The influence of soil-structure interaction on damage spectra of passive energy dissipating structures

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SUMMARY:
The influence of soil-structure interaction (SSI) on damage spectra of passive energy dissipating structures is investigated under seismic loading. A systematic lumped-parameter model is used to modeled the dynamic behaviour of the soil. The passive energy dissipation devices are assumed to be viscous type. The structure is modeled as a single degree of freedom system which is based on the bilinear model. The system is then subjected to two different earthquake ground motions as the representative motion recorded on different soil conditions. The results are presented in the form of damage spectra of the key parameters variations. For building systems without energy dissipation devices, the SSI substantially increases the damage index of short-period buildings. However, the SSI decreases the damage index of long-period buildings. For the structures with passive energy dissipation devices, especially for the structures with high damping, SSI gradually increases the damage index of short-period and long-period buildings. Therefore, SSI has more influence on structures with passive energy dissipation devices than on structures without the devices.

Key words: Soil-structure interaction, Passive energy dissipating structures, Damage index, Damage spectra, Takeda hysteretic model

1. GENERAL INSTRUCTIONS

Passive energy dissipation is an emerging new technology that may be used to enhance the seismic performance of buildings by adding extra damping (and in some cases strength and/or stiffness) to the structure. In recent years, tremendous efforts have been undertaken to develop the concept of passive energy dissipation or supplemental damping into a workable technology and a large number of passive energy dissipation devices has been developed and tested. Broadly speaking, these can be classified as metallic-yielding, friction, viscous and viscoelastic. Excellent reviews of previous experimental and analytical studies are provided (Zhang and Soong 1992; Skinner et al. 1980; Aiken and Kelly 1992; Soong 1997; Soong 2002; Nakashima 1996; Bergman 1993; Shen et al. 1995).

Since 1990s, performance-based seismic design theory has received wide attention by researchers from various countries and has been carried out extensive studies. To have a better judgment and screening on the structure performance, there is a need for reliable building evaluation techniques and a damage index with the ability of predicting the level of damage in the structure under design earthquake. A number of damage index models were defined by different researchers (Powell and Allahabadi 1988; Chai et al. 1995; Iwan 1997; Park et al. 1987; Fajfar 1994). A notable exception is the study by Park and Ang who developed a simple damage index (Park and Ang 1985). The Park and Ang damage index (PADI) measure includes not only the maximum response but the effect of repeated cyclic loading as well.

It is well known that energy dissipating devices have been used in recent years to control structural response and reduce seismic damage index. However, this damage spectra is always computes for fix-based passive energy dissipating structural models. This means that the influence of the soil-structure interaction (SSI) on damage spectra of passive energy dissipating structures is disregarded. Therefore, it is expected that the passive energy dissipating structures experiences different values of damage when the effect of the SSI is taken into account. In this research, the influence of SSI on damage spectra of passive energy dissipating structures is investigated parametrically under seismic loading. A systematic lumped- parameter model is used to modeled the dynamic behaviour of the foundation sitting on soil. The passive energy dissipation devices are assumed to be viscous type. The structure is modeled as a single degree of freedom (SDOF) system which is based on the bilinear model.

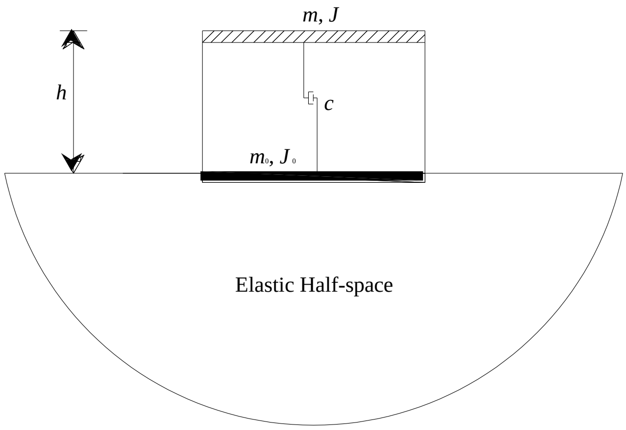


Figure 1. Structure-foundation-soil system

2. SOIL-STRUCTURE MODEL

To consider SSI effects, the analysis should be extended from the structure to include the total structure-foundation-soil system (Figure 1). The substructure method, in which the discrete superstructure and the unbounded continuous soil are separately modelled, is commonly adopted in the SSI analysis to take advantage of the appropriate formulations for the respective subsystems.

2.1 Description of energy dissipating structure model

The structure is modeled as a Bilinear-SDOF system with 2% strain hardening ratio and the same period T_{fix} and the critical damping ratio ξ_b for fundamental mode of the fixed-base structure. In the Figure 1, m is the effective mass for the first mode of the fixed-base structure, J is the structural mass moment of inertia, m_0 is the foundation mass , J_0 is the foundation mass moment of inertia. When the energy dissipation devices are added on the structure, their contribution are expressed in the form of damping coefficient *C*. For structure systems without energy dissipation devices, *C* equals 0.

In this study, viscous dampers are used for providing damping to the structure systems. Without considering additional stiffness provided by the viscous dampers, the critical damping ratio ξ_v for fundamental mode of the fixed-base structure provided by the viscous dampers can be calculated through the damping coefficient *C*. It can be expressed as follows:

$$\xi_v = \frac{CT_{fix}}{4m\pi} \tag{1}$$

The total equivalent damping ratio of ξ_{eq} the fixed-base structure equipped with energy dissipation devices is:

$$\xi_{eq} = \xi_b + \xi_v \tag{2}$$

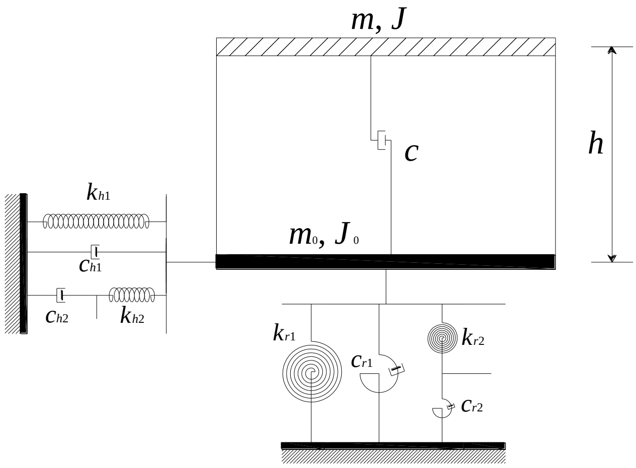


Figure 2. Discrete element model of structure-foundation-soil system

2.2 Description of the soil model

A simple way to incorporate SSI in seismic analysis is to model the stiffness and the damping of the soil around the foundation by using the impedance function (the ratio of the amplitude of the applied load to the resulting displacement). The impedance function is frequency dependent. For the simplification in application, the lumped-parameter model with frequency-independence is commonly adopted to represent the impedance functions in the frequency domain. The advantage of the lumped-parameter model with frequency-independence is that it can be directly applied to the linear/nonlinear dynamic analysis of structures in the time domain.

In this study, systematic lumped-parameter models are developed for efficiently representing the dynamic behaviour of unbounded soil (Wu and Lee 2002). For the case of surface circular foundations, the discrete element model illustrated in Figure 2 is suggested. In addition to a spring with a coefficient k_{l1} (l=h, r) and a dashpot with a coefficient c_{l1}, this model connects in parallel with another element consisting of a spring with a coefficient k_{l2} (l=h, r) and a dashpot with a coefficient c_{l2} combined in series. Ignoring the slight effects of vertical and torsional motions, the dynamic coefficient of springs and dashpots for the horizontal and rocking motions are evaluated using the following formula, respectively (Wu and Lee 2002).

$$k_{h1}=\gamma_{h1}K_{sh}\ ,\quad k_{h2}=\gamma_{h2}K_{sh}\ ,\quad c_{h1}=\frac{\delta_{h1}d}{v_s}K_{sh}\ ,\quad c_{h2}=\frac{\delta_{h2}d}{v_s}K_{sh} \tag{3a}$$

$$k_{r1}=\gamma_{r1}K_{sr}\ ,\quad k_{r2}=\gamma_{r2}K_{sr}\ ,\quad c_{r2}=\frac{\delta_{r1}d}{v_s}K_{sr}\ ,\quad c_{r2}=\frac{\delta_{r1}d}{v_s}K_{sr} \tag{3b}$$

Where γ_{h1} and γ_{h2} are the dynamic coefficients of springs for the horizontal motions, andδ_{h1} andδ_{h2} are the dynamic coefficients of dashpots for the horizontal motions, andγ_{r1} andγ_{r2} are the dynamic coefficients of springs for the rocking motions, and δ_{r1} and δ_{r2} are the dynamic coefficients of dashpots for the rocking motions. These optimal dynamic coefficients are also displayed in table 1 for the soil with Poisson's ratio$v$=1/3. V_s is the shear wave velocity of soil and d is the characteristic length of the foundation (e.g., the radius of a circular foundation). In equation (3), K_{sh} and K_{sr} represents the static horizontal and rocking stiffness of the foundation, respectively. These are evaluated using the following formula, respectively (Wu and Lee 2002).

$$K_{sh}=\frac{8Gd}{2-\upsilon}\qquad K_{sr}=\frac{8Gd^3}{3(1-\upsilon} \tag{4}$$

in which, G and$v$are the shear modulus and Poisson's ratio of the soil, respectively.

Table 1 The dynamic coefficient of springs and dashpots of the systematic lumped-parameter models (surface circular foundations, v=1/3) (Wu and Lee 2002)

Horizontal				Rocking			
γ_{h1}	γ_{h2}	δ_{h1}	δ_{h2}	γ_{r1}	γ_{r2}	δ_{r1}	δ_{r2}
1	-0.178	1	-0.0633	1	-0.6106	0.3917	-0.3990

2.3 Parameters of the model

The parameters of the Soil-structure model that were studied as part of this investigation are:

(1) The period of vibration of the fixed-base structure T_{fix}.

(2) The damping ratio provided by the viscous dampers ξ_v.

(3) The shear wave velocity of soil V_s.

(4) The target ductility in the fixed-base state μ_{fix}.

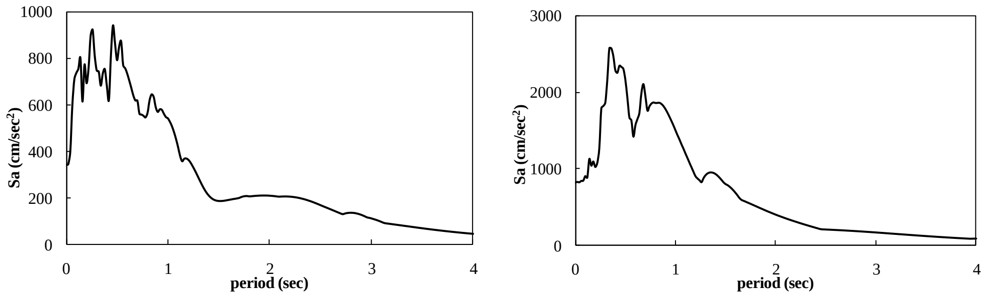
(5) Structure height to foundation half width $2h/d$.

(6) Foundation to structure mass ratio m_0/m.
(7) The critical damping ratio of the fixed-base structure ξ_b.
(8) Poisson's ratio of soil v.
The ranges of the first four parameters considered for each of these variables are shown in Table 2. The other parameters may be set to typical values for ordinary buildings. The structure height to foundation half width $2h/d$ is assigned 6. The foundation to structure mass ratio m_0/m is assigned 0.2. The critical damping ratio of the fixed-base structure ξ_b is considered to be 5%. The Poisson's ratio of soil v is considered to be 1/3.

Table 2 Parameters for the inelastic analysis

Parameters	Values
T_{fix}	Range from 0.05 to 4s
ξ_v	0, 5%, 15%, 20%
V_s	100m/s, , 200m/s, 300m/s
μ_{fix}	3, 6

Two earthquake ground motions were selected as representative of motions: (1)*EI Centro*. The N-S component recorded at the Imperial Valley Irrigation District substation in El Centro, California, during the Imperial Valley, California earthquake of May 18, 1940. (2) *Kobe*. The N-S component recorded at the Kobe Japanese Meteorological Agency (JMA) station during the Hyogo-ken Nanbu earthquake of January 17, 1995. The 5% damped linear elastic response spectra of the two motions are shown in Figure 3.



(a) EI Centro (b) Kobe

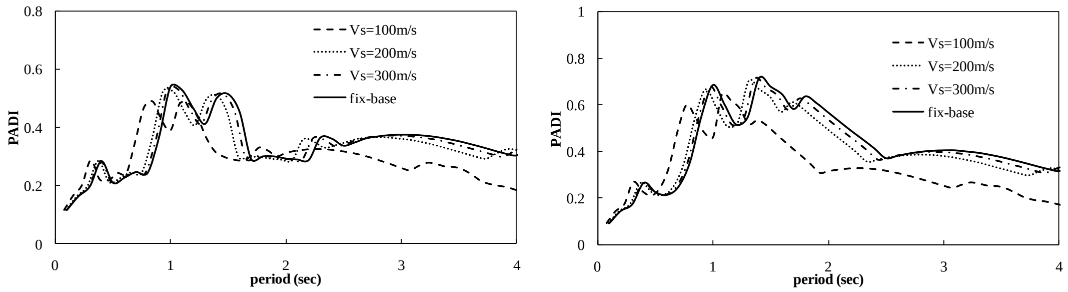
Figure 3: The 5% damped linear elastic response spectra

3. PARK & ANG DAMAGE INDEX (PADI) AND DAMAGE SPECTRA

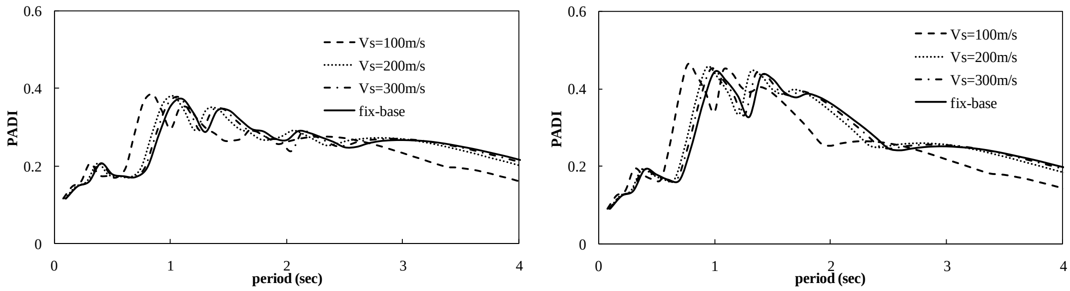
Damage indexes are based on either a single or combination of structural response parameters. A notable exception is the study by Park and Ang who developed a simple damage index (Park and Ang 1985), given as

$$PADI = \frac{x_{\max}}{x_u} + \beta \frac{E_H}{f_y x_u} \tag{5}$$

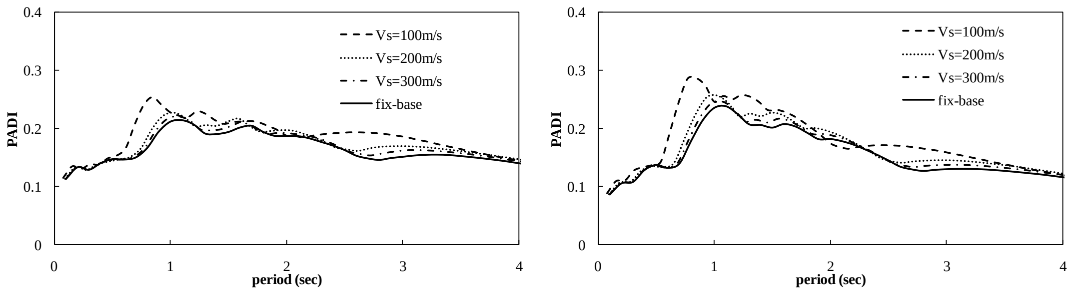
Here $x_{\max}$ and E_H are maximum displacement and dissipated hysteretic energy under the earthquake. PADI measure includes not only the maximum response but the effect of repeated cyclic loading as well. x_u is the ultimate deformation capacity under monotonic loading. β is a positive constant that weights the effect of cyclic loading on structural damage and is set equal to 0.2 as suggested by Bertero (Bertero and Bertero 2002).Damage spectrum represents the variation of the damage index versus the structural period for a series of SDOF systems subjected to a ground motion record.



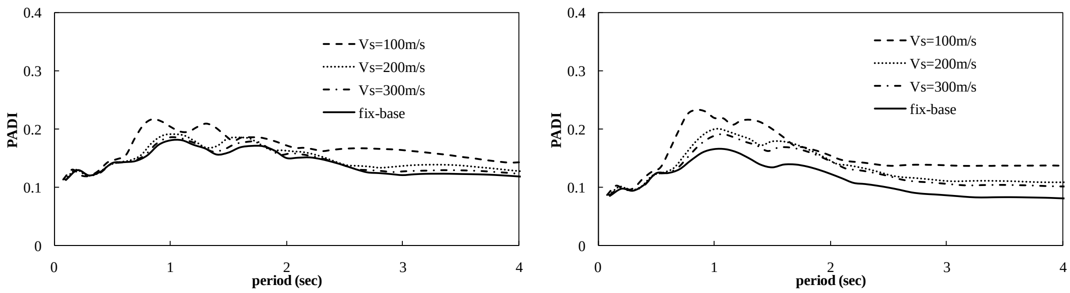
(a) $\xi_v = 0$



(b) $\xi_v = 5\%$

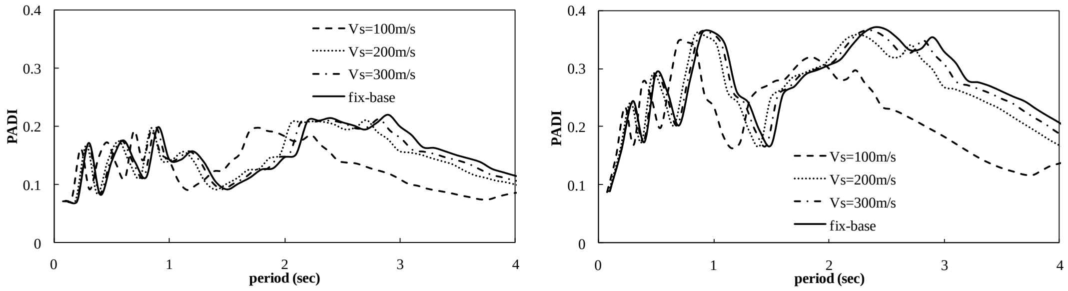


(c) $\xi_v = 15\%$

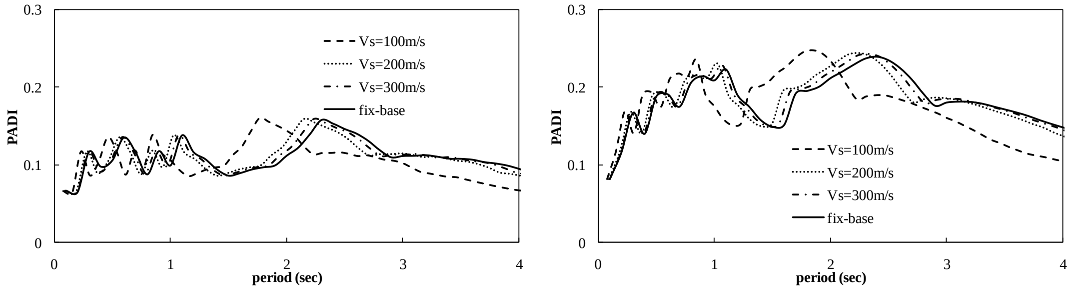


(d) $\xi_v = 20\%$

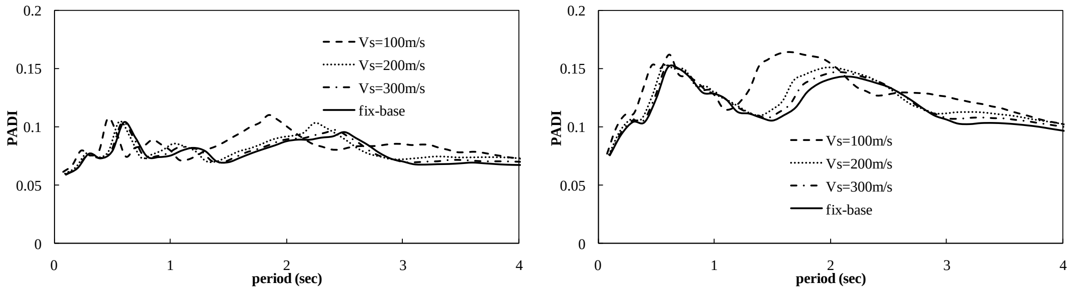
Figure 4: Effect of SSI on PADI spectra under the Kobe earthquake for $\mu_{fix} = 3$ (left) and $\mu_{fix} = 6$ (right).



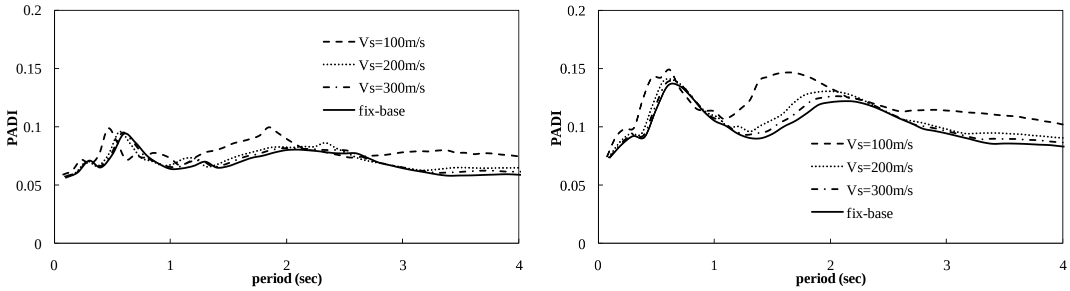
(a) $\xi_v = 0$



(b) $\xi_v = 5\%$



(c) $\xi_v = 15\%$



(d) $\xi_v = 20\%$

Figure 5: Effect of SSI on PADI spectra under the EI Centro earthquake for $\mu_{fix} = 3$ (left) and $\mu_{fix} = 6$ (right).

4. ANALYSIS OF RESULTS

The analysis is done directly in time domain by direct step-by-step integration, using Newmark-β method. The results are presented in the form of damage spectra of parameters variations. The yield strength considered for a building located on soil is taken equal o the yield strength that the corresponding fixed-base building would have to reach the predetermined target ductility due to the earthquake record. In this section the effect of SSI on the damage spectra of energy dissipation devices in increasing the damping ratio of the building systems is investigated.

Figure 4 shows the damage spectra for the Kobe ground motion for four different amounts of the damping ratio ξ_v provided by the viscous dampers: 0, 5%, 15%, 20% damping ratio are compared. The graphs in the left and right of each figure are respectively for μ_{fix} values of 3 and 6 with the values of varying from 100m/s to 300m/s. The horizontal axis displays the period of the fixed-base building. For building systems without energy dissipation devices, it can be seen from Figure 4(a) that the shift gradually towards up and left. The damage spectra in Figure 4(a) imply that when the shear wave velocity of soil V_s decreases, the SSI substantially increases the damage index of short-period buildings. However, the damage index of long-period buildings decreases with the decrease of the shear wave velocity of soil V_s.

For building systems with energy dissipation devices, especially for the structures with high damping, it is show in Figure 4(b) to Figure 4(d) that the damage index of buildings substantially decreases with the increase of the damping ratio ξ_v. It can be seen from Figure Figure 4(b) to Figure 4(d) that the SSI gradually increases the damage index of short-period and long-period buildings with the increase of the damping ratio ξ_v. The reason is mainly related to the reduction effect of the energy dissipating structure. In fact, the SSI has influence on the behavior of energy dissipating structure.

Comparing the spectra in the left and right side of Figure 2 gives an insight into the effect of the target ductility in the fixed-base state μ_{fix} values of 3 and 6. The main difference is that the amplitudes of the spectra are larger in μ_{fix} values of 6.

Figure 5 displays the damage spectra for the EI Centro ground motion for four different amounts of the damping ratio ξ_v provided by the viscous dampers: 0, 5%, 15%, 20% damping ratio are compared, respectively. It can be seen that Figure 5 display the same features as Figure 4. For building systems without energy dissipation devices, the damage spectra in Figure 5(a) implies that when the shear wave velocity of soil V_s decreases, the SSI substantially increases the damage index of short-period buildings. However, the damage index of long-period buildings decreases with the decrease of the shear wave velocity of soil V_s. It can be seen that the SSI gradually increases the damage index of short-period and long-period buildings with the increase of the damping ratio ξ_v.

5. CONCLUSIONS

The influence of soil-structure interaction (SSI) on damage spectra of passive energy dissipating structures is investigated under seismic loading. The well-known model of Park and Ang was selected for damage estimation. A systematic lumped-parameter model is used to modeled the dynamic behaviour of the foundation sitting on soil. The passive energy dissipation devices are assumed to be viscous type. The structure is modeled as a single degree of freedom (SDOF) system which is based on the bilinear model. The results are presented in the form of damage spectra of parameters variations. For building systems without energy dissipation devices, it is found that when the shear wave velocity of soil V_s decreases, the SSI substantially increases the damage index of short-period buildings. However, the damage index of long-period buildings decreases with the decrease of the shear wave velocity of soil V_s. For the structures with passive energy dissipation devices, especially for the structures with high damping, SSI gradually increases the damage index of short-period and long-period buildings. Therefore, SSI has more influence on structures with passive energy dissipation devices than on structures without the devices.

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