Influence of Soil-Structure Interaction Effects on the Performance of Viscous Energy Dissipation Systems

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SUMMARY
In this paper, the effects of soil structure interaction (SSI) on a 7-storey frame structure with and without viscous energy dissipation system (VES) are studied. Finite element models of the structure with different surrounding soils are constructed and excited by three kinds of earthquake excitation. Utilizing time-stepping solution method, the structural seismic response and the load-displacement relationship curves of the dampers are investigated. The results show that the seismic response of the whole structure system is affected by consideration of SSI effects. The energy dissipation systems designed based on the rigid foundation hypothesis maybe fail to achieve the expected seismic objective while SSI goes into effect. Furthermore, the control effectiveness of the VES is decreased when SSI is considered, and the extent of the reduced efficiency will be increased as the soil becomes softer. The mechanism of SSI influencing the performance of the VES is also discussed in this research.

Keywords: Soil-structure interaction; Viscous energy dissipation system; Seismic response.

1. INSTRUCTIONS

Passive control using energy dissipation devices has received considerable attention in recent years. Among various damping devices, viscous damper (VD) is one kind of widely used energy dissipaters in civil engineering. Many studies concerning the effect of the VDs on the seismic performance of building structures have been conducted in the past, such as that conducted by Uriz (2001), Martinez-Rodrigo (2003), Dicleli (2007), Barone (2008), Mansoori (2009), Antonio (2009). However, the most previous studies were carried out with the assumption of rigid foundation and neglected the effect of soil-structure interaction (SSI) on the seismic response of structures. Actually, many structures were built on soft soil and strong interaction between the soil and the structure should occur. Post studies about SSI, including that carried out by Edward and Dimitris (2008), Spyrakos (2009), Anestis (1974), have shown that SSI significantly modified the dynamic characteristics of a structure, including frequencies, damping and mode shapes, etc. So, the performance of the VDs which is closely related with the structural dynamic characteristics will surely be affected by SSI effect. If SSI is neglected, the VDs might be improperly applied to a structure due to overestimation of the structural response or the control effectiveness of the viscous energy dissipation system (VES). Therefore, it is very important and of great urgency to carry out the research on the performance of the VES with SSI effect.

In this paper, a single span framework with 7 stories being chosen as a sample, the seismic response of the soil-viscous damped structure system is investigated with the finite element method. The emphasis of the study is placed on the law of the VES control effectiveness varying with the soil characteristics. The mechanism of the SSI effect on the performance of the VES is also discussed.

2. GENERAL DESCRIPTION

The structure that serves as the basis of this paper is a reinforced concrete frame with seven stories and the dimensions as shown in Fig.2.1. It is designed according to Chinese code for seismic design of buildings, and assumed to be built on four types of foundation such as rigid foundation, hard soil, medium soil and soft soil. Indeed, structures built on rigid foundation are equivalent with that with a fixed base. And the aforementioned three kinds of flexible foundation are classified by the shear-wave velocity, v_s, which is given as Eqn. 2.1.

$$v_s = aH^b \tag{2.1}$$

Where H denotes the depth of soil, a and b are two parameters related to the soil behavior. With reference to the work of Cen (2007), b is assigned to 0.3, while a is specified to be 160, 120 and 80 for hard soil, medium soil and soft soil respectively.

In the analysis, two different models of the superstructure were considered for each ground conditions: moment-resisting frame model (MRF) and moment-resisting frame model retrofitted with viscous energy dissipation devices (VF). For VF, the viscous dampers adopted have a damping coefficient of 1000 (kN s/m), are arranged following the scheme as shown in Fig.2.1, and are connected to the frame through chevron braces.

3. BUILDING MODELS

ANSYS code is frequently utilized for studying SSI systems, such as Christopher (2002), Livaoglu (2007), Leonardo (2007). So, it is adopted in this study. The soil-structure interaction FE model developed in the analysis is shown in Fig.3.1.

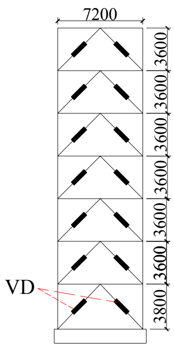

Figure 2.1. MRF retrofitted with VD

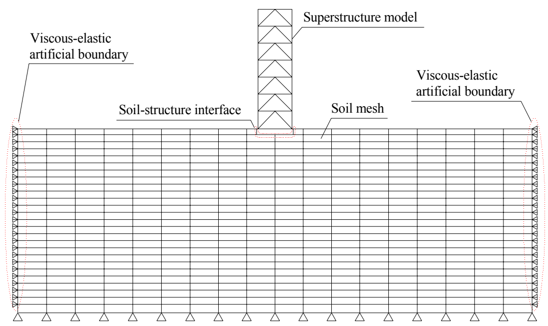

Figure 3.1. Soil-structure interaction model

3.1. Superstructure

Columns and beams of the frame are modeled with the 2D beam element--BEAM 3, while the base is simulated by the 2D solid element--PLANE 42. The material parameters of the structural elements are summarized in Table 3.1. In real structures, the structural beams support gravity loads that transmitted from the floors. On this consideration, an added mass per unit length of 7200kg/m is specified to the elements which model the beams. Furthermore, viscous energy dissipation devices applied to VF are modeled by the spring-damper element--COMBIN14, whose stiffness constant and linear damping coefficient are appointed to be 0 and 1e6 N·s/m respectively.

Table 3.1. Material parameters of structural components

Material parameters	Base	Column		Beam
		Bottom columns	The other columns	
Density（kg/m^3）	2500	2500	2500	2500
Elastic modulus （Gpa）	36.0	34.8	33.8	30.2
Poisson ratio	0.2	0.2	0.2	0.2

3.2. Soil Layer

The soil zone of 109.2m in width and 39m in depth, as shown in Fig.3.1, is meshed with the 2-D structural solid element--PLANE 42. The height of the mesh is taken as 1.5m, which is dependent on the maximum frequency of the input seismic waves and the shear-wave velocity of the soils. And the viscous-elastic artificial boundary suggested by Liu (2006) was adopted to model the radiation of waves from the finite element mesh into the far field. For the soil's constitutive relation, the equivalent linear dynamic viscous-elastic model developed by Cen (2007) is adopted to reflect the dynamic characteristic of the soils. It is described as Eqn. 3.1 and Eqn. 3.2.

$$G / G_{\max} = 1 - \{(\gamma_a / \gamma_0)^{2B} / [1 + (\gamma_a / \gamma_0)^{2B}]\}^A \tag{3.1}$$

$$\lambda = \lambda_0 (1 - G / G_{\max})^{\beta} \tag{3.2}$$

Where G and λ are the dynamic shear modulus and the dynamic damping ratio of soil respectively; A, B, γ_0, β are the experimental parameters for evaluating soil indexes; G_{max}, γ_a, λ_0 denotes, the maximum shear modulus, the strain amplitude, the maximum damping ratio of soil, respectively. With reference to the work of Cen (2007), A, B, γ_0, β and λ_0 are assigned to 1.375, 0.413, 4.0e-4, 0.874, 0.2 in sequence, while Gmax is obtain as Eqn. 3.3.

$$G_{\max} = \rho_s v_s^2 \tag{3.3}$$

Where ρ_s denotes the density of soil and is specified to be 2e3 kg/m^3. v_s is the shear-wave velocity of soil and calculated according to Eqn. 2.1.

3.3. Soil-Structure Interfaces

The structure and the soil are in contact on the surfaces of structural base. As the structural base is much stiffer than the soil, the base-to-soil contact problem may be assumed to be rigid-to-flexible contact. In the ANSYS modeling, contact element pair composed of TARGE169 and CONTA171 are adopted to capture the opening condition and frictional sliding that may take place in the base-to-soil interface during the seismic events. And the interface coefficient of friction is specified to be 0.2.

3.4. Damping of SSI Systems

Accounting for great difference between the damping characteristic of the soil and the structure, material dependent damping is applied in the SSI model. For the above method, the form of the damping matrix, [C], is given as Eqn. 3.4.

$$[C] = \sum \mu_j [K_j] \tag{3.4}$$

Where [K_j] is the portion of structure stiffness matrix based on material j. μ_j denotes the stiffness matrix multiplier for material j and can be obtain as Eqn. 3.5.

$$\mu_j = 2\xi_j / \omega_0 \tag{3.5}$$

Where ξ_j and ω_0 are respectively the damping ratio of material j and the circular natural frequency of structure. According to the work of Guo (2007), ω_0 are taken as the fundamental circular frequency of the SSI system. The damping ratios of the soil layer and the superstructure are assigned to 0.15 and 0.05, respectively.

4. GROUND MOTIONS

Three different seismic waves such as the N-S component of the El Centro Earthquake, the E-W component of the Taft Earthquake and an artificial wave (denoted as ARW) were used as the input motion and applied in the horizontal direction. The acceleration time history of the ARW and its corresponding Fourier spectrum are shown in Fig. 4.1 and Fig. 4.2 respectively. The peak values of acceleration of these waves are modified according to the method adopted by Zai (1997) and as follows: for structures with a fixed base, the values are adjusted to be equal to 0.2g, while for SSI systems, they are adjusted to make the peak acceleration response of the base bottom be equal to 0.2g.

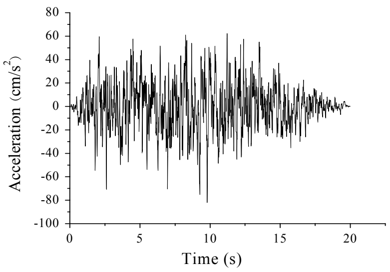

Figure 4.1. Time history of the ARW

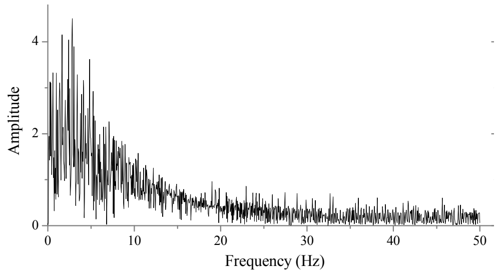

Figure 4.2. Fourier spectrum of the ARW

5. RESULTS AND DISCUSSIONS

Twenty four analysis cases with different combinations of superstructure model, ground condition, and earthquake wave excitation, are carried out to study the influence of SSI effect on the seismic reduction effectiveness of the VES. To compare the seismic response of the frames with and without the energy dissipation systems, a control effectiveness factor, α, is defined as Eqn. 5.1.

$$\alpha = (c - c^{`}) / c \qquad (5.1)$$

Where c and c` are the absolute values of the seismic peak response of the frame without and with energy dissipation devices respectively. They can refer to any parameter characterizing seismic responses of frame. In this paper, the horizontal displacement at the frame top and the story drift were examined.

In the following discussions, the maximum horizontal displacement at the top of the frame and the corresponding control effectiveness of the VES are denoted as D_{max} and α_D respectively. While the maximum story drift of any inter-storey and the corresponding control effectiveness are respectively denoted as $[S_{max}]_i$ and $[\alpha_S]_i$ with the subscript i being the storey-number. An additional explanation is necessary here: from bottom to top, the structural stories are in sequence numbered 1, 2, … , 7.

5.1. Influence of SSI effect on the performance of the VES

All D_{max} for each aforementioned analysis case are provided in Table 5.1. It shows that, under the same seismic wave input, (1) D_{max} of the MRF is decreased by considering the SSI effect. This result agrees well with many previous studies such as that conducted by Zai (1997) and Liua (2008), indicating that the proposed FE models can reasonably reflect soil characteristics. (2) D_{max} of the VF built on hard or medium soil site is less than that of the VF with a fixed base. Such phenomenon stimulates the idea that when VDs are used to prevent the structure on the hard or medium soil site against earthquake, the seismic goal may be gained with fewer dampers if the SSI effect is taken into account. (3) D_{max} of the VF-soft soil system are usually greater than that of the VF-rigid foundation system, which implies that the VES designed with the rigid foundation hypothesis may fail to achieve the prospective control objective when they are applied to the buildings located on the soft soil site in practical engineering.

Table 5.1. D_{max} of MRF and VF for various ground conditions and seismic wave excitations (cm)

Ground conditions	MRF			VF		
	El Centro	Taft	ARW	El Centro	Taft	ARW
Rigid foundation	12.4	24.8	19.8	6.6	9.1	7.6
Hard soil	8.1	18.8	15.1	4.9	7.4	7.0
Medium soil	6.1	16.8	13.9	4.0	7.9	7.3
Soft soil	10.4	13.9	17.5	8.6	9.0	11.3

Fig.5.1 shows the relationships between α_D and soil types. The diagram reveals that (1) the VES can make certain contribution to reducing the structural displacement response regardless of ground conditions and seismic wave inputs; (2) the control efficiency of the VES is decreased by considering SSI effect, and the extent of the efficiency reduced will be increased as the soil becomes softer.

Denoting the average value of $[\alpha_S]_i$ under the excitation of the three above-mentioned seismic waves as $[\alpha_S]_{iave}$, the relation curves of $[\alpha_S]_{iave}$ and i for each ground condition are provided in Fig. 5.2. It is illustrated that, the reduction of each storey drift contributing to VES are nearly consistent along the height of the building. Furthermore, the effectiveness of VES in controlling the storey drift decreases significantly due to SSI effect, and the softer the soil is, the worse the control efficiency of the VES is.

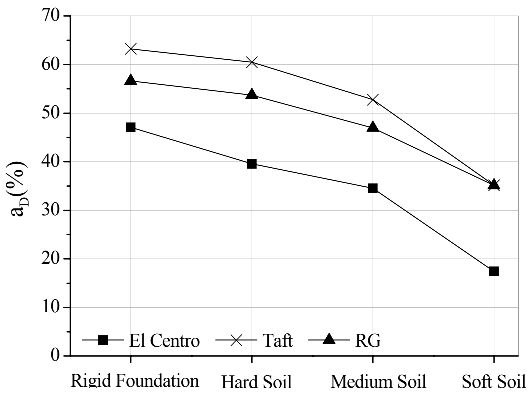

Figure 5.1. Relation curves of α_D versus soil type

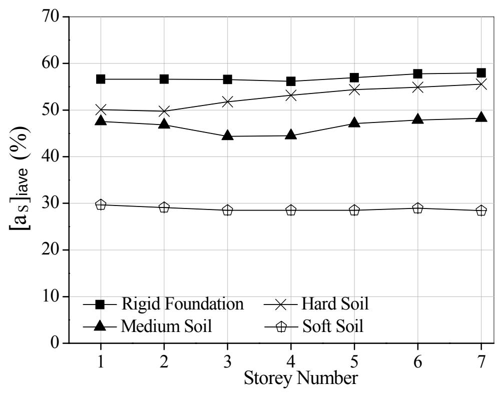

Figure 5.2. Storey drift reduction of each inter-story

5.2. Mechanism of SSI effect influencing the performance of VES

The first free natural vibration frequencies, f_j (j =1, 2, 3), of MRF with varying ground conditions are given in Table 5.2. It is evident that stiffer foundation corresponds to greater value of f_j. This result agrees well with the testing data obtain by Lou (2004). Generically, a frame with smaller value of f means that it vibrates more slowly during an earthquake which results in lower exaction frequency for the VDs placed in it. And post studies conducted by Zhou (2006) about VDs show that under the same excitation amplitude, the energy dissipation effect of such dampers gets worse as the excitation frequency reduces. Consequently, with the foundation of VF becoming softer, the VES displays less effective performance.

To illustrate the above statement, the hysteretic response of the VD installed in the bottom inter-storey is taken as an example in the analysis. Figure.5.3 provides the load-displacement hysteretic curves of the aforesaid VD for the VF locating on different soil sites and excited by the ARW. It can be seen obviously from the figure that along with the foundation softening, the hysteretic loops become sparser and flatter. This implies that the energy dissipation effect of the VD gets poorer. Hence, according to the order of rigid foundation--hard soil--medium soil--soft soil, the control effectiveness of the VES gradually decreases.

Table 5.2. The natural vibration frequency of the MRF with various ground conditions (Hz)

No. of the vibrantion mode	Ground conditions			
	Rigid foundation	Hard soil	Medium soil	Soft soil
1st vibrantion mode	0.60	0.58	0.56	0.53
2nd vibrantion mode	1.89	1.87	1.63	1.05
3rd vibrantion mode	3.44	2.44	1.88	1.58

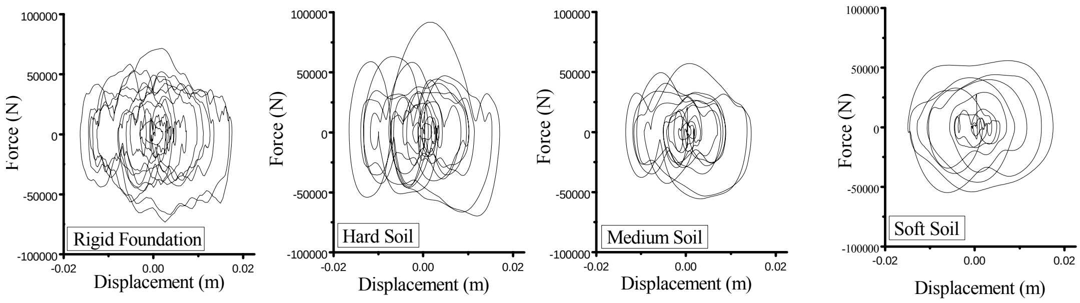

Figure 5.3. Hysteretic loops of the viscous damper installed in the bottom inter-storey

5. RESULTS AND DISCUSSIONS

(1)The seismic response of the VF is obviously affected by SSI effects. The VES designed with the rigid foundation hypothesis may fail to achieve the prospective control objective when they are actually applied to buildings located on soft soil site.

(2) The control efficiency of VES is decreased by SSI effect, and the extent of the efficiency reduced will be increased as the soil becomes softer.

(3) The main reason for the above phenomena is that the vibration frequency of the structure during the seismic motions gets lower along with the foundation softens.

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