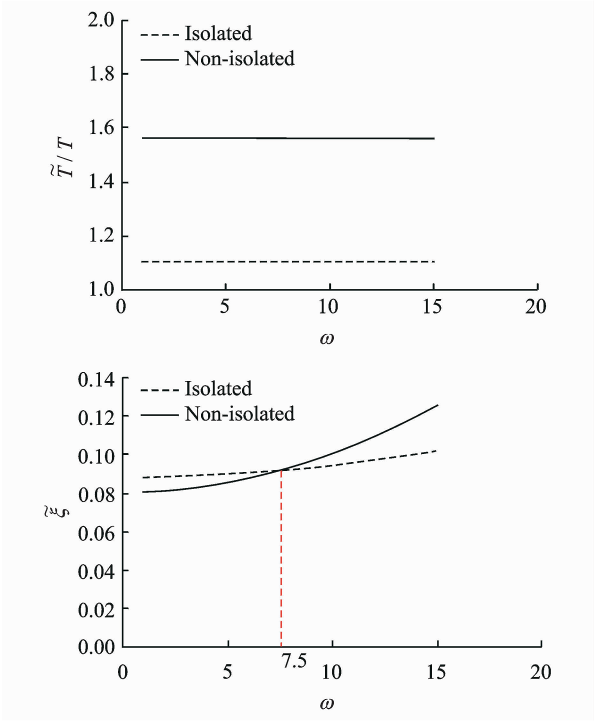


Fig. 8 Natural period and damping of an SSI system as a function of the circular excitation frequency (ω): $\upsilon=0.41$, $\xi_s=0.05$, $K_x^F/K_x^P=1.33$, $1/\sigma=0.214$

soil-structure system, especially on those of the non-isolated structure. Generally, for the non-isolated structure, the damping of the structure increases rapidly when the wave parameter is quite small, the rate of increase subsequently slows down with the increasing in the wave parameter, and increases faster once again after a certain wave parameter is exceeded. However, for the base-isolated structure, if the wave parameter is less than a certain value (approximately 0.26 in this paper), the damping of the base-isolated structure decreases to a tiny value and subsequently increases more rapidly with the increase in the wave parameter.

Generally, for the base-isolated structure, the damping is larger than that of the non-isolated structure but becomes smaller when the wave parameter ($1/\sigma$) is more than a certain value (approximately 0.42), which also means that the isolation layer should decrease the damping of the SSI system if the soil foundation is sufficiently softened (the wave parameter is large enough). How to decide on the critical value of the wave parameter for the intersection in Fig. 6 is a question that should be studied in further detail.

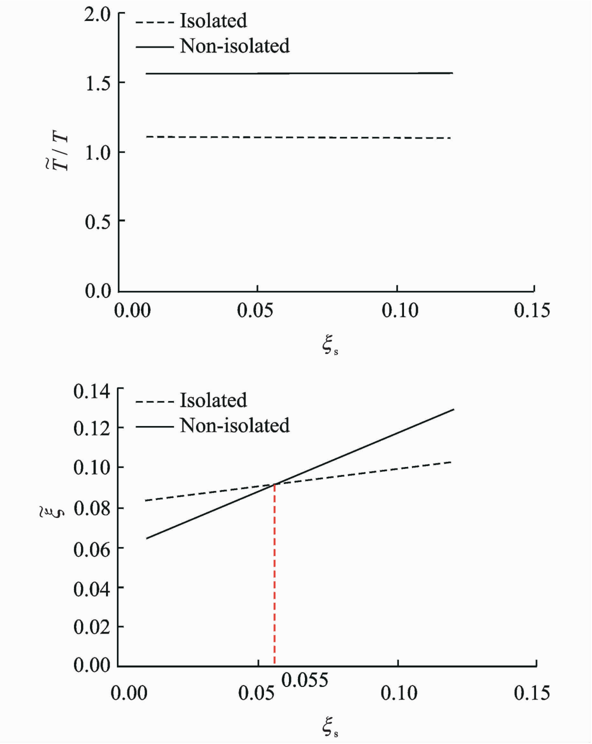


Fig. 9 Natural period and damping of an SSI system as a function of the soil hysteretic damping (ξ_s): $\omega=2\pi$, $\upsilon=0.41$, $K_x^F/K_x^P=1.33$, $1/=0.214$

In Figs. 7—9, the stiffness ratio of the soil foundation to the piles (K_x^F/K_x^P), the circular excitation frequency (ω), and the soil hysteretic damping (ξ_s) have rather small effects on the natural period ratio ($\widetilde{T}/T$); however, these parameters have an obvious effect on the damping ($\tilde{\xi}$) of the SSI system.

Furthermore, according to Figs. 6—9, the following findings approximate the effect of the soil foundation on the dynamic characteristics of structure: (1) For a certain model structure in this paper, the SSI effect has more influence on the dynamic characteristics of the non-isolated structure than those of the base-isolated structure; (2) For a soft soil foundation, the dynamic characteristics of the non-isolated structure are quite similar to those of the base-isolated structure, which also means that the isolation layer gradually loses its isolation function with the softening of the soil foundation; (3) For the damping only, the existing piles should obviously decrease the damping of the SSI system, especially for the non-isolated structure; (4) Generally, these parameters have more of an effect on the damping of the non-isolated structure than that on the base-isolated structure; (5) The natural isolation efficiency of the soft soil foundation should not be neglected in the seismic design of buildings and can be treated simply as the foundation isolation layer.

6 Conclusions

A simple oscillator supported on buried footings with piles is used to model the base-isolated structure, and a simplified method for determining the dynamic characteristics of the base-isolated structure is advanced and verified in a series of shake table tests. For the model isolated structure, the main conclusions are described as follows:

(1) The simplified method proposed in this paper can effectively estimate the dynamic characteristics of the base-isolated structure with buried footings on a pile foundation. The simplified method is mainly suitable for seismic response analysis of base-isolated structure with small aspect ratio with the SSI effect.

(2) When using parameter analysis, for the model base-isolated structure, the physical properties of the soil foundation have less effect on its dynamic characteristics than on those of the non-isolated structure.

(3) For the damping only, with the increase in the parameter of soil foundation selected in this paper, the damping of the base-isolated structure is larger than that of the non-isolated structure at first but subsequently becomes smaller than that of the non-isolated structure after a certain value of the parameter is exceeded. The question of how to determine these certain values of the parameters and the relationships between them should be studied in depth in future work.

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