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Dynamic structure-soil-structure interaction of piled high-rise buildings under earthquake excitations II: Influence of key parameter

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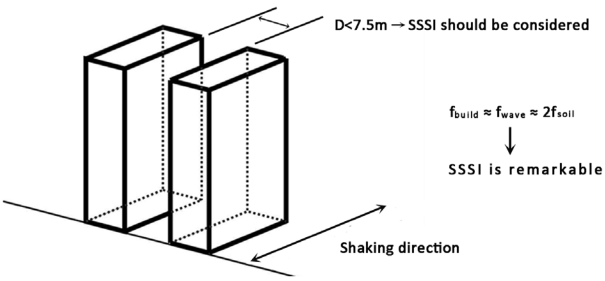
Abstract

A numerical study is performed on the structure-soil-structure interaction (SSSI) between high-rise buildings. ANSYS has been further developed for calculation in the frequency domain, in which hysteretic damping can be considered for both soil and structures. This study is presented in two subsequent papers. The first part[1] focuses on the influence of the SSSI on each kind of dynamic response, while the second part, i.e., this paper, is a parameter study that focuses on the influence of each key parameter, including the separation distance between structures; the damping ratio, thickness and shear wave velocity of the soil; the length of the pile; the damping ratio, style, material stiffness, mass and story number of the superstructure; and the position and number of the structure, on the SSSI. The interaction decreases with the increase in the separation distance between structures, the increase in the damping ratio and shear wave velocity of the soil, the increase in the damping ratio and mass of the superstructure, or the decrease in the material stiffness of the superstructure in a fluctuating manner.

Keywords

structure-soil-structure interaction; seismic interaction; adjacent structure; clustering structure; building cluster.

Graphical Abstract



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1 Introduction

An increasing human population and the existence of limited available habitable urban space have resulted in densely located buildings in most busy places. The concentration of high-rise buildings in metropolises located in high seismic activity regions has made the occurrence of a special seismic phenomenon possible, that is, the structure-soil-structure interaction (SSSI) of adjacent structures.

This paper is the following part of Ref.[1]. Combined with the first part[1], the SSSI of piled high-rise buildings is analyzed by a series of three-dimensional detailed finite element models. The first part[1] of this study focuses on the influence of the SSSI on each kind of dynamic response of the structure. The second part of this study, i.e., this paper, is a parameter study and focuses on the influence of each key parameter, including the separation distance between structures; the damping ratio, thickness and shear wave velocity of the soil; the length of the pile; the damping ratio, style, material stiffness, mass and story number of the superstructure; and the position and number of the structure, of a dynamic system on the SSSI effect.

The relevant background and study status are stated in detail in the first part[1] of this study and omitted here for brevity. In the next section, the problem is first stated, and the parameters and properties are defined. Then, to evaluate the influence of the key parameters, the variations in the story shear force are taken into account, and the assessment of the calculated effects is compared with the case of standalone structures.

2 Problem definition

The first part[1] of this study concludes that, compared to the other configurations (CON.1, CON.2, and CON.3), the influence of the SSSI on the dynamic response (story shear force, interstory drift angle, foundation sway, displacement, velocity and acceleration) of the superstructure is greatest when the shaking direction of the exciting wave is perpendicular to the direction of the structure arrangement and the direction of the structure arrangement is parallel to the lateral axis of the structure (CON.4). Thus, this configuration, as shown in Fig.1, is selected to further study the influence of key parameters on the SSSI effect. In addition, as a widely used engineering demand parameter for the design and assessment of buildings, the story shear force at each story is chosen for the assessment of the SSSI effect.

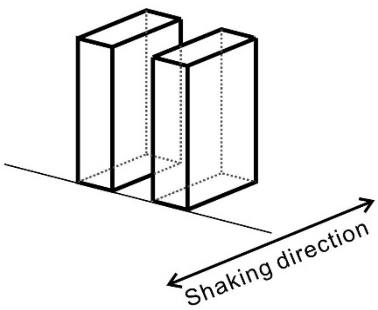

Fig.1 Relative arrangement of the structures and shaking direction of the exciting wave.

The key parameters of the soil-structure system are shown in Tab.1. Here, $1.0E$ indicates that the material stiffness of the superstructure is the same as that in the first part[1] of this study, while $0.8E$ and $1.2E$ indicate that the material stiffness of the superstructure decreases or increases by 20%, respectively. Similarly, $1.0M$ indicates that the mass of the superstructure is the same as that in the first part[1] of this study, while $0.8M$ and $1.2M$ indicate that the mass of the superstructure decreases or increases by 20%, respectively. The frame-shear wall structure, as shown in Fig.2, comes from the frame structure aforementioned in the first part[1] of this study with the addition of four

L-shaped shear walls on each story. The other parameters and properties of the dynamic system, dynamic inputs, calculation method and model are the same as in the first part[1] of this study and omitted here for brevity.

Tab.1 Key parameters

Parameter	Symbol	Value
Separation distance between buildings	d	0.01 / 0.1 / 0.5 / 1.0 / 3.0 / 6.0
Damping ratio of the soil	ζ_S	0.05 / 0.10 / 0.15 / 0.20
Thickness of the soil	H	$40m$ / $60m$ / $80m$
Shear wave velocity of the soil	c_s	$200m/s$ / $300m/s$ / $400m/s$ / $500m/s$
Pile length	L_{pile}	$12m$ / $18m$ / $24m$
Damping ratio of the superstructure	ζ_B	0.02 / 0.05 / 0.08
Style of the superstructure	-	$Frame$ / $Frame-shear\ wall$
Material stiffness of the superstructure	E	$0.8E$ / $1.0E$ / $1.2E$
Mass of the superstructure	M	$0.8M$ / $1.0M$ / $1.2M$
Story number of the superstructure	N_S	6 / 10 / 14 / 18
Number of the buildings	N	2 / 3 / 6 / 7

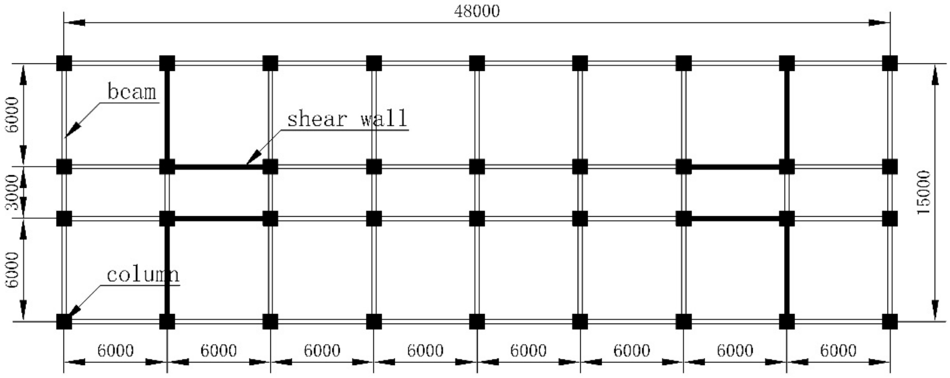

Fig.2 Typical plan of the frame-shear wall structure (unit: mm).

3 Numerical results and analysis

The influence of each key parameter of the dynamic system on the SSSI effect is addressed in this section. To explicitly show the SSSI effect, as in the first part[1] of this study, the influence of the SSSI is illustrated by the influence coefficient e, defined as $\left(r^{SSSI}-r^{SSI}\right)/r^{SSI}$, where r^{SSI} is the dynamic response, which is the steady-state story shear force amplitude under a harmonic wave or the seismic story shear force amplitude under a seismic wave, of a high-rise building in the single-structure-soil system, and r^{SSSI} is that of a high-rise building in the multistructure-soil system.

3.1 Influence of the separation distance between buildings

The influence of the separation distance between structures on the interaction is investigated in Fig.3 and Fig.4, which show the influence coefficients of the story shear force at each story with different separation distances under seismic waves and harmonic waves, respectively. Unless otherwise stated, the figure legends of the latter figures, which also show the influence coefficients of the dynamic response under seismic waves and harmonic waves, are the same as in Fig.3 and Fig.4 and omitted for brevity. Here, the separation distance (D) is from $0.15m$, which is almost the closest distance for buildings where a lesser distance would result in the impossibility of construction, to $90m$, where a distance farther than that would lead to a negligible interaction between the buildings verified in the following, i.e., the dimensionless separation distance $d = D / B = 0.01 \sim 6.0$, where B is the width of the structure along the lateral axis. The other key parameters are the same as those in the first part[1] of this study and are given as follows: the damping ratio of the soil is $\zeta_S = 0.05$, the thickness of the soil is $H = 60m$, the shear wave velocity of the soil is $c_s = 300m / s$, the pile length is $L_{pile} = 18m$, the damping ratio of the superstructure is $\zeta_B = 0.05$, the style of the superstructure is a $Frame$, the material stiffness of the superstructure is $1.0E$, the mass of the superstructure is $1.0M$, the story number of the superstructure is $N_S = 10$, and the number of buildings is $N = 2$.

When the separation distance (D) is as small as $0.15m$, i.e., $d = 0.01$, the interaction between structures reaches its maximum, and the influence coefficients can reach 15% under seismic waves, while they can reach 22% under harmonic waves. When the separation distance (D) is as large as $90m$, i.e., $d = 6.0$, the influence coefficients are all within $\pm 5\%$ under seismic waves, while they are all within $\pm 10\%$ under harmonic waves.

For all seismic waves and for harmonic waves with different frequencies, the interaction between structures decreases with the increase in the separation distance in a fluctuating but not monotonous manner. With the increase in the separation distance, the energy of the scattered wave from the vibrating structure decreases, and the interaction between structures fades away.

Under harmonic waves, with the increase in the separation distance, the influence coefficients corresponding to high-frequency excitation approach zero quickly, and the interaction focuses on the frequencies around the natural frequencies of the superstructure. In general, the velocity of the reduction in the interaction with the increase in the separation distance corresponding to low-frequency excitation is slower than that corresponding to high-frequency excitation. This can be explained by wave motion theories. When a wave propagates in an elastomer, the displacement (U) can be described as follows:

$$U = \frac{1}{2\pi} e^{-\omega \frac{\zeta}{c} x} e^{-i\omega \frac{x}{c}} \tag{1}$$

where ω is the wave frequency; ζ is the damping ratio; c is the wave velocity; and x is the propagation distance. In the SSSI systems of this paper, $\omega > 0$, $\zeta > 0$, $c > 0$, $x > 0$ and $\omega \zeta x / c < 1$; thus,

$$\frac{\partial |U|}{\partial x} = -\frac{1}{2\pi} \omega \frac{\zeta}{c} e^{-\omega \frac{\zeta}{c} x} < 0 \tag{2}$$

$$\frac{\partial |U|}{\partial \zeta} = -\frac{1}{2\pi} \omega \frac{x}{c} e^{-\omega \frac{\zeta}{c} x} < 0 \tag{3}$$

$$\frac{\partial^2 |U|}{\partial x \partial \omega} = -\frac{1}{2\pi} \frac{\zeta}{c} e^{-\omega \frac{\zeta}{c} x} \left(1 - \omega \frac{\zeta}{c} x \right) < 0 \tag{4}$$

$$\frac{\partial^2 |U|}{\partial \zeta \partial \omega} = -\frac{1}{2\pi} \frac{x}{c} e^{-\omega \frac{\zeta}{c} x} \left(1 - \omega \frac{\zeta}{c} x \right) < 0 \tag{5}$$

$$\frac{\partial^2 |U|}{\partial \zeta \partial x} = -\frac{1}{2\pi}\frac{\omega}{c} e^{-\omega\frac{\zeta}{c}x}\left(1-\omega\frac{\zeta}{c}x\right) < 0 \tag{6}$$

Obviously, the larger the wave frequency (ω) is, the lager the velocity of the reduction in the displacement with the increase in the propagation distance (x). As the velocity of the reduction in the interaction with the increase in the separation distance varies with the excitation frequency under harmonic waves, it naturally varies for different seismic waves.

In general, under seismic waves, when the separation distance between structures (D) is not larger than $0.5B$, the SSSI effect should be considered. This separation distance is slightly larger than Gan's work[2]. This is mainly due to the frequency components of the seismic wave, which is one of the main influencing factors in the SSSI problem.

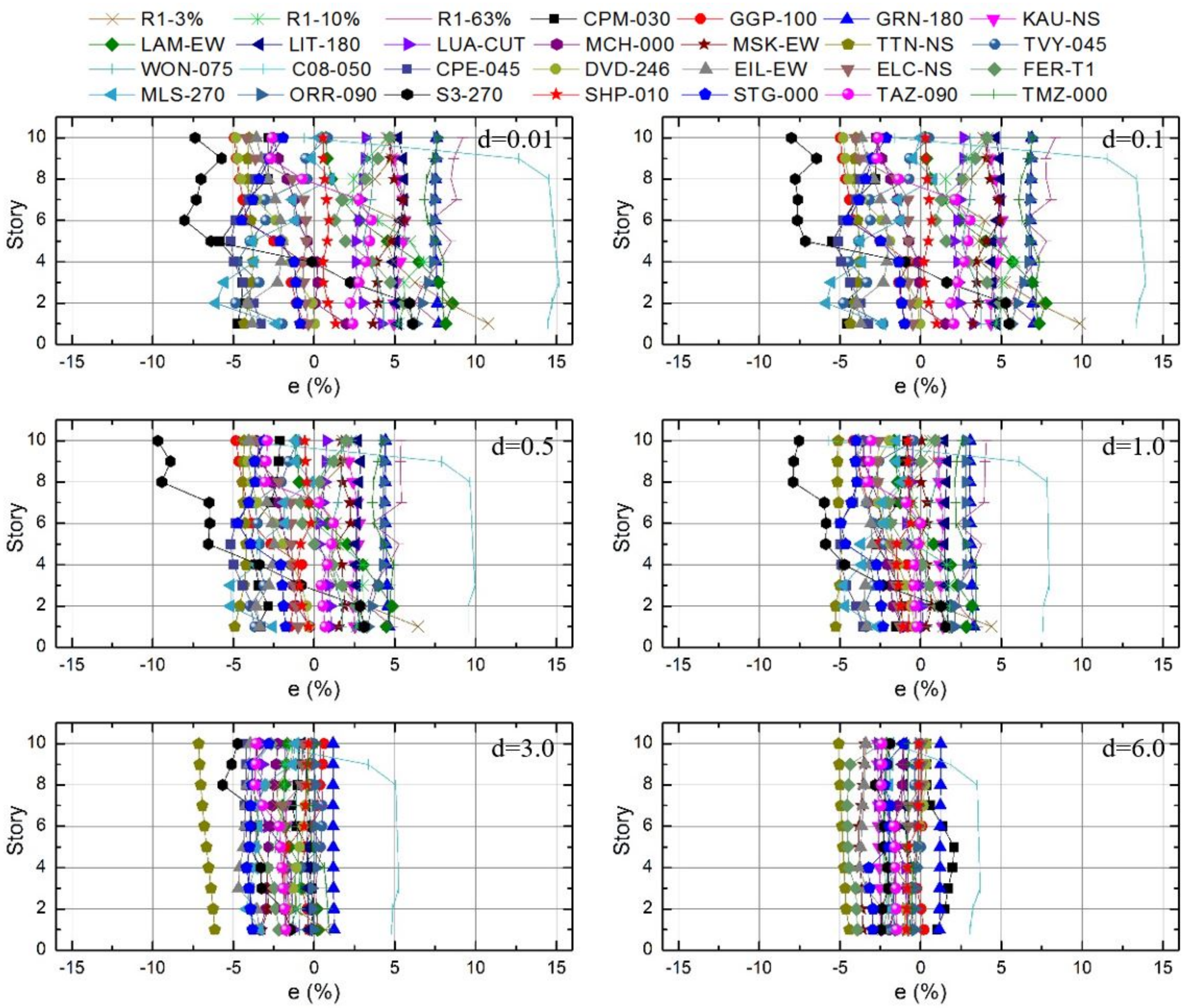

Fig.3 Influence coefficients of the story shear force at each story with different separation distances under seismic waves.

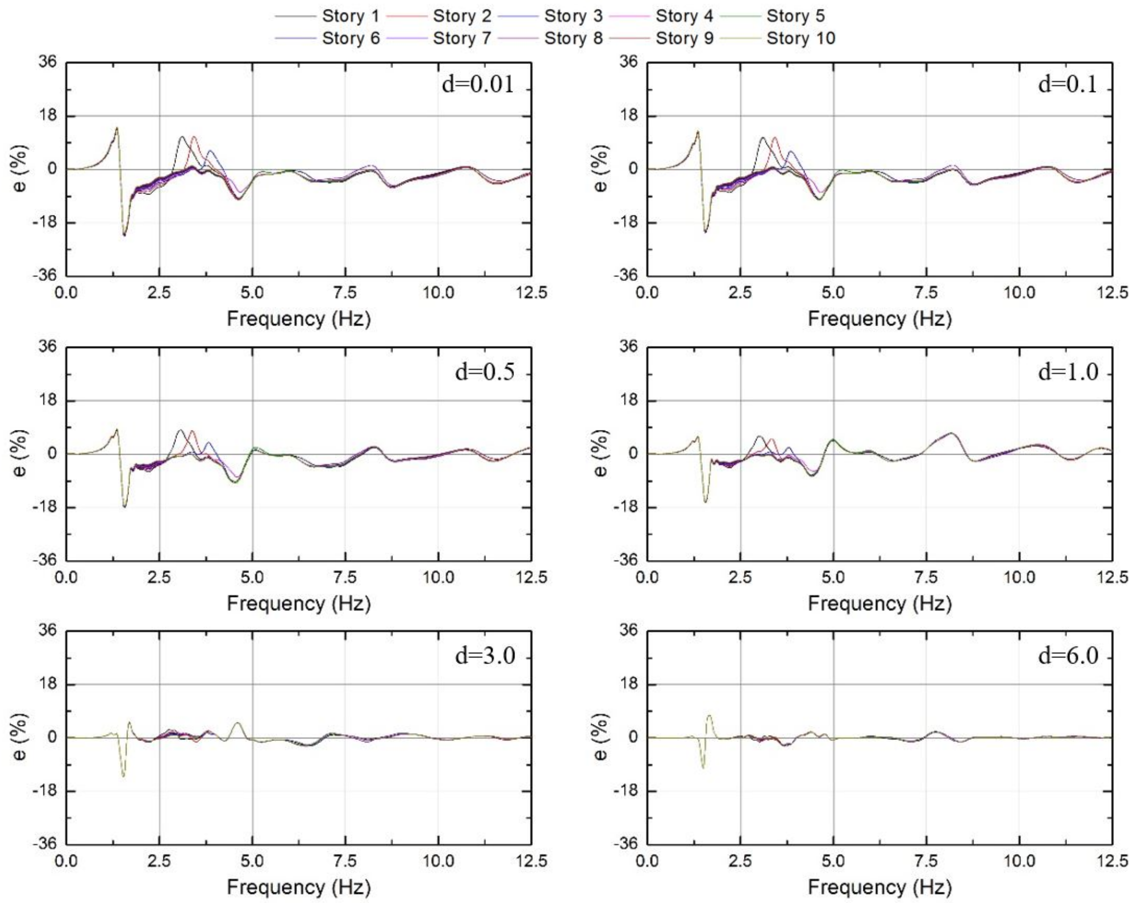

Fig.4 Influence coefficients of the story shear force at each story with different separation distances under harmonic waves.

3.2 Influence of the damping ratio of the soil

The influence of the damping ratio of the soil on the interaction is investigated in Fig.5 and Fig.6, which show the influence coefficients of the story shear force at each story with different soil damping ratios under seismic waves and harmonic waves, respectively. Here, the damping ratios of the soil are $\zeta_S = 0.05/0.10/0.15/0.20$, the dimensionless separation distance is $d = 1.0$ and the other key parameters are the same as those in the first part[1] of this study and are given as follows: the thickness of the soil is $H = 60m$, the shear wave velocity of the soil is $c_s = 300m/s$, the pile length is $L_{pile} = 18m$, the damping ratio of the superstructure is $\zeta_B = 0.05$, the style of the superstructure is a $Frame$, the material stiffness of the superstructure is $1.0E$, the mass of the superstructure is $1.0M$, the story number of the superstructure is $N_S = 10$, and the number of buildings is $N = 2$.

The influence of the soil damping ratio on the interaction is the same as that of the separation distance between structures. For all seismic waves and for harmonic waves with different frequencies, the interaction between structures decreases with the increase in the soil damping ratio in a fluctuating but not monotonous manner. With the increase in the soil damping ratio, the energy of the scattered wave from the vibrating structure decreases, and the interaction between structures fades away.

As the separation distance between structures, under harmonic waves, with the increase in the soil damping ratio, the influence coefficients corresponding to high-frequency excitation are quickly close to zero, and the interaction focuses on the frequencies around the natural frequencies of the superstructure. In general, the velocity of the reduction in the interaction with the increase in the soil damping ratio corresponding to low-frequency excitation is slower than that corresponding to high-frequency excitation. This can also be explained by wave motion theories (Eq.(1)~(6)). The larger the wave frequency (ω) is, the larger the velocity of the reduction in the displacement with the increase in the soil damping ratio ($\left|\partial\left|U\right|/\partial\zeta\right|$). As the velocity of the reduction in the interaction with the increase in the soil damping ratio varies with the excitation frequency, it naturally varies with different seismic waves.

Fig.7 shows the influence coefficient of the story shear force at each story with different soil damping ratios under harmonic waves, and here, the dimensionless separation distance is $d = 0.1$. Compared with Fig.6 ($d = 1.0$), the velocity of the reduction in the interaction with the increase in the soil damping ratio for $d = 0.1$ is slower than that for $d = 1.0$. This can also be explained by wave motion theories (Eq.(1)~(6)). The larger the propagation distance (x) is, the larger the velocity of the reduction in the displacement with the increase in the soil damping ratio ($\left|\partial\left|U\right|/\partial\zeta\right|$).

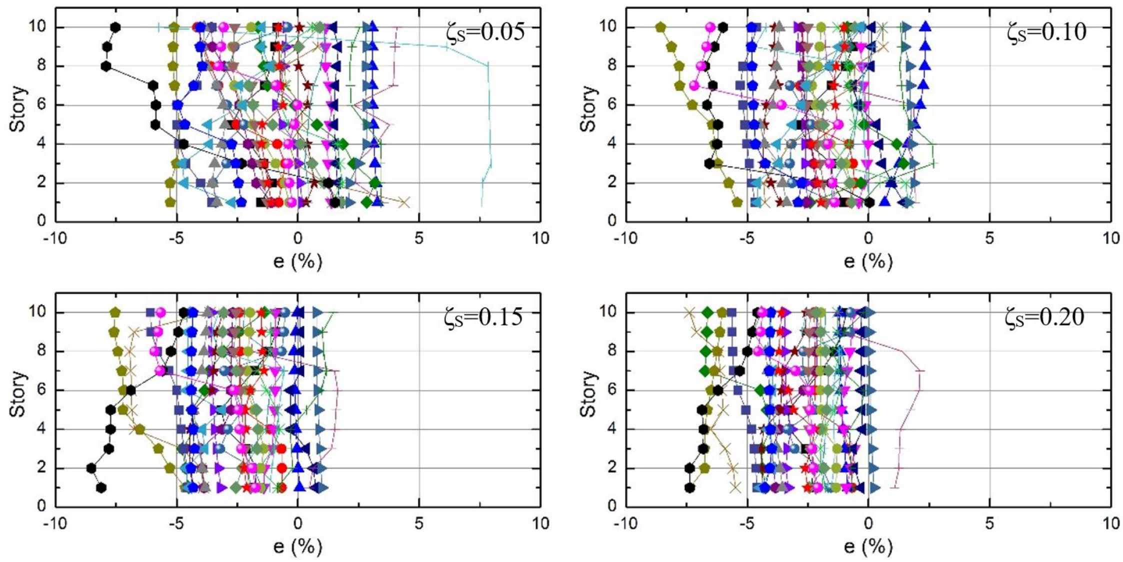

Fig.5 Influence coefficients of the story shear force at each story with different damping ratios of the soil under seismic waves ($d = 1.0$).

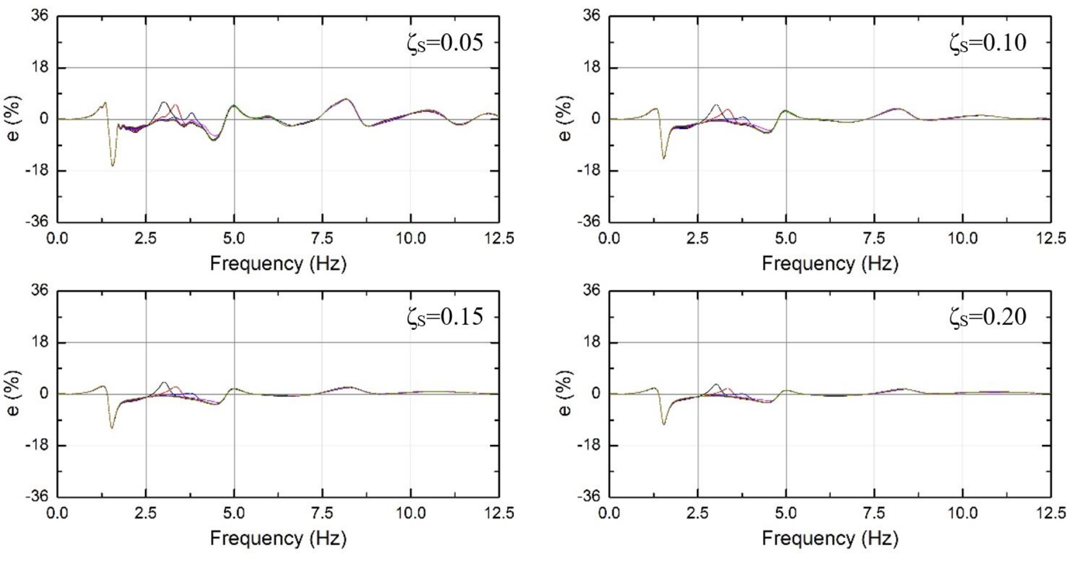

Fig.6 Influence coefficients of the story shear force at each story with different damping ratios of the soil under harmonic waves ($d = 1.0$).

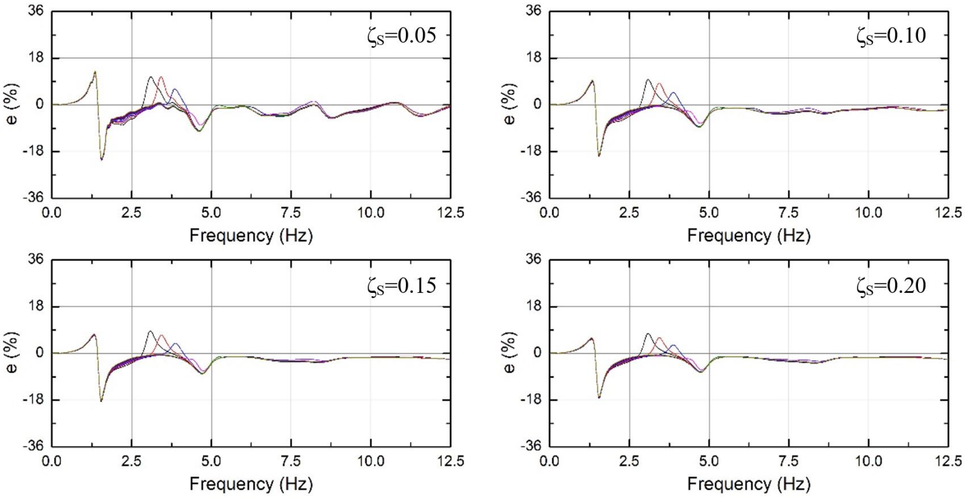

Fig.7 Influence coefficients of the story shear force at each story with different damping ratios of the soil under harmonic waves ($d = 0.1$).

3.3 Influence of the thickness of the soil

The influence of the thickness of the soil on the interaction is investigated in Fig.8 and Fig.9, which show the influence coefficients of the story shear force at each story with different soil thicknesses under seismic waves and harmonic waves, respectively. Here, the soil thicknesses are $H = 40/60/80m$ and the other key parameters are the same as those in the first part[1] of this study and are given as follows: the damping ratio of the soil is $\zeta_S = 0.05$, the shear wave velocity of the soil is $c_s = 300m/s$, the pile length is $L_{pile} = 18m$, the damping ratio of the superstructure is $\zeta_B = 0.05$, the style of the superstructure is a $Frame$, the material stiffness of the superstructure is $1.0E$, the mass of the superstructure is $1.0M$, the story number of the superstructure is $N_S = 10$, the number of buildings is $N = 2$, and the dimensionless separation distance is $d = 0.1$.

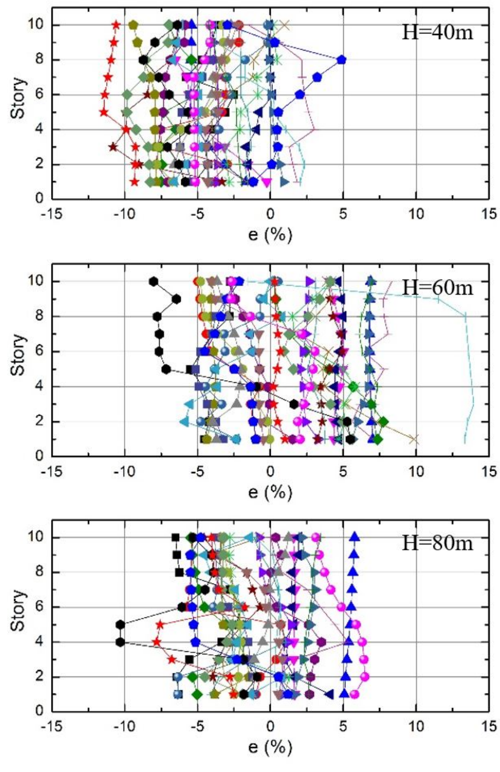

Fig.8 Influence coefficients of the story shear force at each story with different soil thicknesses under seismic waves.

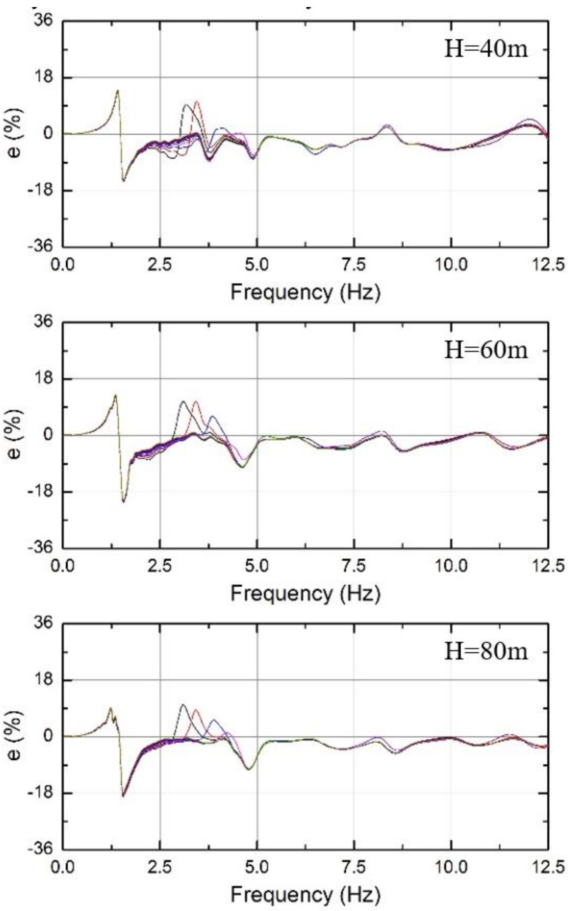

Fig.9 Influence coefficients of the story shear force at each story with different soil thicknesses under harmonic waves.

Under harmonic waves, the influence coefficient curves are almost the same for different soil thicknesses, and the peaks on the influence coefficient curves around the first-order natural frequency of the superstructure show a little difference. The maximum absolute value of the peaks is 15% for $H=40m$, 19% for $H=80m$ and 21% for $H=60m$. Under seismic waves, although the influence coefficient for a certain story varies with different soil thicknesses, the influence coefficients of all the stories under seismic waves are all within $\pm 15\%$. Thus, the influence of the thickness of the soil on the SSSI is limited.

3.4 Influence of the shear wave velocity of the soil

In wave motion theories, the larger the wave velocity (c) is, the larger the displacement ($|U|$ in Eq.(1)), namely, for the scattered wave from the structure, the velocity of the reduction in the displacement with the increase in the distance corresponding to a low wave velocity is faster than that corresponding to a high wave velocity. However, this does not mean a less intense interaction between structures for a low wave velocity or a more intense interaction between structures for a high wave velocity.

The influence of the shear wave velocity of the soil on the interaction is investigated in Fig.10 and Fig.11, which show the influence coefficients of the story shear force at each story with different shear wave velocities of the soil under seismic waves and harmonic waves, respectively. Here, the shear wave velocities of the soil are $c_s = 200/300/400/500m/s$, and the other key parameters are the same as those in the first part[1] of this study and are given as follows: the damping ratio of the soil is $\zeta_S = 0.05$, the thickness of the soil is $H = 60m$, the pile length is $L_{pile} = 18m$, the damping ratio of the superstructure is $\zeta_B = 0.05$, the style of the superstructure is a $Frame$, the material stiffness of the superstructure is $1.0E$, the mass of the superstructure is $1.0M$, the story number of the superstructure is $N_S = 10$, the number of buildings is $N = 2$, and the dimensionless separation distance is $d = 0.1$.

As the shear wave velocity of the soil increases from $200m/s$ to $500m/s$, under harmonic waves, the maximum absolute value of the peak of the influence coefficient curve around the first-order natural frequency of the superstructure decreases from 36% to 6%, while under seismic waves, the variation range of the influence coefficients decreases from $\pm 15\%$ to $\pm 5\%$.

For all seismic waves and for harmonic waves with different frequencies, the interaction between structures decreases with the increase in the shear wave velocity of the soil in a fluctuating but not monotonous manner. This is mainly because the higher the shear wave velocity of the soil is, the higher the rigidity of the soil, the less intense the interaction between the soil and structure, the less energy scattered from the shaking structure, and the less influence on the adjacent structure.

Although the thickness and shear wave velocity of the soil both have an influence on the total rigidity of the soil, which has an influence on the SSI, the influence of the thickness on the SSSI is limited and that of the shear wave velocity is prominent. This means that the local rigidity of the soil is more important for the SSSI.

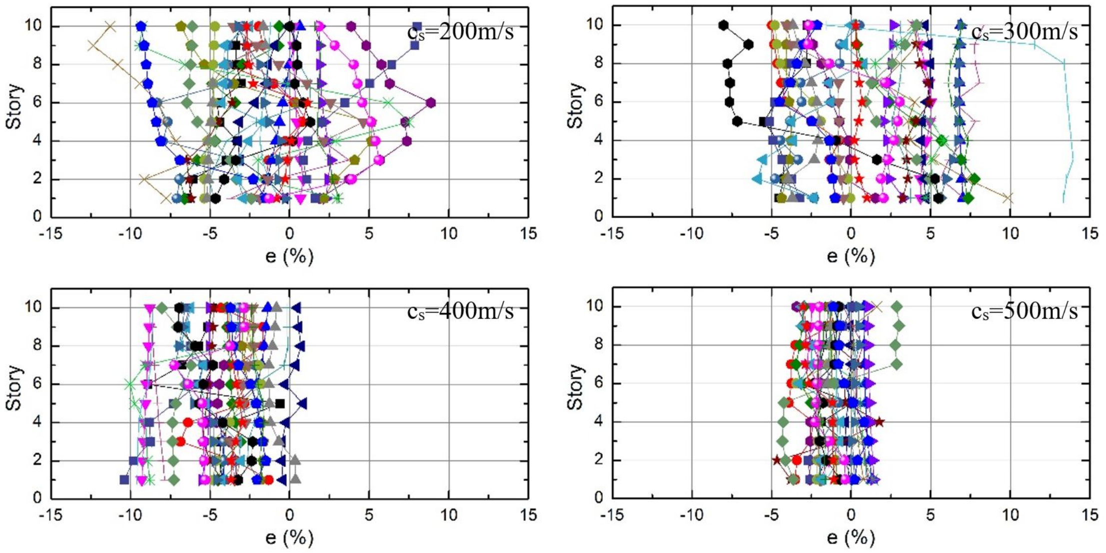

Fig.10 Influence coefficients of the story shear force at each story with different shear wave velocities of the soil under seismic waves.

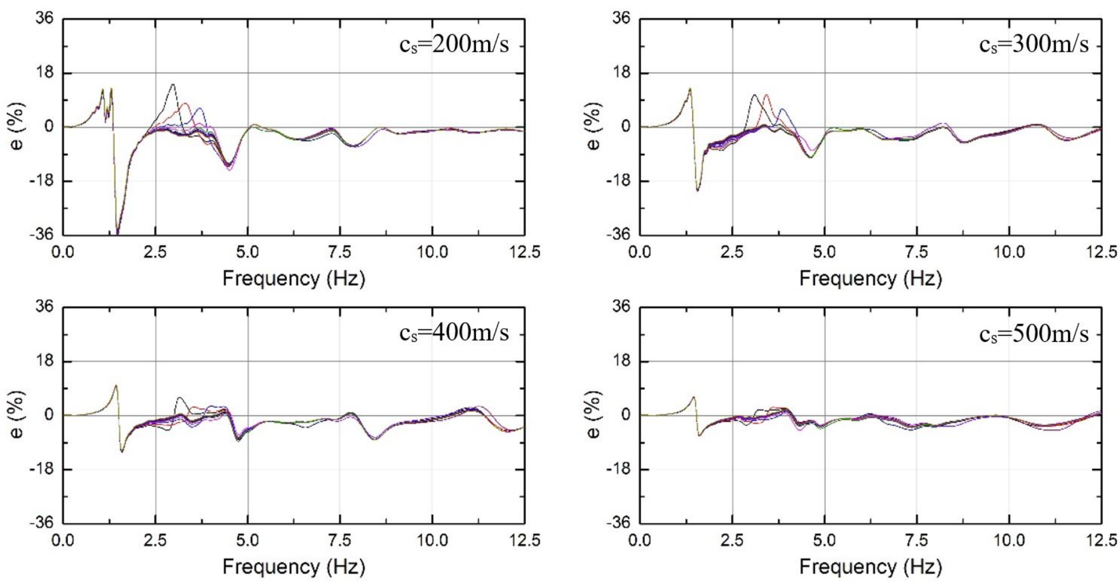

Fig.11 Influence coefficients of the story shear force at each story with different shear wave velocities of the soil under harmonic waves.

3.5 Influence of the pile length

The influence of the pile length on the interaction is investigated in Fig.12 and Fig.13, which show the influence coefficients of the story shear force at each story with different pile lengths under seismic waves and harmonic waves, respectively. Here, the pile lengths are $L_{pile} = 12/18/24m$ and the other key parameters are the same as those in the first part[1] of this study and are given as follows: the damping ratio of the soil is $\zeta_S = 0.05$, the thickness of the soil is $H = 60m$, the shear wave velocity of the soil is $c_s = 300m/s$, the damping ratio of the superstructure is $\zeta_B = 0.05$, style of the superstructure the a $Frame$, the material stiffness of the superstructure is $1.0E$, the mass of the superstructure is $1.0M$, the story number of the superstructure is $N_S = 10$, the number of buildings is $N = 2$, and the dimensionless separation distance is $d = 0.1$.

For all seismic waves and for harmonic waves with different frequencies, the influence coefficients with different pile lengths are almost the same, and the pile length has a negligible influence on the interaction between structures.

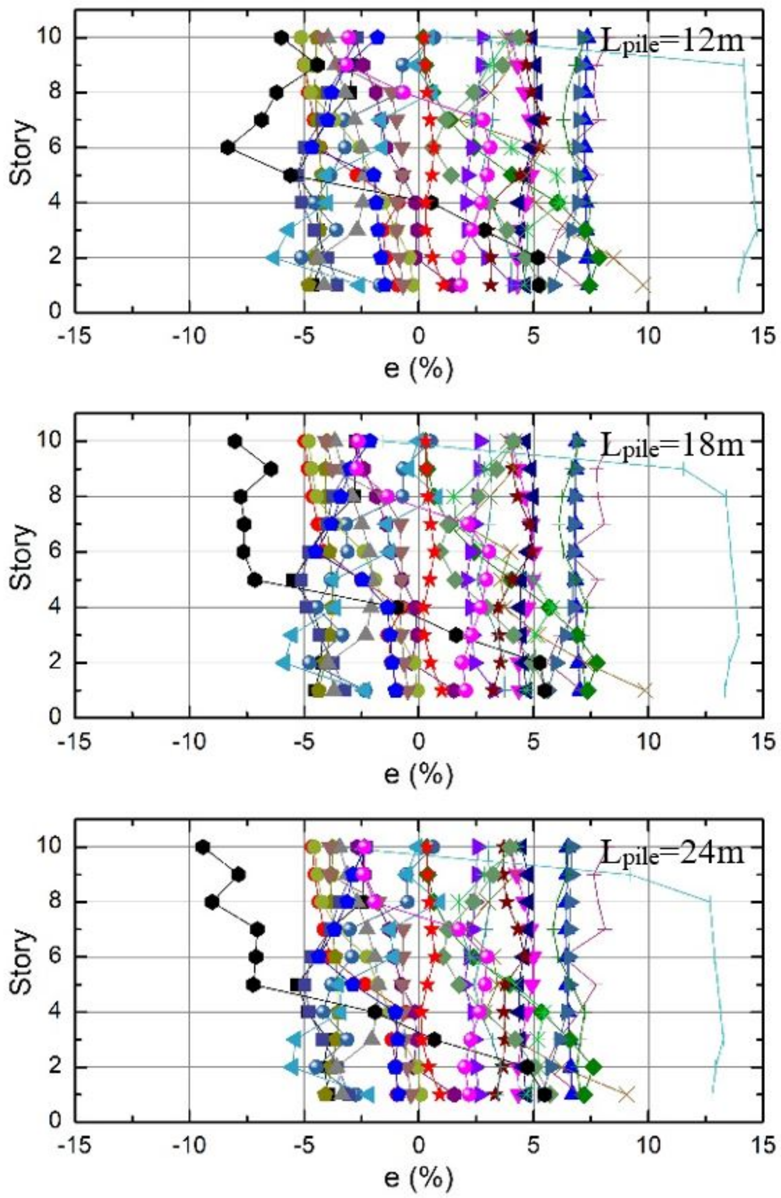

Fig.12 Influence coefficients of the story shear force at each story with different pile lengths under seismic waves.

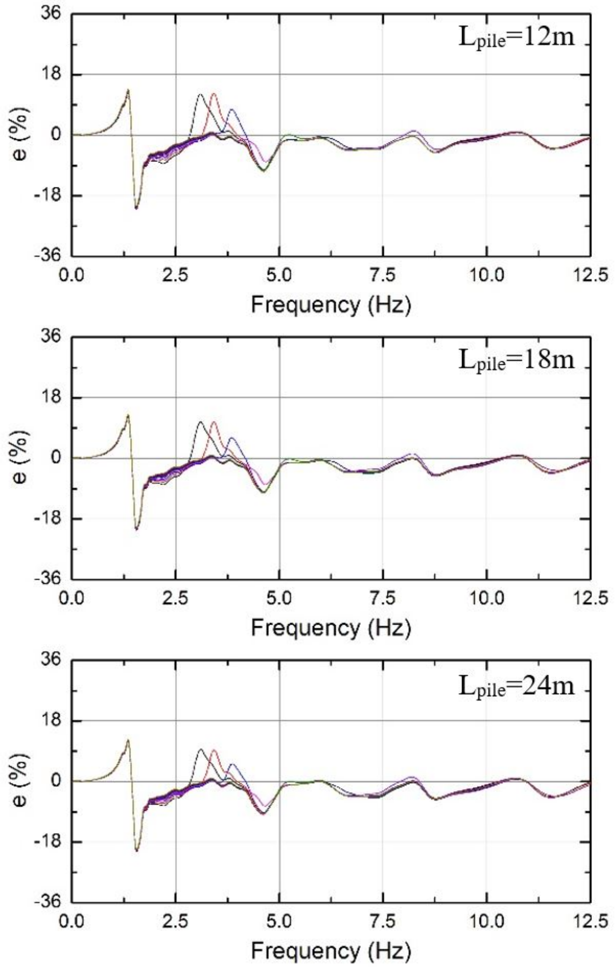

Fig.13 Influence coefficients of the story shear force at each story with different pile lengths under harmonic waves.

3.6 Influence of the damping ratio of the superstructure

The influence of the damping ratio of the superstructure on the interaction is investigated in Fig.14 and Fig.15, which show the influence coefficients of the story shear force at each story with different damping ratios of the superstructure under seismic waves and harmonic waves, respectively. Here, the damping ratios of the superstructure are $\zeta_B = 0.02/0.05/0.08$, and the other key parameters are the same as those in the first part[1] of this study and are given as follows: the damping ratio of the soil is $\zeta_S = 0.05$, the thickness of the soil is $H = 60m$, the shear wave velocity of the soil is $c_s = 300m/s$, the pile length is $L_{pile} = 18m$, the style of the superstructure is a $Frame$, the material stiffness of the superstructure is $1.0E$, the mass of the superstructure is $1.0M$, the story number of the superstructure is $N_S = 10$, the number of buildings is $N = 2$, and the dimensionless separation distance is $d = 0.1$.

For all seismic waves and for harmonic waves with different frequencies, the interaction between structures decreases with the increase in the damping ratio of the superstructure in a fluctuating but not monotonous manner. The maximum absolute value of the peak of the influence coefficient curve around the first-order natural frequency of the superstructure decreases from 35% to 17% under harmonic waves, while the variation range of influence coefficients decreases from $\pm 20\%$ to $\pm 10\%$ under seismic waves as the damping ratio of the superstructure increases from 0.02 to 0.08. With the increase in the damping ratio of the superstructure, the energy of the scattered wave from the structure decreases, and the interaction between structures fades away.

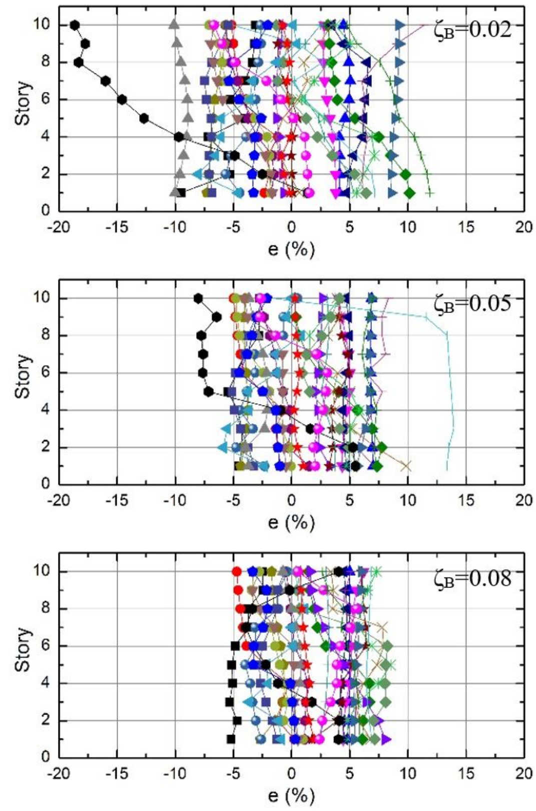

Fig.14 Influence coefficients of the story shear force at each story with different damping ratios of the superstructure under seismic waves.

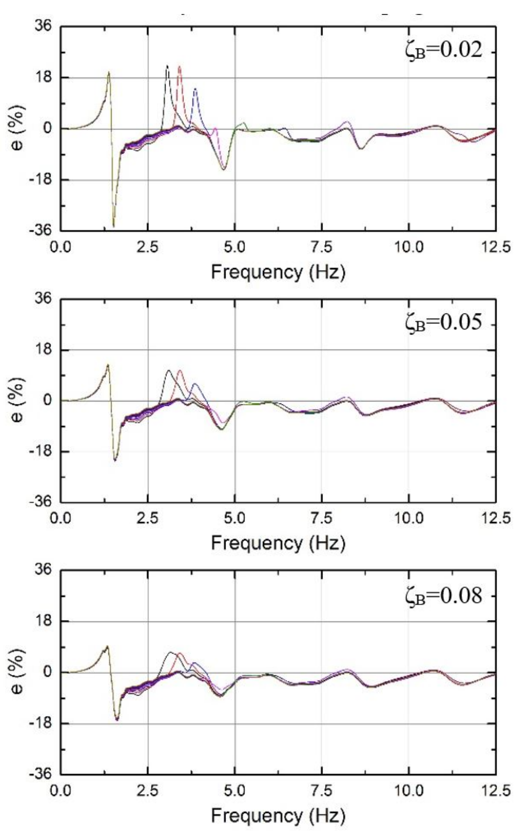

Fig.15 Influence coefficients of the story shear force at each story with different damping ratios of the superstructure under harmonic waves.

3.7 Influence of the style, material stiffness and mass of the superstructure

The influence of the style of the superstructure on the interaction is investigated in Fig.16 and Fig.17. Fig.16 shows the influence coefficients of the story shear force at each story with different superstructure styles under seismic waves. Fig.17 shows the story shear force at each story of a single-structure-soil system and the influence coefficients of the SSSI with different superstructure styles under harmonic waves. Here, the style of the superstructure is a $Frame\,/\,Frame-shear\ wall$ type, and the other key parameters are the same as those in the first part[1] of this study and are given as follows: the damping ratio of the soil is $\zeta_S = 0.05$, the thickness of the soil is $H = 60m$, the shear wave velocity of the soil is $c_s = 300m/s$, the pile length is $L_{pile} = 18m$, the damping ratio of the superstructure is $\zeta_B = 0.05$, the material stiffness of the superstructure is $1.0E$, the mass of the superstructure is $1.0M$, the story number of the superstructure is $N_S = 10$, the number of buildings is $N = 2$, and the dimensionless separation distance is $d = 0.1$.

Under harmonic waves, although the superstructure styles are different, the influence coefficient curves of the frame-shear wall structure are generally the same as those of the frame structure. Additionally, the peaks of the former are higher, approximately double, than those of the latter; namely, around the fundamental frequency, the interaction of the frame-shear wall structures is more intense than that of frame structures. The reason for this is the same as the reason for the reduction in the interaction between structures with the increase in the shear wave velocity of the soil. The rigidity of the frame-shear wall structure is higher; thus, the interaction between the soil and structure is more intense, and the influence on the adjacent structure is more remarkable. Although the influence coefficients corresponding to high frequencies ($6 \sim 11Hz$) of the frame-shear wall structure, which are larger than those of the frame structure, are not negligible under harmonic waves, they do not result in intense interactions between structures under seismic waves, which is verified by Fig.17. This is because the dynamic responses corresponding to high frequencies of the frame-shear wall structure, as shown in Fig.17, are very small.

Under seismic waves, the variation range of the influence coefficients of the frame-shear wall structure is just slightly larger than, not double, that of the frame structure. This is because a seismic wave includes different frequency components, and the positive influence and the negative influence cancel each other out. In addition, the difference in the influence coefficient of each story for the frame-shear wall structure is very small and less than that for the frame structure. This is because the difference in the harmonic response spectrum of each story for the frame-shear wall structure is less than that for the frame structure, as shown in Fig.17.

Obviously, the style of the superstructure only affects the value but not the rule of the SSSI. Therefore, based on this, we can predict that the material stiffness and mass of the superstructure, when varied within a reasonable range, will not affect the rule of the SSSI, although they will affect the dynamic response of the soil-structure system. This can be verified by Fig.18, Fig.19, Fig.20 and Fig.21, which show the influence coefficients of the story shear force at each story with different material stiffnesses and masses of the superstructure under seismic waves and harmonic waves, respectively. Here, the material stiffness and mass of the superstructure are $0.8E/1.0E/1.2E$ with $1.0M$ or $0.8M/1.0M/1.2M$ with $1.0E$. The other key parameters are the same as those in the first part[1] of this study and are given as follows: the damping ratio of the soil is $\zeta_S = 0.05$, the thickness of the soil is $H = 60m$, the shear wave velocity of the soil is $c_s = 300m/s$, the pile length is $L_{pile} = 18m$, the damping ratio of the superstructure is $\zeta_B = 0.05$, the style of the superstructure is a $Frame$, the story number of the superstructure is $N_S = 10$, the number of buildings is $N = 2$, and the dimensionless separation distance is $d = 0.1$.

Under harmonic waves, with the decrease in the material stiffness or the increase in the mass of the superstructure, the interaction between structures decreases in a fluctuating but not monotonous manner. The reason for this is the same reason as that for the reduction in the interaction between structures with the increase in the shear wave velocity of the soil. The smaller the material stiffness or the larger the mass is, the lower the integral rigidity of the superstructure, the less the intense interaction between the soil and structure, the less energy scattered from shaking the structure, and the less influence on the adjacent structure.

Under seismic waves, the abovementioned rule, i.e., the interaction between structures decreases with the decrease in the material stiffness or the increase in the mass of the superstructure, is presented but is not so conspicuous, and the variation range of the influence coefficients decreases from $\pm 15\%$ to $\pm 10\%$ as the material stiffness of the superstructure decreases from $1.2E$ to $0.8E$ or as the mass of the superstructure increases from $0.8M$ to $1.2M$. The variation in the influence coefficients is not as acute as that under harmonic waves because a seismic wave includes different frequency components and the positive influence, and the negative influence cancel each other out. In general, the influence coefficients are all still within $\pm 15\%$.

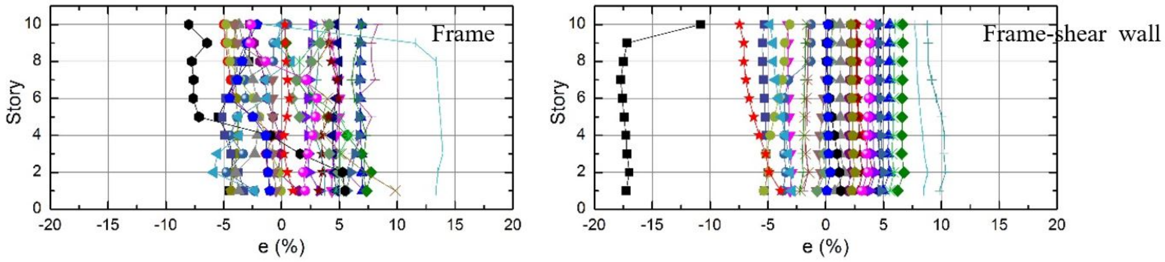

Fig.16 Influence coefficients of the story shear force at each story with different superstructure styles under seismic waves.

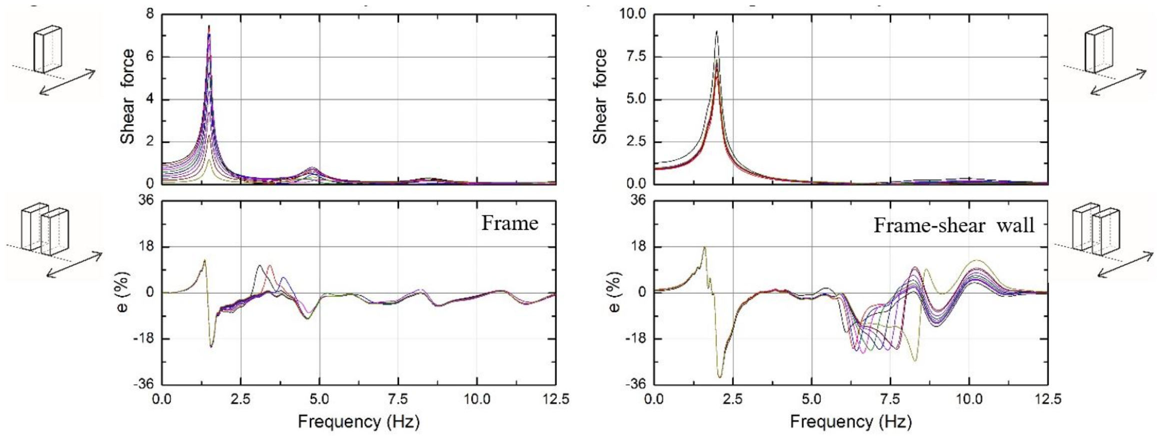

Fig.17 Story shear force at each story of a single-structure-soil system and influence coefficients of the SSSI with different superstructure styles under harmonic waves.

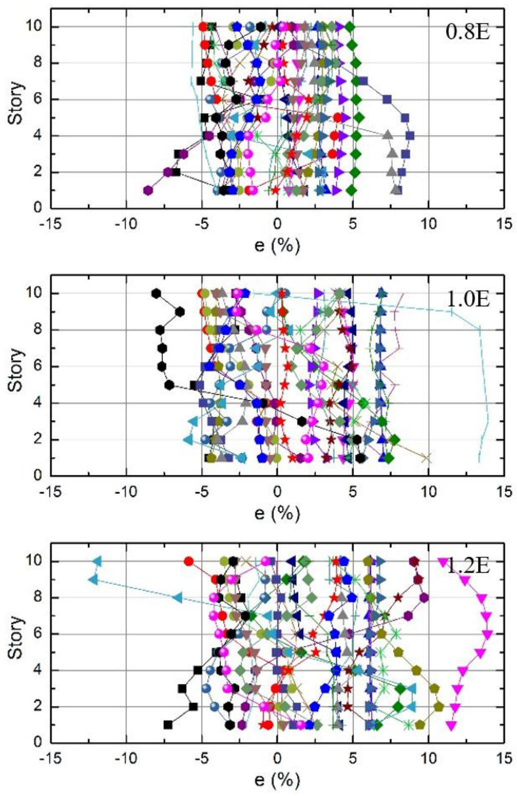

Fig.18 Influence coefficients of the story shear force at each story with different material stiffnesses of the superstructure under seismic waves.

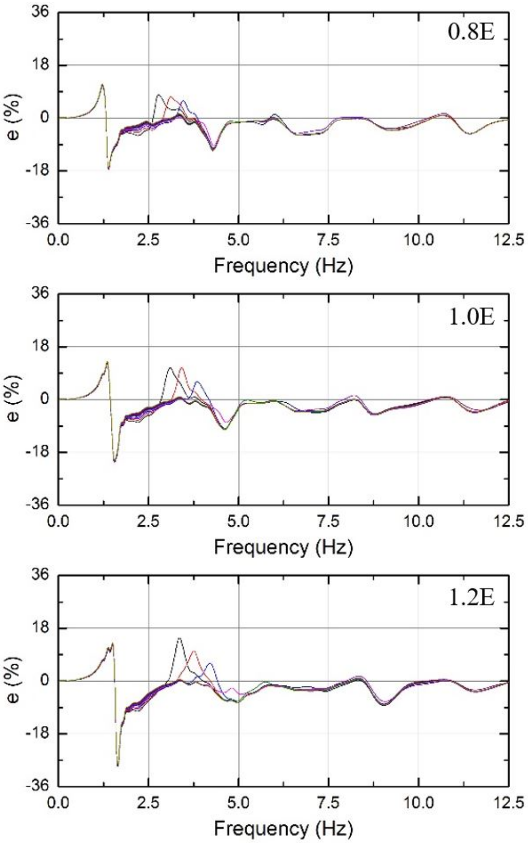

Fig.19 Influence coefficients of the story shear force at each story with different material stiffnesses of the superstructure under harmonic waves.

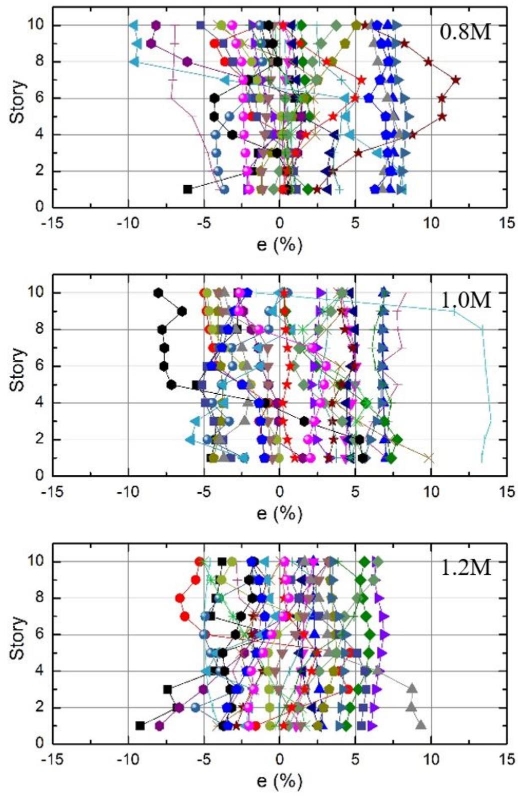

Fig.20 Influence coefficients of the story shear force at each story with different masses of the superstructure under seismic waves.

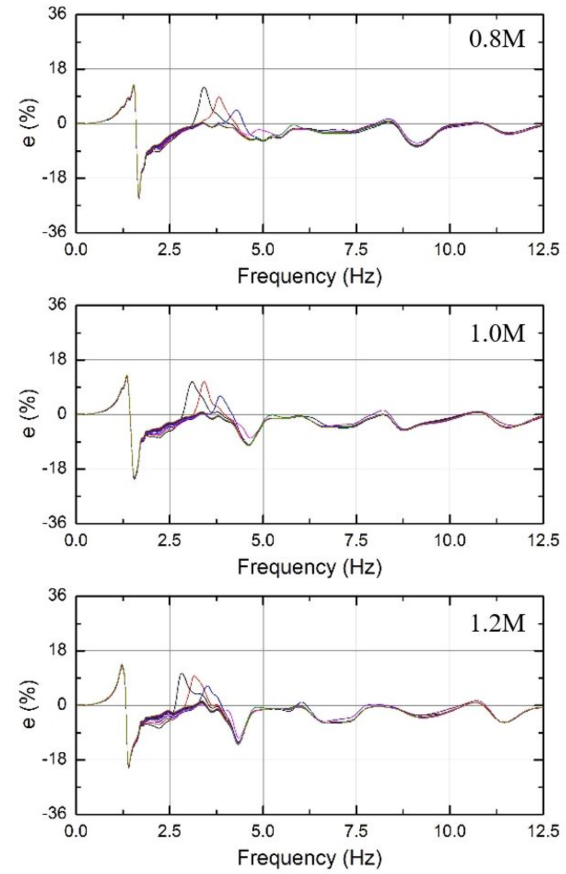

Fig.21 Influence coefficients of the story shear force at each story with different masses of the superstructure under harmonic waves.

3.8 Influence of the story number of the superstructure

The influence of the story number of the superstructure on the interaction is investigated in Fig.22, Fig.23, Fig.24 and Fig.25. Fig.22 shows the influence coefficients of the story shear force at each story with different story numbers of the superstructure under seismic waves. Fig.23 shows the story shear force at each story of a single-structure-soil system and the influence coefficient of the SSSI with different story numbers of the superstructure under harmonic waves. Here, the values for the story number of the superstructure are $N_S = 6/10/14/18$, which are the same for both structures, and the other key parameters are the same as those in the first part[1] of this study and are given as follows: the damping ratio of the soil is $\zeta_S = 0.05$, the thickness of the soil is $H = 60m$, the shear wave velocity of the soil is $c_s = 300m/s$, the pile length is $L_{pile} = 18m$, the damping ratio of the superstructure is $\zeta_B = 0.05$, the style of the superstructure is a $Frame$, the material stiffness of the superstructure is $1.0E$, the mass of the superstructure is $1.0M$, the number of buildings is $N = 2$, and the dimensionless separation distance is $d = 0.1$.

Under harmonic waves, with the increase in the story number of the superstructure, the peaks on the influence coefficient curves around the first-order natural frequency of the superstructure decrease, while the peaks around the other orders increase. Additionally, the velocity of the decrease for the former is faster than the velocity of the increase for the latter.

Under seismic waves, the variation range of the influence coefficients decreases from $\pm 15\%$ to $\pm 10\%$ as the story number of the superstructure increases from 6 to 18. The variation in the influence coefficients is not as acute as that under harmonic waves for two reasons. First, the first-order mode is dominant in the total dynamic response of the structure; second, a seismic wave includes different frequency components, and the positive influence and the negative influence cancel each other out. In general, the influence coefficients are all still within $\pm 15\%$.

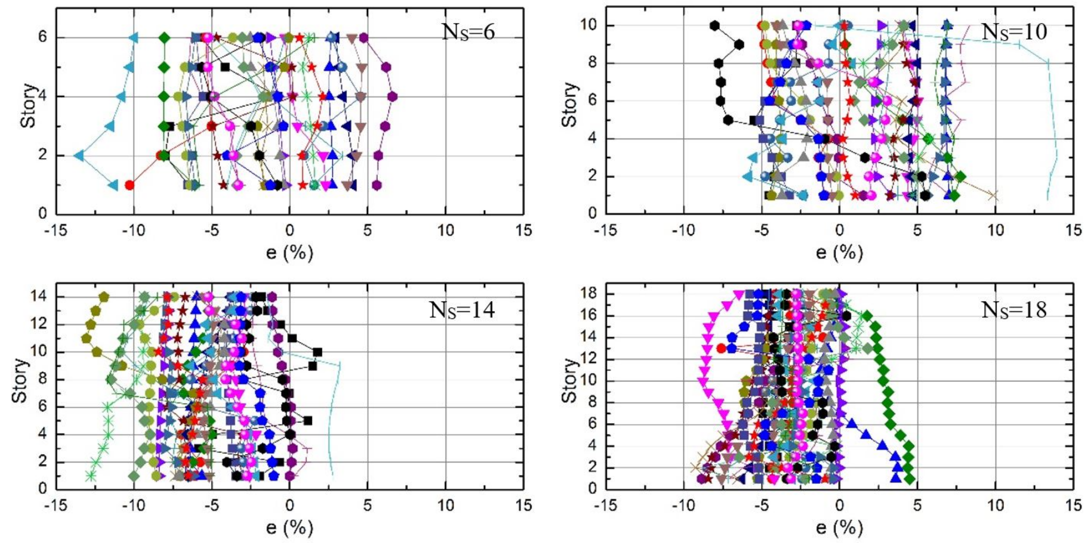

Fig.22 Influence coefficients of the story shear force at each story with different story numbers of the superstructure under seismic waves. (The story numbers of the two adjacent structures are the same.)

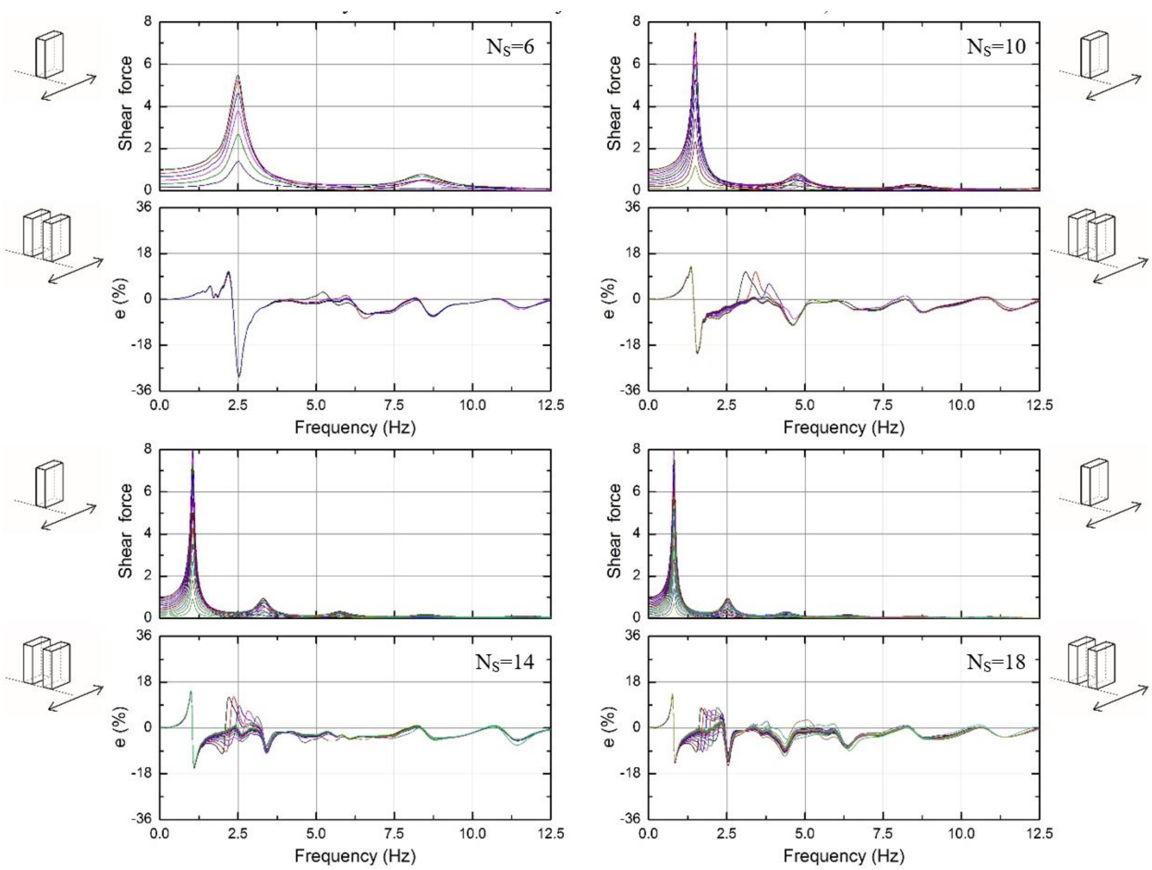

Fig.23 Story shear force at each story of a single-structure-soil system and influence coefficient of the SSSI with different story numbers of the superstructure under harmonic waves. (The story numbers of the two adjacent structures are the same.)

In the following, the interaction between two structures with different story numbers is investigated in Fig.24 and Fig.25, which show the influence coefficient of the story shear force at each story with different story numbers of the superstructure under seismic waves and harmonic waves, respectively. Here, the story numbers of the two adjacent structures are different. The story number of the structure of concern is N_{S1}=10 and the story numbers of the adjacent structure are N_{S2}=6/14/18. The other key parameters are the same as those in the first part[1] of this study and are given as follows: the damping ratio of the soil is $\zeta_S = 0.05$, the thickness of the soil is $H = 60m$, the shear wave velocity of the soil is $c_s = 300m/s$, the pile length is $L_{pile} = 18m$, the damping ratio of the superstructure is $\zeta_B = 0.05$, the style of the superstructure is a $Frame$, the material stiffness of the superstructure is $1.0E$, the mass of the superstructure is $1.0M$, the number of buildings is $N = 2$, and the dimensionless separation distance is $d = 0.1$.

As mentioned in the first part[1] of this study, under harmonic waves, as shown in Fig.25, there are peaks on the influence coefficient curves around each-order natural frequency of the superstructure. Combined with the harmonic spectra in Fig.23, these peaks are around the natural frequencies of the adjacent structure but not the structure of concern. Similar to the interaction between two structures with identical story numbers, with the increase in the story number of the superstructure, the peaks on the influence coefficient curves around the first-order natural frequency of the superstructure decrease, while the peaks around the other orders increase. The velocity of the decrease for the former is faster than the velocity of the increase for the latter.

However, the higher peaks around the first-order natural frequency for the lower adjacent structure or the higher peaks around the high-order natural frequencies for the higher adjacent structure do not always indicate that the interaction under seismic waves is greater since the dynamic responses corresponding to these peaks are slight in these configurations with two different structures. As shown in Fig.23, in the configuration with two identical structures, the frequencies corresponding to the peaks on the influence coefficient curves are the same as those corresponding to the peaks on the harmonic spectra. Thus, under seismic waves, as shown in Fig.22 and Fig.24, the interaction between two identical structures is usually stronger than that between two different structures.

In addition, for N_{S1}=10 together with N_{S2}=14, there are peaks on the influence coefficient curves around $3Hz$. This is because the dynamic response corresponding to those frequencies is too small, and a slight difference will lead to a large impact. Although the influence is not negligible here, the dynamic response is small enough, and thus, for a seismic wave with different frequency components, it will not lead to remarkable interaction.

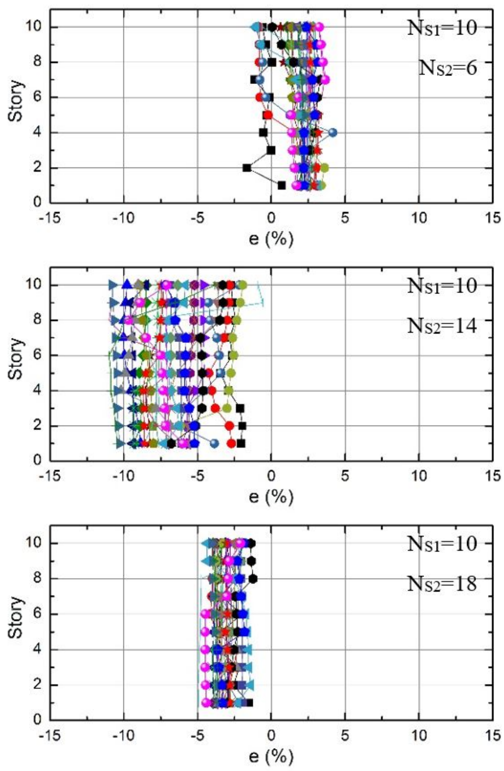

Fig.24 Influence coefficients of the story shear force at each story with different story numbers of the superstructure under seismic waves. (The story numbers of the two adjacent structures are different.)

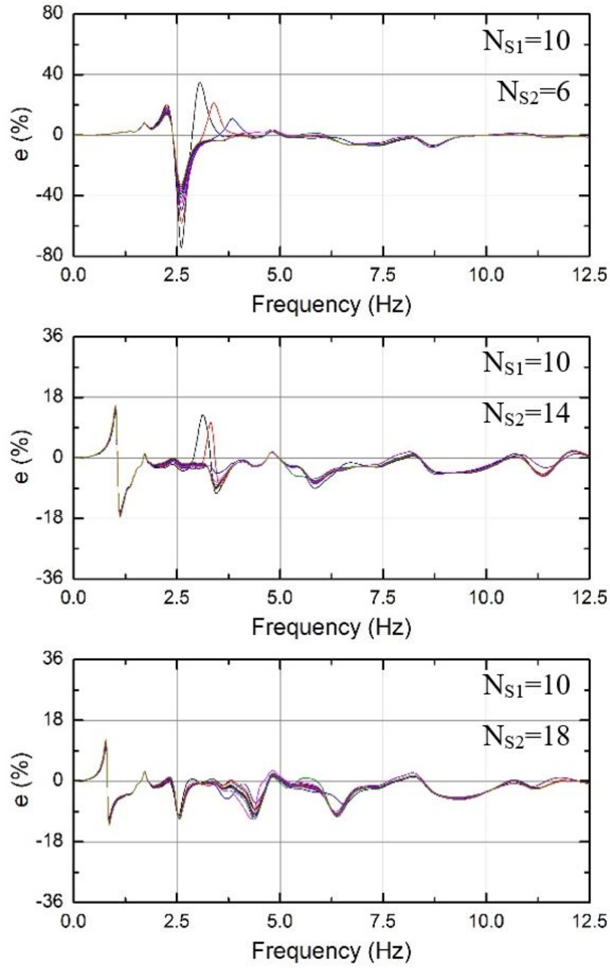

Fig.25 Influence coefficient of the story shear force at each story with different story numbers of the superstructure under harmonic waves. (The story numbers of the two adjacent structures are different.)

3.9 Influence of the position and number of buildings

The influence of the position and number (N) of the structure on the interaction is investigated in Fig.26 to Fig.29, which show the influence coefficients of the story shear force at each story with different structure numbers under seismic waves and harmonic waves. The gray structure is the structure of concern. Here, the numbers of buildings are $N = 2/3/6/7$ and the other key parameters are the same as those in the first part of this study and are given as follows: the damping ratio of the soil is $\zeta_S = 0.05$, the thickness of the soil is $H = 60m$, the shear wave velocity of the soil is $c_s = 300m/s$, the pile length is $L_{pile} = 18m$, the damping ratio of the superstructure is $\zeta_B = 0.05$, the style of the superstructure is a $Frame$, the material stiffness of the superstructure is $1.0E$, the mass of the superstructure is $1.0M$, the story number of the superstructure is $N_S = 10$, and the dimensionless separation distance is $d = 0.1$.

For different structure positions, under harmonic waves with different frequencies, the curves of the influence coefficient are similar. That is, the influence of the SSSI on each structure at different positions is similar. The closer to the structure group center the structure of concern is, the greater the absolute values of the influence coefficients due to the greater energy of the scattered wave from two sides. For example, as shown in Fig.29, for $N = 7$, the maximum absolute value of the peak of the influence coefficient curve around the first-order natural frequency increases from 45% (the structure of concern located at the edge of the structure group) to 63% (the structure of concern located at the center of the structure group). Likewise, under seismic waves, the absolute values of the influence coefficients increase as the structure of concern approaches the center of the structure group, and taking $N=7$ as an example, the variation range of the influence coefficients changes from $-26\% \sim 20\%$ (the structure of concern located at the edge of the structure group) to $-22\% \sim 38\%$ (the structure of concern located at the center of the structure group). Moreover, the closer to the structure group center the structure of concern is, since it is affected by more structures, the faster the increase velocity of the influence coefficient with the increase in the structure number.

For different structure numbers, under harmonic waves with different frequencies, the curves of the influence coefficient are also similar. The larger the structure number is, the greater the influence of the SSSI on each structure. For instance, as shown in Fig.27 and Fig.29, for the structure located at the edge of the structure group, the maximum absolute value of the peak of the influence coefficient curve around the first-order natural frequency increases from 32% ($N=3$) to 45% ($N=7$), while for the structure located at the center of the structure group, the maximum absolute value of the peak of the influence coefficient curve around the first-order natural frequency increases from 37% ($N=3$) to 63% ($N=7$). Likewise, under seismic waves, the absolute values of the influence coefficients increase with increasing structure number. For example, for the structure located at the edge of the structure group, the variation range of influence coefficients changes from $-11\% \sim 21\%$ ($N=3$) to $-26\% \sim 20\%$ ($N=7$), while for the structure located at the center of the structure group, the variation range of the influence coefficients changes from $-10\% \sim 25\%$ ($N=3$) to $-22\% \sim 38\%$ ($N=7$).

In addition, with the increase in the structure number, the influence coefficients of the structure located at the edge of the structure group under harmonic waves tend to be the same, and the velocity of this tendency for high-frequency waves is faster than that for low-frequency waves. Based on wave motion theories (Eq.(1)~(6)), this occurs because the velocity of energy reduction of the scattered wave from the adjacent vibrating structures with the increase in the propagation separation distance for high-frequency waves is faster than that for low-frequency waves. As shown in Fig.28 and Fig.29, the influence coefficients of the structure located at the edge of the structure group under harmonic waves and seismic waves are almost the same for $N=6$ and $N=7$. That is, when several structures stand in line, the adjacent 6 structures on each side of the structure of concern should be included for the SSSI effect.

Since the rules of the SSSI for two structures and those for more structures are similar, the abovementioned regularity of the influence of the key parameters on the SSSI is effective and applicable to the interaction of more than two structures.

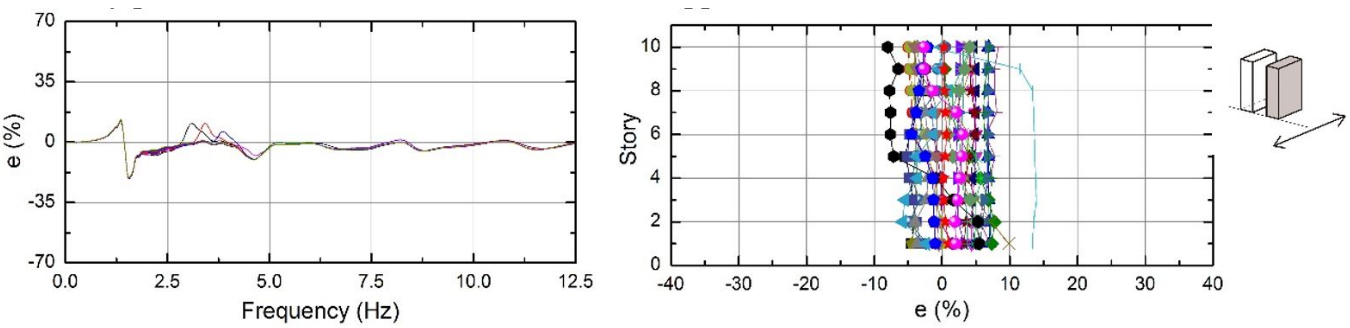

Fig.26 Influence coefficients of the story shear force at each story under harmonic waves and seismic waves. ($N=2$)

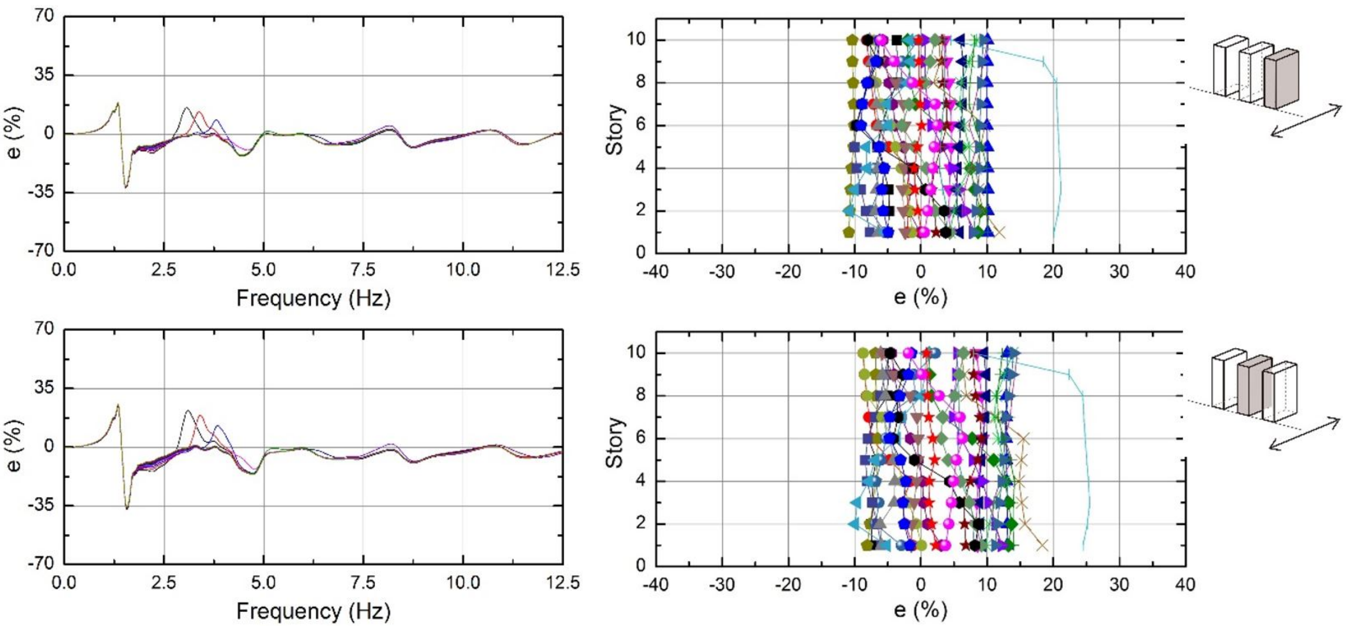

Fig.27 Influence coefficients of the story shear force at each story under harmonic waves and seismic waves. ($N=3$)

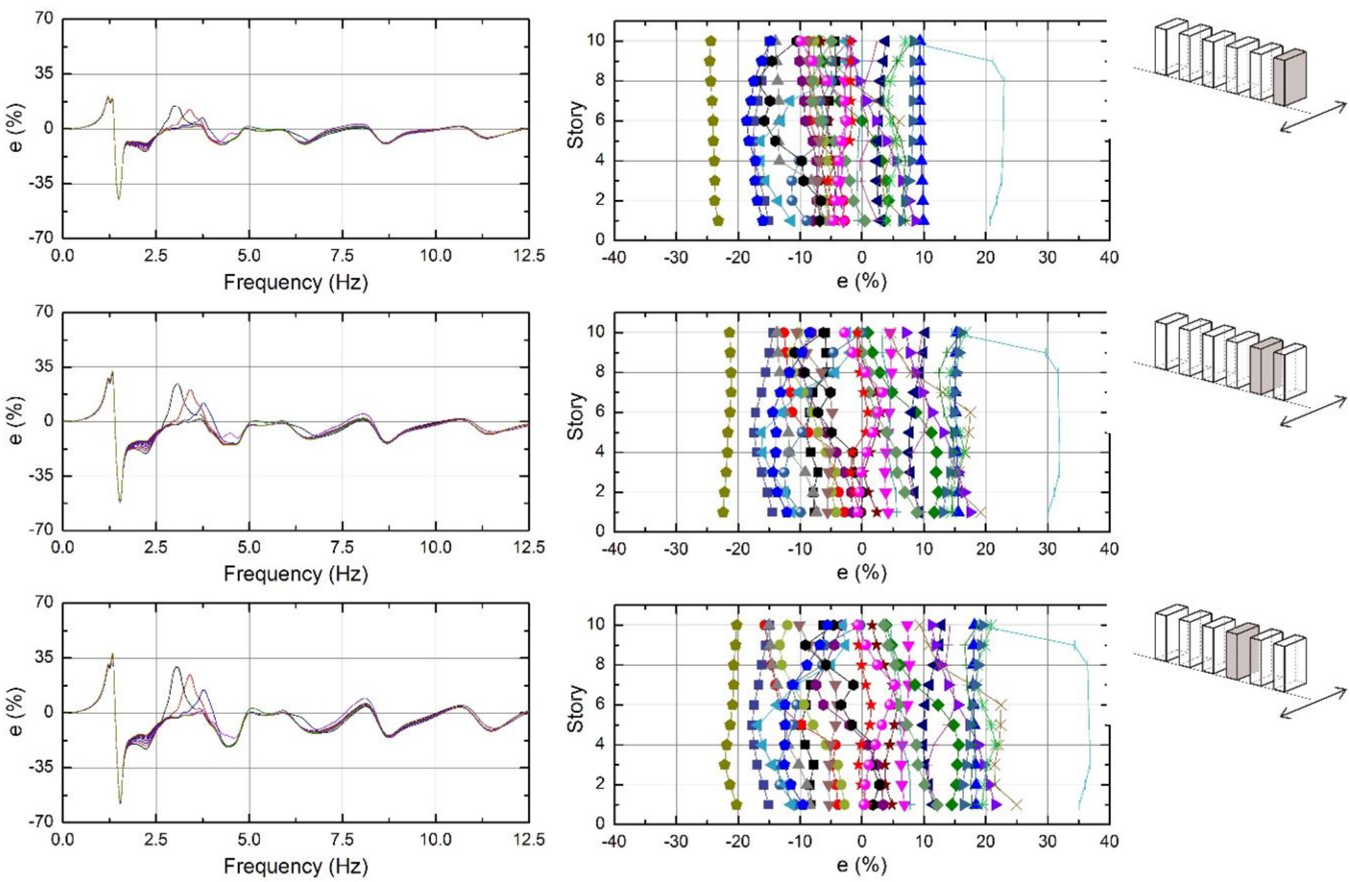

Fig.28 Influence coefficients of the story shear force at each story under harmonic waves and seismic waves. ($N=6$)

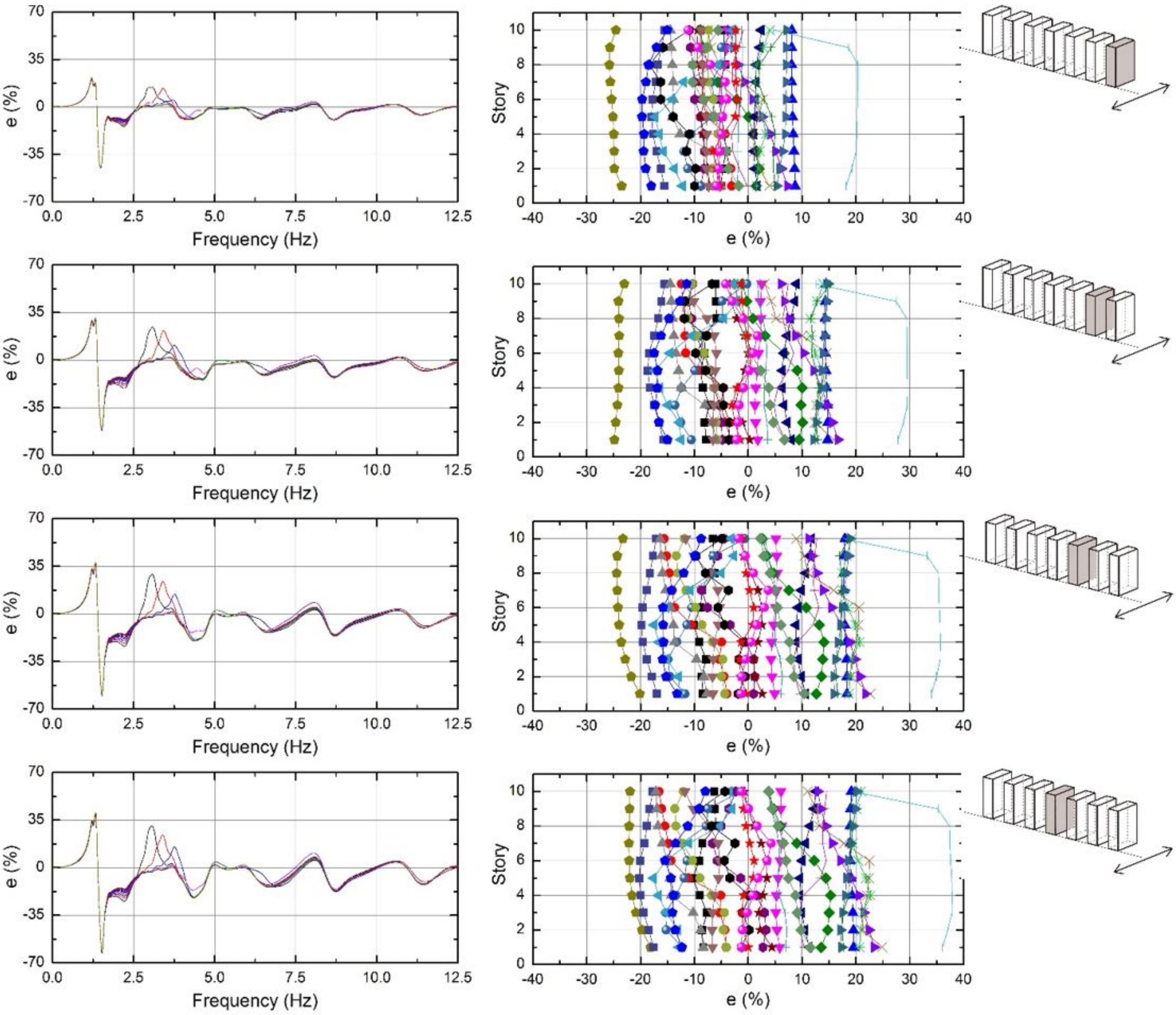

Fig.29 Influence coefficients of the story shear force at each story under harmonic waves and seismic waves. ($N=7$)

4 Compare and contrast

Comparing Fig.9, Fig.11, Fig.17, Fig.19, Fig.21 and Fig.23, a hidden phenomenon is revealed. That is, the closer to $2f$, where $f = c_s / (4H)$ is the foundational frequency of the soil, each-order natural frequency of the superstructure is, the higher the peak on the influence coefficient curve. The authors postulate that the scattered wave from the adjacent vibrating structure passes through the soil layer and reflects at the interface of the soil and bedrock; then, it goes back to the surface of the soil and affects the structure of concern. When the natural frequency of the superstructure is close to $2f$, the time for the scattered wave to travel from the surface to the bottom and then back to the surface of the soil, which is $2H / c_s$, is close to the time for the superstructure to complete a vibration cycle ($T = 1/(2f) = 2H / c_s$). Thus, the phase of the scattered wave matches the vibration phase of the structure of concern, and the interaction between the structures reaches its maximum.

The interaction between structures decreases with the increase in the separation distance between structures, the increase in the damping ratio and shear wave velocity of the soil, the increase in the damping ratio and mass of the superstructure, or the decrease in the material stiffness of the superstructure. However, for a certain story under a certain seismic wave or a harmonic wave with a certain frequency, the correlation fluctuates but is not monotonous. The authors postulate that this is mainly due to the relative relationship of the phase of the scattered wave and the vibration phase of the structure of concern.

5 Conclusion

A three-dimensional numerical procedure for the dynamic analysis of pile-supported multistory frame structures has been used in this work to solve the problem of through-soil interaction between high-rise buildings. Commercial software (ANSYS), based on the finite element method, has been further developed and enhanced for calculation in the frequency domain, in which hysteretic damping has been considered for both the soil and structures, and linear assumptions have been put forward for rigorous three-dimensional modeling. The time domain result under seismic waves is conducted through a fast Fourier transform from the frequency domain result. In this way, SSSI phenomena are implicitly included in the model. The influence of each key parameter, including the separation distance between structures; the damping ratio, thickness and shear wave velocity of the soil; the length of the pile; the damping ratio, style, material stiffness, mass and story number of the superstructure; and the position and number of the structure, of a dynamic system on the SSSI effect under harmonic waves and under real or artificial seismic waves is analyzed. The conclusions from this paper can be summarized as follows:

1) In the SSSI problem, the separation distance between structures and the relative relation of each-order natural frequency of the superstructure and the foundational frequency of the soil is the parameter that has the most important influence on the interaction between structures. Under seismic waves, when the separation distance between structures is not larger than $0.5B$ ($7.5m$), the SSSI effect should be considered. Under harmonic waves, the closer to $2f$, where f is the foundational frequency of soil, each-order natural frequency of the superstructure is, the more intense the interactions between structures around this natural frequency.
2) The interaction between structures decreases with the increase in the separation distance between structures, the increase in the damping ratio and shear wave velocity of the soil, the increase in the damping ratio and mass of the superstructure, or the decrease in the material stiffness of the superstructure in a fluctuating but not monotonous manner.
3) Although the thickness and shear wave velocity of the soil both have an influence on the total rigidity of the soil, which has an influence on the SSI, the influence of the thickness on the SSSI is limited and that of the shear wave velocity is prominent. This means that for the SSSI, the local rigidity is more important than the total rigidity of the soil.
4) The essence of the interaction between frame structures and between frame-shear wall structures is the same, and the style of the superstructure only affects the value but not the rule of the SSSI through the relative rigidity of the soil and structure.
5) Under seismic waves, the interaction between structures generally decreases with the increase in the story number of the superstructure.
6) The influence of the SSSI on each structure at different positions is similar. The closer to the structure group center the structure of concern is, the more intense the interaction between structures.

7) The larger the structure number is, the greater the influence of the SSSI on each structure. When several structures stand in line, the adjacent 6 structures on each side of the structure of concern should be included to determine the SSSI effect.

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Editor: Pablo Andrés Muñoz Rojas.

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