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ANALYSIS ON SEISMIC PERFORMANCE OF BUILDING WITH VISCOUS DAMPERS CONSIDERING SOIL-STRUCTURE INTERACTION

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Abstract

Buildings are usually constructed on soft soil, so there exists the soil-structure-dynamic interaction (SSI). The SSI has been considered to be an important factor in the study of structure vibration control because soil-structure interaction is generally known have effect on the dynamic response of a building structure. In this paper, the general finite element analysis program ANSYS was adopted to analyse the dynamic responses of the frame structures with viscous dampers considering soil-structure-dynamic interaction. The structures were ten-story cast-in-place concrete frames with six bays and three spans. The piled raft foundation was adopted as the foundation. In the analysis model, the equivalent linearization method was used to analyse the nonlinear behaviour of the soft soil. A material damping input method available in ANSYS was adopted to account for the difference of the soil damping ratio and that of the concrete superstructure in SSI systems. Shanghai bedrock waves were selected as the input earthquake, called SHW1 wave and SHW2 wave. In the process of meshing, the soft soil was meshed using the three-dimensional solid elements, the beams, columns of the superstructure and the group pile foundation were meshed using the three-dimensional beam elements, the slabs were meshed using the shell elements, and the viscous dampers were meshed using the combine elements. The dynamic responses of energy dissipation structures in which the coefficient of dampers, soil parameters and foundation forms were discussed considering soil-structure interaction and assuming fixed-base case. The results indicate that the viscous dampers have suppress the vibrations of structures considering the SSI effect and fixed-base case. The influence of SSI effect on the structure's floor displacement and inter-story damping effect of viscous dampers is not always increasing with the rise of damper's coefficient, but decreases when coefficient comes to a certain degree. Moreover, the larger the ratio of damping rate is, the greater influence of SSI is on the damping effect of viscous dampers. In addition, the degree of soft and hard of soil was varied to study the influence of soil parameters on the damping effect, and the results show that degree of soft-hard soils could influence the even degree that damping effect along the floors. Finally, two forms of foundation, box foundation and piled raft foundation, were adopted and the results of box foundation were compared with that of piled foundation, elucidating that the damping effect of box foundation is worse than that of piled raft foundation, but different SSI effects on the two forms of foundation could make up the different damping effect.

Keywords: structure-soil-structure interaction; frame structure; viscous dampers; damping effect

1. Introduction

In recent decades, with the further development of structural vibration control, the soil-structure-dynamic interaction (SSI) has been considered an important factor in the study of structure vibration control because soil-structure interaction is generally known to have effect on the seismic response of a building structure [1][2][3].

Smith et al. [4] developed an optimal control algorithm considering soil-structure-interaction effect for the application to a general MDOF SSI system. Results showed that the algorithm considering SSI effect was more effective in suppressing the structural response but required more control force when compared to the corresponding results for a control algorithm assuming a fixed-base system. Luco [5] presented a simple procedure to include the interaction effects on the control gains. Zhang et al. [6] used a hybrid control system for seismic-resistant building structures with and without soil-structure interaction and developed an intelligent algorithm for the hybrid system. It was found that the interaction could significantly affect the control effectiveness. Ghosh et al. [7] studied the effects of soil-structure interaction (SSI) while designed the liquid column damper (LCD) for seismic vibration control of structures. Wang et al. [8] established a LQG controller based on the finite element model of SSI system to optimally control the responses of SSI system and validated AMD controller strategy designed based on the proposed method through a serial of shaking table tests. Lee et al. [9] evaluated the performance of an MR damper in mitigating the seismic response of a building structure considering the SSI effects. Manolis et al. [10] introduced a distributed mass representation of the superstructure that has four possible dynamic response models, namely flexure, shearing, torsion and axial vibrations. Li et al. [11] introduced the results of an experimental study to demonstrate the feasibility and capability of magnetorheological (MR) dampers commanded by a decentralized control algorithm for seismic control of nonlinear civil structures considering soil-structure interaction (SSI). Zou et al. [12] studied the interaction of soil and structural parameters on structural vibration control. Cacciola et al. [13] [14] for the first time exploited the structure-soil- structure mechanism to develop a device able to absorb part of the seismic energy so to reduce the vibration of neighbouring structures.

Based on the general-purpose finite element program ANSYS, this paper aims to carry out the influence of SSI effect on the seismic performance of structures with viscous dampers. A rational finite element model of the structures with viscous dampers considering SSI was built in this paper builds. Then the key factors such as the coefficient of dampers, soil parameters and foundation forms have been discussed to study the SSI effect in detail. In addition, the damping effect of floor displacement and inter-story shear in each case are analyzed.

2. Modeling Method of the Building with Viscous Dampers Considering SSI Effect

In this part, the modeling method is introduced to set up the finite model of the building with viscous dampers considering soil-structure dynamic interaction.

2.1 General situation of the engineering

As shown in Fig. 1, the superstructure is 10-story cast-in-place concrete frames with six bays and three spans that have a piled raft group foundation which is embedded in deep Shanghai soft soil deposits. The overall dimensions of the structure are 30 m × 15 m in plane and 36 m in height (the height of each story is 3.6 m). All the columns have a constant rectangular cross section (550 mm height by 550 mm width) over height of the structure. Similarly, all the beams have the same cross section (500 mm height by 300 mm width). The concrete slabs have thickness of 120 mm. The dead load of the standard floor is 5.0 kN/m^2 and the live load is 2.0 kN/m^2. The axial compressive strength of concrete is 16.7 MPa. The pile foundation is composed of RC pile cap and 66 RC piles. The pile cap is designed to have sufficient rigidity, with 1 m in thickness. The piles have the same cross section (450 mm height by 450 mm width), with 35 m in depth.

2.2. The input earthquake

Shanghai bedrock waves are selected as the input earthquake, which are labelled SHW1 and SHW2 hereafter. Fig. 2 and 3 show the acceleration time-history and the corresponding Fourier spectrum of SHW1 and SHW2 waves.

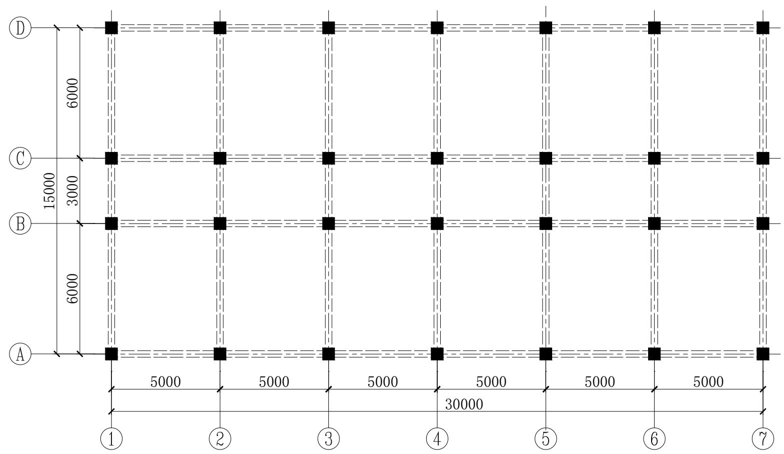


Fig. 1 - The plan of the standard floor (unit: mm)

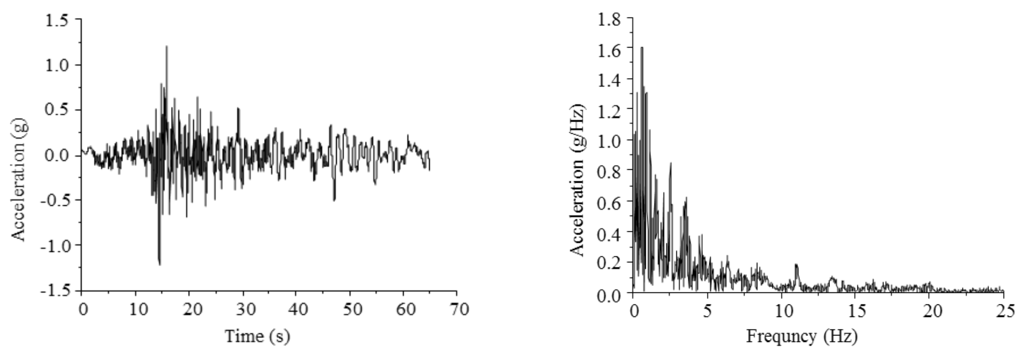


Fig. 2 - The acceleration time-history and the corresponding Fourier spectrum of SHW1 wave

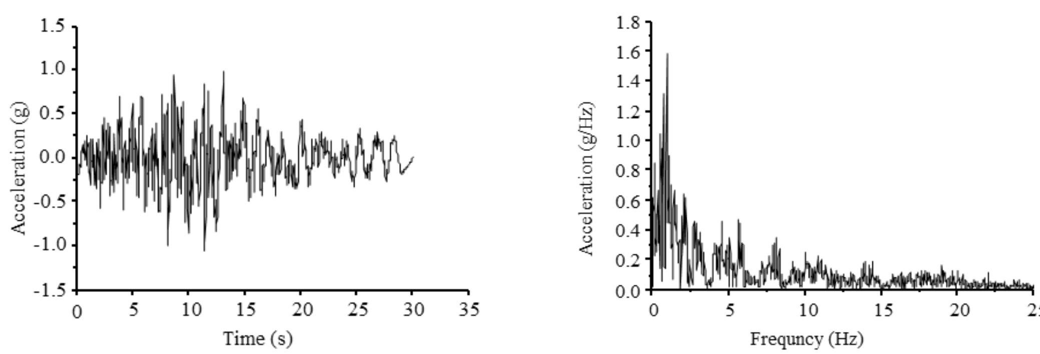


Fig. 3 - The acceleration time-history and the corresponding Fourier spectrum of SHW2 wave

2.3 Damping model

In SSI systems the soil damping ratio is usually larger than that of the concrete superstructure. In order to account for this difference, a material damping input method available in ANSYS is used. As is well known, the Rayleigh damping ratio can be calculated by Eq. (1).

$$\xi_i = \alpha/2\omega_i + \beta\omega_i/2 \tag{1}$$

where ξ_i is the ratio of actual damping to critical damping for a particular mode of vibration i, and ω_i is the natural circular frequency of mode i.

In many practical structural problems, alpha damping (or mass damping) can be ignored ($\alpha = 0$). In such cases, β can be evaluated from known values of ξ_i and ω_i as Eq. (2) lists:

$$\beta = 2\xi_i / \omega_i \tag{2}$$

Material-dependent damping allows one to specify beta damping (β) as a material property. Different damping ratios can be input for different materials by this method (ANSYS program). The initial damping ratio of soil was taken as 0.05, which was then iteratively determined from the $D-\gamma_d$ curves measured by material tests. The damping ratio of the superstructure was taken as 0.05.

2.4 Soil Dynamic Constitutive Model

In SSI systems, there are two points to be noted when selecting the soil dynamic constitutive model: the real performance of soil can be well reflected and the model is simple and useful. So the equivalent linearization method Davidenkov model was used to analyse the nonlinear behaviour of the soil. The relationship of the modular ratio $G/G_{\max} \sim \gamma$ is described as Eq. (3):

$$\frac{G}{G_{\max}} = 1 - H(\gamma) \tag{3}$$

$$H(\gamma) = \left[\frac{(|\gamma|/\gamma_r)^{2B}}{1+(|\gamma|/\gamma_r)^{2B}} \right]^A \tag{4}$$

As to $D/D_{\max} \sim \gamma$, it can be shown by Eq. (5):

$$\frac{D}{D_{\max}} = (1 - \frac{G}{G_{\max}})^{\beta} \tag{5}$$

where $G_{\max}$、$D_{\max}$ is the maximum dynamic shear modulus and the maximum damping ratio, $\gamma = \tau_{\max}/G$ is the amplitude shear strain, $\tau_{\max}$ is the final amplitude stress, β is the shape coefficient of $D/D_{\max} \sim \gamma$ curve. To most soils, β is 0.2 to 1.2, to soft soil it is 1.0. Table 1 is the reference for the parameters of Davidenkov model of soft soil.

Table 1 - The reference for the parameters of Davidenkov model of soft soil

Soil type	A	B	D_{max}	γ'_γ (10^{-3})
Clay soil	1.62	0.42	0.30	0.6
Silt soil	1.12	0.44	0.25	0.8
Sand	1.10	0.48	0.25	1.0
Medium-coarse sand	1.10	0.48	0.25	1.2

2.5 The Design of Building Setting Viscous Dampers

The damping force of viscous dampers is described as Eq. (6):

$$f_D = Cu \tag{6}$$

where f_D is the damping force, C is the coefficient of viscous damper, u is the relative displacement at each end of the dampers.

The damping rate of structure is defined by Eq. (7):

$$\mu_d = \frac{\Delta u_{0,\max} - \Delta u_{c,\max}}{\Delta u_{0,\max}} \tag{7}$$

$\Delta u_{0,\max}$ and $\Delta u_{c,\max}$ are the maximum inter-strory drift of the structures without and with viscous dampers respectively.

By calculation, the total damping coefficient of each story is $1.46\times10^7 N \cdot s / m$. Four identical viscous dampers, with damping coefficient is $3.65\times10^6 N \cdot s / m$, are installed in each story of the building. Diagonal bracing is used in the building facades. Fig. 4 is the layout of the viscous dampers, and "X" denotes the viscous dampers.

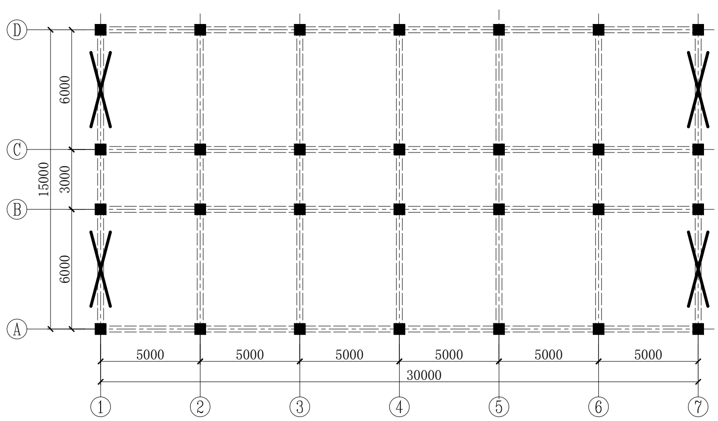


Fig. 4 - Floor plan of viscous dampers

2.6 Meshing and Boundary Conditions

In the ANSYS program, the soil was meshed with the three-dimensional solid elements. Beams and columns of the superstructure and the group pile foundation were meshed with three-dimensional beam elements, and the slabs were meshed with shell elements. The viscous dampers were meshed with combine elements, which are named COMBIN14 in AYSYS program. The COMBIN14 element is composed of a damper element and a spring element. The modeling was based on the following principles.

(1) Wave motion constraint on meshing. The high-frequency component of the wave motion is difficult to transmit if the size of the element is too large. A study by Gupta et al. (1982) showed that in the case of a shear wave transmitted vertically, the height of the element $h_{\max}$ can be taken as $(\frac{1}{5} \sim \frac{1}{8})v_s / f_{\max}$, where v_s denotes the velocity of the shear wave and $f_{\max}$ denotes the highest wave frequency intercepted. The limitation of mesh size in the plane is not as strict as that in the height direction, and the size in the plane was chosen as 3 to 5 times $h_{\max}$. In this case, the maximum mesh size in the height was taken as 1m, and the maximum mesh size in the plane was taken as 3m.

(2) Effect of meshing on precision. With finer mesh and more degrees of freedom, precision is higher and the time taken for calculation is longer. Thus, a proper grid size should be used.

(3) Computed region of the soil and the artificial boundary are important to the property and practical of the model. The calculation results show that the semi-infinite domain of soil could be well modelled when the lateral size of soil is 20 times of the structure's lateral size and the viscous-spring artificial boundary is applied to

the boundary.

Fig. 5 shows the meshing and the boundary of the model, which satisfies the above modeling requirements.

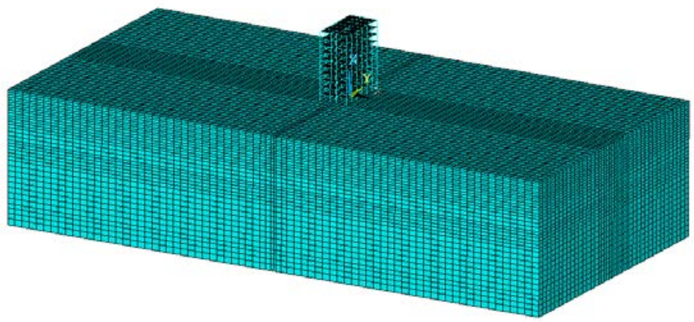


Fig. 5 - Meshing and boundary of the model

3. The influence of coefficient of dampers on building's seismic performance

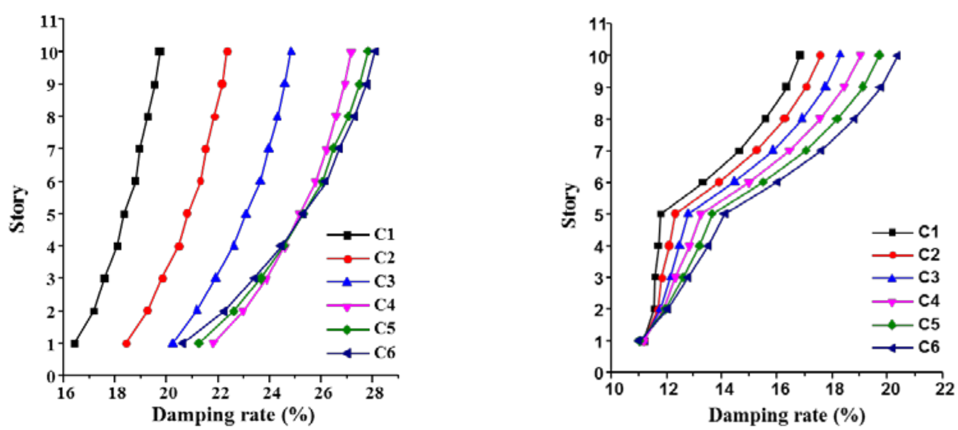
The coefficients of dampers are varied, which are listed in Table 2, in order to study the influence of SSI on the damping effect of buildings with viscous dampers.

Table 2 - The coefficient of viscous damper (unit: $N \cdot s / m$)

Parameter	C 1	C 2	C 3	C 4	C 5	C 6
Value	3.0×10^6	3.5×10^6	4.0×10^6	4.5×10^6	5.0×10^6	5.5×10^6

3.1 The Damping Effect of Floor Displacement

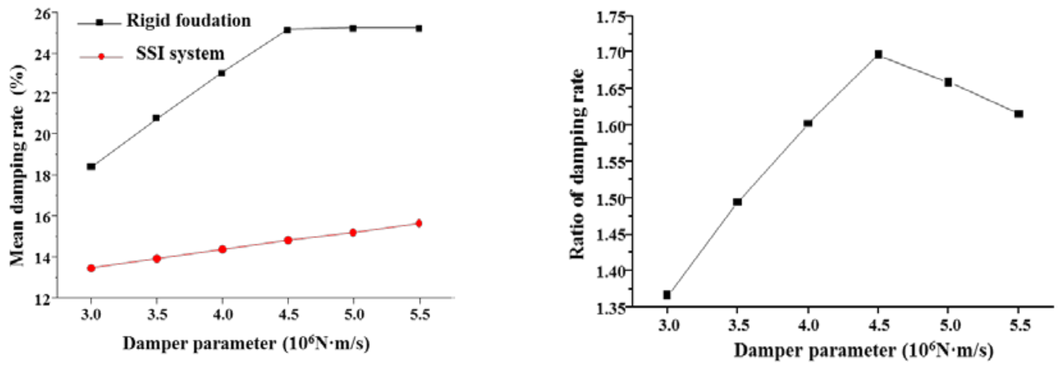
The elastic deformation of SSI system is compared with that of fixed-base (rigid foundation) system model. Fig. 6 shows the damping rate of floor displacement, which could be seen that the damping rates increase not only with the increasing of damping coefficients but the story in both systems, while the shapes of damping rate are different in the two systems. The damping rate at bottom layers decrease gradually in fixed-base system when the coefficient of dampers surpasses C 4.



(a) Rigid foundation system
(b) SSI system

Fig. 6 - The damping rate of floor displacement

The ratio of mean damping rate of rigid foundation structure to that of SSI system structure has been described the influence SSI effect on the damping effect of viscous dampers. The bigger ratio of damping rate means the greater influence of SSI on the damping effect of viscous dampers.



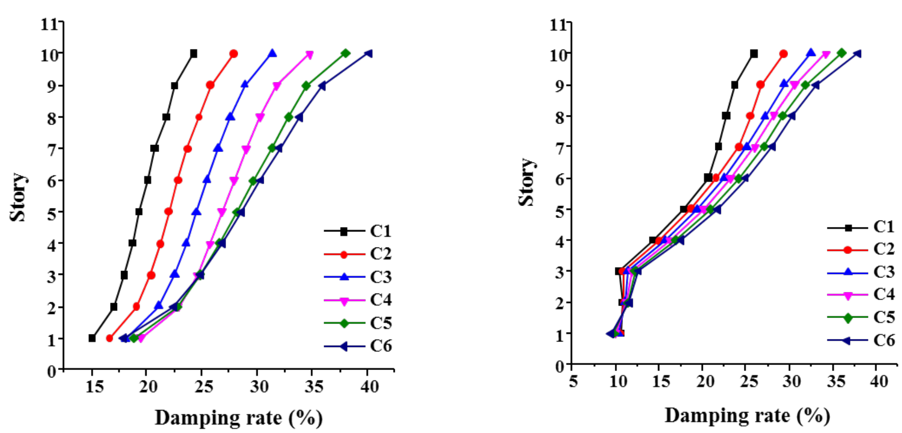
(a) Mean damping rate (b) Ratio of damping rate

Fig. 7 - The mean damping rate and ratio of damping rate of floor displacement

It can be seen from the Fig. 7 (a) that the mean damping rate of floor displacement in SSI system structure is increasing linearly with the rise of damping parameter. While the mean damping rate of fixed-base increases linearly first and then almost does not change later. Seen from the Fig. 7 (b) the ratio of damping rate increases first and then decreases with the rise of the coefficient of dampers. This illustrates that the influence of SSI effect on the damping effect of viscous dampers is not always increasing with the rise of damping parameter, but decreases when damping parameter comes to a certain degree. The direct reason is that the mean damping rate of floor displacement varying with the damping parameter is different in SSI system and fixed-base system.

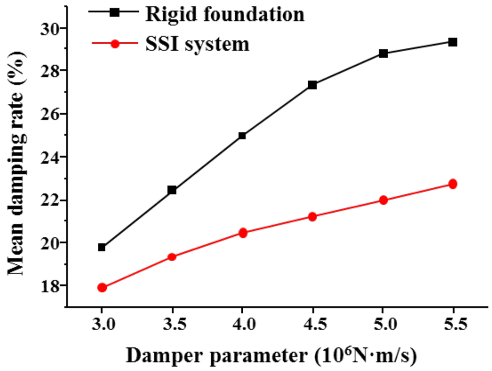
3.2 The Damping Effect of Inter-Story Shear

As shown in Fig. 8, the damping rate of inter-story shear increases gradually with the rise of damping coefficient in both fixed-base system and SSI system. The turning point is on the third floor when considering SSI effect. From Fig. 9, it can be seen that the mean damping rate of inter-story shear increases gradually with the rise of damping parameter, but it increases slowly when the damping parameter surpasses C 4 in rigid foundation structure. The ratio of damping rate also illustrates that the influence of SSI effect on damping effect is not increasing with the rise of damping parameter but increases first and decreases later.

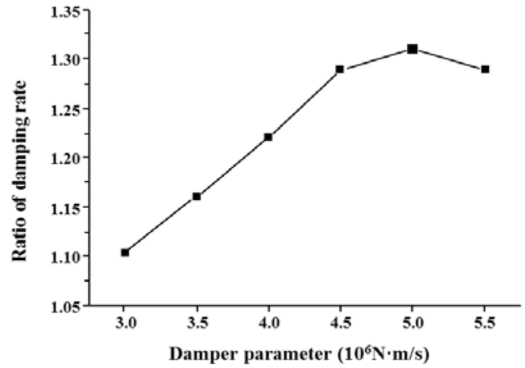


(a) Rigid foundation system (b) SSI system

Fig. 8 - The damping rate of inter-story shear



(a) Mean damping rate



(b) Ratio of damping rate

Fig. 9 - Mean damping rate and ratio of damping rate curves of inter-story drift

4. The influence of soil parameters on building's seismic performance

The degree of soft and hard of soil is varied to study the influence of soil parameters on the damping effect. The dynamic shear modulus of soil is called G initially and the finite element models have been built up which the dynamic shear modulus of soil is 0.125 G, 0.25 G, 0.5 G, 2 G, 4 G and 8 G.

4.1 The Damping Effect of Floor Displacement

It can be seen from Fig. 10 that the damping rate of floor displacement is almost the same along the story when the dynamic shear modulus of soil is 0.125 G, 0.25G and 0.5G, which illustrates the damping rate is evenly distributed along the floors. But when the dynamic shear modulus surpasses 1 G, the damping rate of the floor displacement is not evenly distributed along the floors. So it shows that the degree of soft and hard of soil affects the evenness extent of damping rate along the floors. It can be seen from Fig. 11 that the mean damping rate of floor displacement increases roughly as the soil gets harder. But when the dynamic shear modulus gets to 1 G, the mean damping ratio suddenly decreases, which makes the whole curve of the mean damping rate be M shape. This may be because the natural vibration frequencies of the soil and the superstructure change as the degree of soft and hard of soil varies, resulting in the mode of vibration varying.

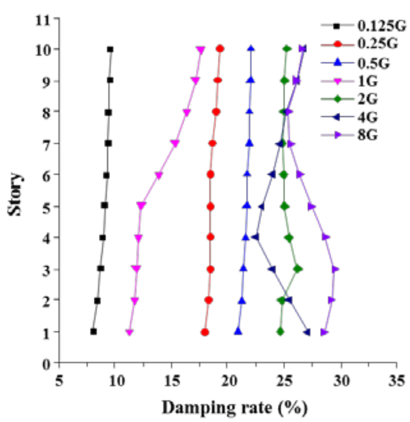


Fig. 10 - The damping rate of floor displacement

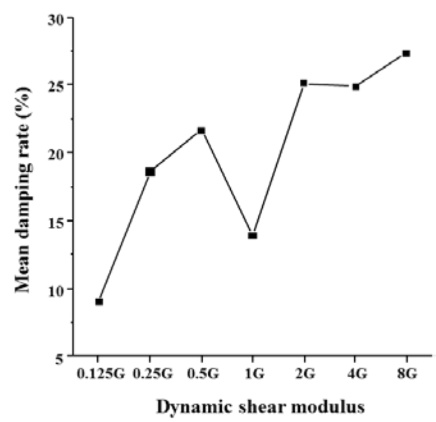
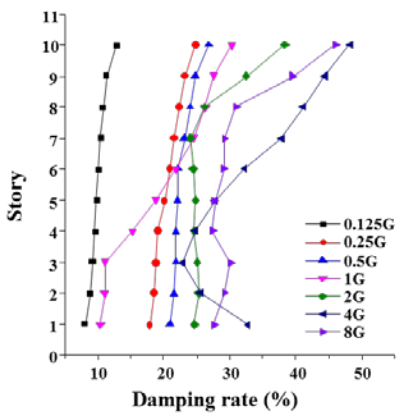


Fig. 11 - The mean damping rate of floor displacement

4.2 The Damping Effect of Inter-Story Shear Force

The damping rate of inter-story shear is almost the same along the floor when the dynamic shear modulus of soil is 0.125 G, 0.25 G and 0.5 G in Fig. 12. The curve of the mean damping rate of inter-story shear is also M shape in Fig. 13, which is similar to that of floor displacement. This show the viscous dampers have the same influence on the damping effect of inter-story shear and floor displacement.



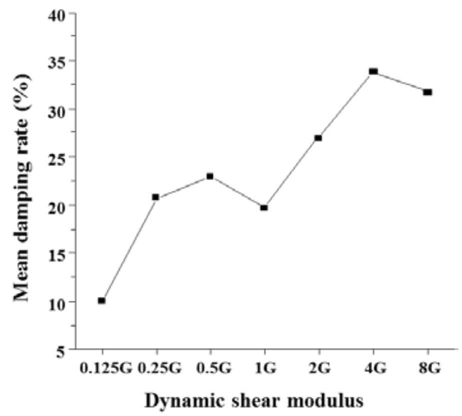


Fig. 12 - The damping rate of inter-story shear force Fig. 13 - The mean damping rate of inter-story shear force

5. The influence of foundation forms on building's seismic performance

Foundation form is one of the key factors affect the superstructure in SSI system. In order to study the influence of foundation forms on the damping effect, the superstructure is unchanged while the box foundation is adopted. The results of box foundation are compared with that of piled raft foundation. In this part, the building without and with viscous dampers are called SSI system and damping system respectively.

5.1 The Damping Effect of Floor Displacement

As shown in Fig. 14 and Fig. 15 that the shapes of floor displacement are shear deformation both in the cases of box foundation and piled raft foundation and the viscous dampers have reduced the elastic deformation of structures effectively in the two cases. The mean damping rate of floor displacement in the box foundation system is 10.88 % in contrast to 14.07 % in piled raft foundation system, which illustrates that the damping effect of piled raft foundation is better. In SSI system, the peak values of piled raft foundation are bigger than that of box foundation, which indicates that the influence of SSI effect on the superstructure is more obvious when box foundation has been adopted. This may be because the soil has base isolation effect when pile foundation deepens reaching to the hard soils. So it can transmit the ground motion to the structure more effectively. What is more, in damping system, the peak values of box foundation are also smaller than that of piled raft foundation. So it can be concluded that the damping effect of box foundation is worse than that of piled raft foundation, but the different damping effects could be made up with the different influences of SSI effect on the two forms of foundation.

5.2 The Damping Effect of Inter-Story Shear Force

Fig. 16 and Fig. 17 show the peak inter-story shear of box foundation and piled raft foundation which can be observed that the viscous dampers have reduced the inter-story of structures effectively in the two cases. The mean damping rates are 11.81 % and 19.71 % in the form of box foundation and piled raft foundation respectively. It also can be seen that the values of box foundation are smaller than that of piled raft foundation. It is also because the SSI effect has different influence on the two forms of foundation.

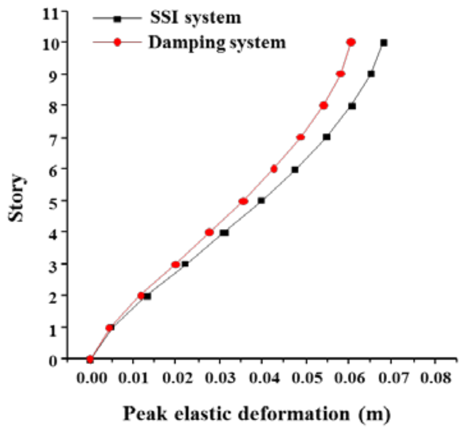


Fig. 14 - Peak elastic deformation of box foundation

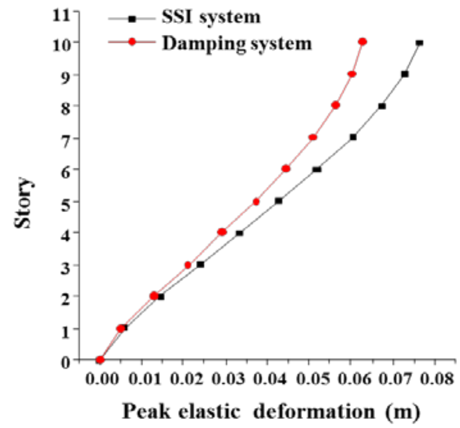


Fig. 15 -Peak elastic deformation of piled raft foundation

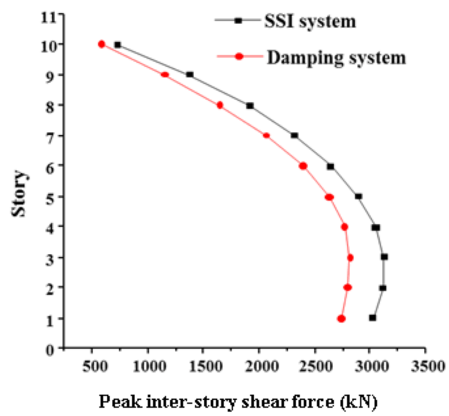


Fig. 16 - Peak inter-story shear force with box foundation

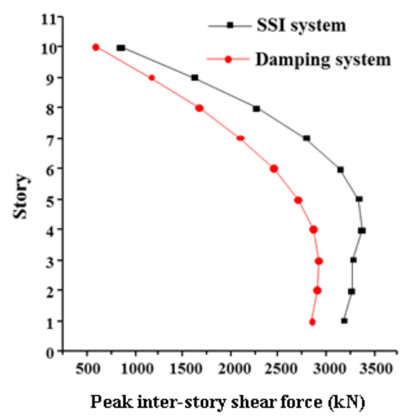


Fig. 17 - Peak inter-story shear force with piled raft foundation

6 Conclusions

By adopting a rational modeling method, the building with viscous dampers considering SSI was analysed using the general finite program ANSYS. The coefficients of viscous dampers, the soil parameters and the forms of foundation have been discussed and the damping effect of floor displacement and inter-story shear in each case were analysed. From these studies, the following conclusions were obtained.

(1) The viscous dampers have suppressed the vibrations of structures considering the SSI effect and fixed-base case.

(2) The influence of SSI effect on the damping effect is not always increasing with the rise of the coefficient of dampers, but decreases when it gets to some extent.

(3) The damping effect gets better when the soil gets harder. But when the harder soil gets to a certain degree, the damping effect could get worse.

(4) The damping effect of piled raft foundation is better than that of box foundation, but different SSI effects on the two forms of foundation could make up the different damping effect.

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