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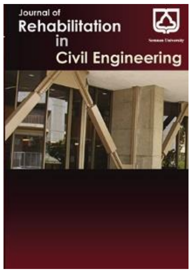

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Active Structural Control by Backstepping Design Considering Soil-Structure Interaction Effects

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ABSTRACT

Considering the dependency of control algorithms to the structural dynamic properties that are affected by soil structure interactions (SSI), the investigation of SSI effect on different control methods has gained great importance. Backstepping design as a recursive lyapanov-based method is one of the powerful active control approaches. However, the effect of soil structure interaction on it has not yet been investigated. This paper studies the performance of backstepping design on mitigating the seismic response of a building structure subjected to base excitations, considering the SSI effect. For this purpose, the SSI model equations were entered in the control algorithm and various shear wave velocities were considered to demonstrate the performance of backstepping control design on soft and stiff soil. According to the numerical results, for structures rested on stiff soil, the variations in the responses of controlled structure caused by SSI is negligible. However, in the case of soft soil, SSI effects cause noticeable changes in dynamic responses of controlled structure that cannot be ignored.

1. Introduction

Structural control with the aim of vibration suppression of buildings subjected to severe lateral dynamic loads such as earthquake and wind has gained great attention in the recent investigations. During the last few decades, various control approaches including active, passive, semi-active and hybrid ones [1–3] have been developed to improve structural performance in terms of serviceability and safety. In active control, the response of structures is mitigated through a set of control forces supplied from external energy sources. This control strategy as a promising approach, with some advantages such as

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enhanced performance in motion reduction and applicability for a wide range of frequencies, has devoted considerable attention [4].

Supporting conditions such as fixed base and soil structure interaction (SSI) significantly affect the seismic behavior of the control systems. The SSI effect causes variations in dynamic properties of the structure such as natural frequencies, damping ratios and mode shapes [5]. Since the inputs of control algorithms depend on dynamic characteristics of the structure, the SSI effect significantly changes the control design. A considerable part of control studies is devoted to SSI effect due to its importance on control design.

Aydin and Ozturk [6] evaluated the performance of dampers as a way of passive structural control for the soil-structure interaction system and determined their optimum design. Al-Ghazali and Shariatmadar [7] applied a hybrid control system including viscous dampers and fuzzy controller on the adjacent buildings with soil-structure interaction system. Wang and Lin [8] investigated the control performance of multiple tuned mass dampers (MTMDs) for soil-irregular building interaction systems. Following their research, Lin *et al.* [5] applied H_∞ control algorithm on a soil-irregular structure interaction system. Golnargesi *et al.* [9] used fuzzy logic algorithm to control buildings with tuned mass damper considering soil-structure interaction. Amini and Shadlou [10] evaluated the effects of foundation embedment on the control of structures. They studied 48 models and 3 earthquake time series to consider a broad range of SSI effects. They assumed that semi-active control devices are installed on all floors. Lee [11] applied active control method on a soil-retaining structure interaction (SRSI) in order to mitigate dynamic responses. To improve the conventional linear quadratic Gaussian (LQG) controller, they combined it with adaptive input estimation method (AIEM) which is a useful method for online estimation of the input. Luco [12] investigated the effect of soil-structure interaction on seismic base isolation. They used equivalent linearization method to achieve dynamic responses of the system to external excitation. Baratta et al. [13] studied the effectiveness of a hybrid control approach applied on a soil-structure interaction system. In order to strengthen their control algorithm, they coupled an active vibration device with the base isolation devices to make an optimized hybrid control system. Nazarimofrad and Zahrai [14] investigated active structural control of SSI systems with irregularity in plan. They applied control process using active tendons and LQR algorithm on a mathematical model and concluded that in soft soil condition, active tendons are not useful enough for mitigating dynamic responses. Zahrayi [15] also, in another paper, used active tendons to control irregular buildings with soil-structure effect and determined the optimal placement of the tendons. Bekdas and Nigdeli [16] tried to optimize the performance of tuned mass dampers to control the structures with SSI effects. They employed harmony search and bat algorithms to optimize the control design of soil-structure interaction system.

This study employs a recursive lyapunov-based method known as backstepping design which is a well-established systematic method of control design. This method provides actual control input to guarantee the stability of closed-loop system using lyapunov's analysis [17]. For this purpose, the output of the first subsystem is controlled by the use of virtual control, and then step back through each integrator until the actual control input appears in the equation. The main assumption is that the system equations are in the strict feedback form. More details about this methodology can be found in [18,19].

2. Dynamic modelling of the soil-structure interaction system

2.1. Preliminaries

There are two approaches in numerical calculations of soil structure interaction: direct method and substructure method. The difference between these two methods is only limited to the definition of boundary conditions of the bounded soil domain. In the direct method, the artificial boundary is far away from the foundation–soil interface, but in the substructure method, the artificial boundary coincides with the foundation soil interface. Direct method deals with nonlinear characteristics of the soil. However, it is not common to use this method in practice because of large amount of computations required due to its complex modeling with a numerous degrees of freedom [20].

2.2. Problem statement

In this study, substructure method is used to model SSI system in which the structure and soil are separately dealt with. For numerical simulation, a base-isolated structure with SSI effect is presented, which has two degrees of freedom (one for the building and one for the base). In general, base isolated buildings tend to behave as rigid body systems. Consequently, single degree of freedom approximations are useful for simulating their response [21]. Figure.1 shows the model used in the study for considering SSI effect. Eq. (1) represents dynamic equations of the SSI system, based on substructure method.

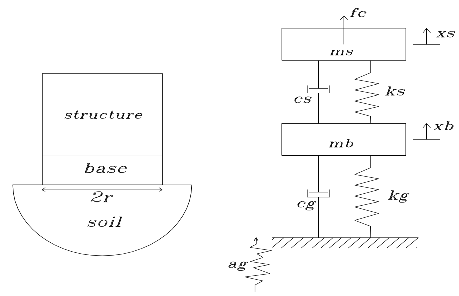


Fig. 1. The model of SSI system based on substructure method.

$$\begin{bmatrix} m_s & 0 \\ 0 & m_b \end{bmatrix}\begin{Bmatrix} \ddot{x}_s \\ \ddot{x}_b \end{Bmatrix}+\begin{bmatrix} c_s & -c_s \\ -c_s & c_s \end{bmatrix}\begin{Bmatrix} \dot{x}_s \\ \dot{x}_b \end{Bmatrix} +\begin{bmatrix} k_s & -k_s \\ -k_s & k_s \end{bmatrix}\begin{Bmatrix} x_s \\ x_b \end{Bmatrix}=-\begin{Bmatrix} m_s\ddot{x}_g \\ m_b\ddot{x}_g \end{Bmatrix}-\begin{Bmatrix} 0 \\ r_b \end{Bmatrix} \quad (1)$$

s and b are related to the structure and base, respectively. x_s and x_b are structural and foundation displacements relative to the ground motion, x_g. r_b is the interaction force applied on the foundation,

$$r_b = c_g\dot{x}_b + k_g x_b \quad (2)$$

c_g and k_g are damping and stiffness coefficients of the soil which are calculated according to the Parmelee's relations based on the exact solution for the circular rigid foundation with an underlying halfspace soil [22]:

$$cg=\frac{6.21}{2.54-\nu}.\rho.V_s.r^2 \text{ , } kg=\frac{6.77}{1.79-\nu}.\rho.V_s^2.r \quad (3)$$

Replacing r_b in Eq.(1), mass, damping and stiffness matrices of SSI system are calculated as follows,

$$\mathbf{M}_{SSI}=\begin{bmatrix} m_s & 0 \\ 0 & m_b \end{bmatrix}$$

$$\mathbf{C}_{SSI}=\begin{bmatrix} c_s & -c_s \\ -c_s & c_s+c_g \end{bmatrix} \quad (4)$$

$$K_{SSI}=\begin{bmatrix} k_s & -k_s \\ -k_s & k_s+k_g \end{bmatrix}$$

In the presence of control force, *u* is added to the right part of Eq. (1) which is *2x1*vector that represents control force. Since it is supposed to apply control force only to the structure, the definition of control force vector will be as Eq. (5),

$$\mathbf{u} = \begin{Bmatrix} f_c \\ 0 \end{Bmatrix} \quad (5)$$

3. Controller design

3.1. Backstepping design

Let's take a look at the equation of motion of the structure. Notice we only have one DOF here:

$$\ddot{x}_s = -\frac{1}{m_s} k_s x_s - \frac{1}{m_s} c_s \dot{x}_s + \frac{1}{m_s} f_c + d \quad (6)$$

Where m_S is mass of the structure, k_S and c_S are stiffness and damping of the structure, respectively. f_c is control force applied on the structure and a_g is considered as ground acceleration. x_s in Eq. (6) is taken as the relative displacement of the structure with respect to the ground. *d* is considered as the external disturbance unknown (unmeasured) to the control designer.

Via a 2-stage standard adaptive backstepping, denote: $\begin{cases} x_1 := x_s \\ x_2 := \dot{x}_s \end{cases}$, the equations of motion can be written in the strict feedback form as below,

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = -\frac{k_s}{m_s} x_1 - \frac{c_s}{m_s} x_2 + \frac{1}{m_s} f_c + d \end{cases} \quad (7)$$

Step 1: Take the first Lyapunov function as $V_1 = \frac{1}{2}\gamma_1 z_1^2$,

Where $z_1 = x_1 - x_r$ and $z_2 = x_2 - \dot{x}_r - \alpha$ are error variables. α is called virtual control which needs to be designed. γ_1 is a positive constant, selected by the designer and x_r is an arbitrary signal we want *x* to act like that, i.e, reference signal. $x_r = 0$, is a usual choice.

$$\dot{V}_1 = \gamma_1 z_1 (z_2 + \alpha) \quad (8)$$

Define $\alpha = -c_1 z_1$, $c_1 \in R^+$ which renders $\dot{V}_1$ negative definite in the absence of z_2.

Step 2: Start by $V_2 = V_1 + \frac{1}{2}\gamma_2 z_2^2$ as the second lyapunov function,

$$\dot{V}_2 = -\gamma_1 c_1 z_1^2 + \gamma_2 z_2 \underbrace{\left(\frac{\gamma_1}{\gamma_2} z_1 - \frac{k_S}{m_s} x_1 - \frac{c_S}{m_s} x_2 + \frac{1}{m_s} f_c + c_1 x_2 + d\right)}_{(*)} \quad (9)$$

Notice that the expression marked by (*) is known, hence they can be eliminated by a proper choice of f_c, but the term *d* is unavailable to the designer. Therefore, till this point we define control force as,

$$f_c = -c_2 m_s z_2 + k_s x_1 + c_s x_2 - \frac{\gamma_1}{\gamma_2} m_s z_1 - c_1 m_s x_2 \quad (10)$$

Here $c_2 \in R^+$ is another design parameter (an arbitrary positive constant), selected by the designer.

Now we need to design an adaptive law and add another term to f_c to compensate the unknown disturbance, "*d*".

Let’s define two new variables, $\hat{d}$ and $\tilde{d}$. $\hat{d}$ is our estimation of actual value of *d* and $\tilde{d} = d - \hat{d}$ is the error of this estimation.

Table 1. Parameters of structure and soil for numerical evaluation.

Structural parameters		soil profile	
m_s(kg)	5000000	ע	0.45
m_b(kg)	5000000	ρ(Kg/m^3)	1500
r(m)	10	Vs(m/s)	70,100,150,200

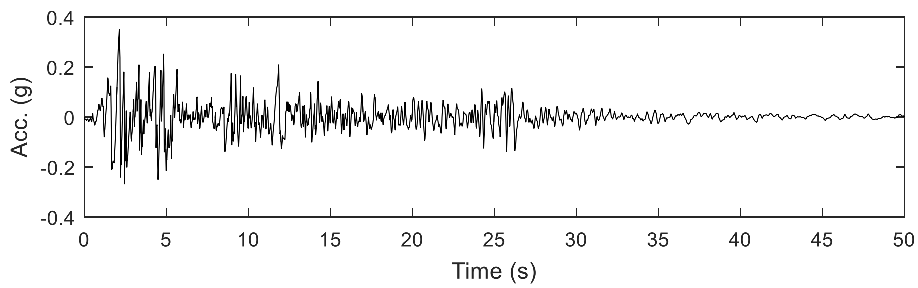


Fig. 2. Ground acceleration time history for Elcentro earthquake.

We update our positive definition for lyapunov function, $V_3 = V_2 + \frac{1}{2}\gamma_3 \tilde{d}^2$. Notice that since $\hat{d} + \tilde{d} = d$, we have

$$\frac{d}{dt}(\hat{d} + \tilde{d}) = 0 \Rightarrow \dot{\hat{d}} = -\dot{\tilde{d}}$$

Hence,

$$\dot{V}_3 = \dot{V}_2 + \gamma_3 \tilde{d}(-\dot{\hat{d}}) \tag{11}$$

Now let's also update our positive definition for control force by including a new term, $\bar{f}_c$, in it. We will design the value of this new term in a way to help us cancel the value of the unknown disturbance, "d".

Now, we have

$$f_c = -c_2 m_s z_2 + k_s x_1 + c_s x_2 - \frac{\gamma_1}{\gamma_2} m_s z_1 + \bar{f}_c - c_1 m_s x_2 \tag{12}$$

Now substitution of all we have in $\dot{V}_3$ yields:

$$\dot{V}_3 = -\gamma_1 c_1 z_1^2 - \gamma_2 c_2 z_2^2 + \gamma_2 z_2 (\hat{d} + \tilde{d} + \frac{\bar{f}_c}{m_s}) + \gamma_3 \tilde{d}(-\dot{\hat{d}}) \tag{13}$$

Rearranging Eq. (13), we have,

$$\dot{V}_3 = -\gamma_1 c_1 z_1^2 - \gamma_2 c_2 z_2^2 + \gamma_3 \tilde{d}\underbrace{(-\dot{\hat{d}} + \frac{\gamma_2}{\gamma_3} z_2)}_{(1)} + \gamma_2 z_2 \underbrace{(\hat{d} + \frac{\bar{f}_c}{m_s})}_{(2)} \tag{14}$$

Notice that $\hat{d}$ is known, now if we define $\dot{\hat{d}} := \frac{\gamma_2}{\gamma_3} z_2$ and $\bar{f}_c := -m_s \hat{d}$ then both bracketed terms, (1) and (2) in Eq. (14) will vanish, which yields $\dot{V}_3 = -\gamma_1 c_1 z_1^2 - \gamma_2 c_2 z_2^2$ that is negative definite. At this point, we can apply La Salle-Yoshizawa theorem to this lyapunov function and the system we are studying. This guarantees the convergence of z_1 and z_2 to zero.

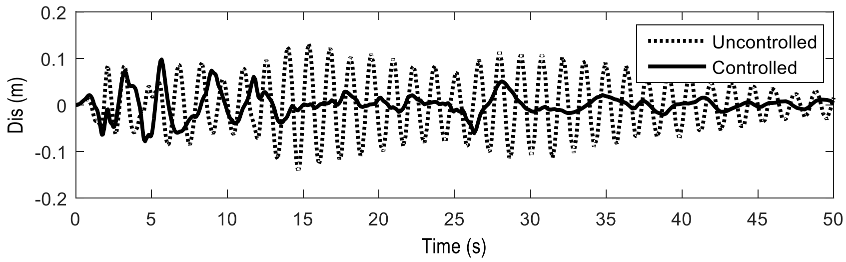
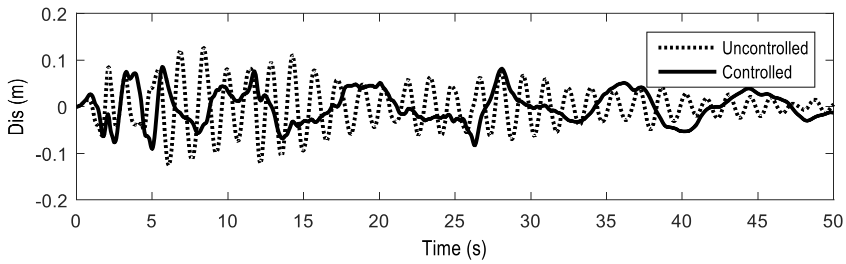


Fig. 3. Uncontrolled and controlled displacement response for fixed-base structure,



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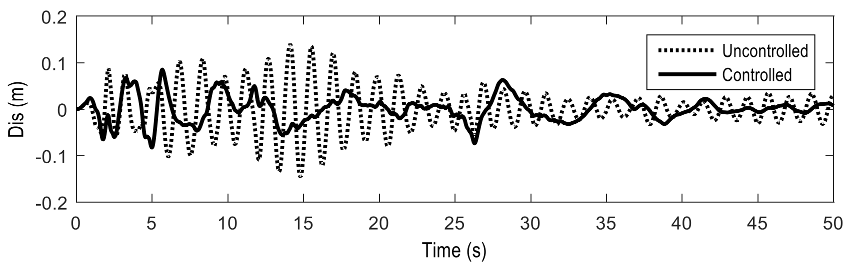

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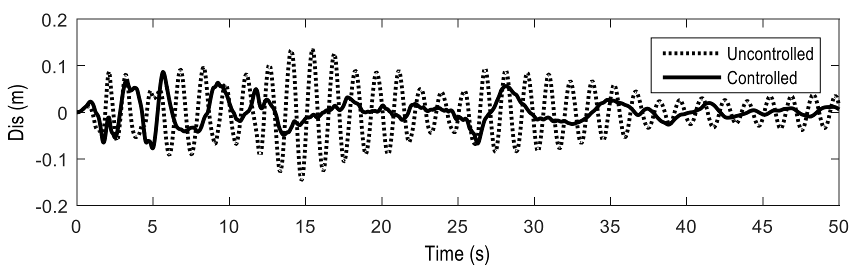

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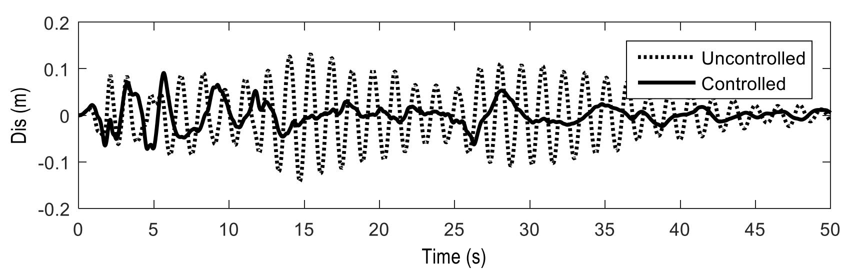


Fig. 4. Uncontrolled and controlled displacement response for SSI system with (a)Vs=70m/s (b)Vs=100m/s (c)Vs=150m/s (d)Vs=200m/s.

$$\begin{cases} z_1 \to 0 \Rightarrow x_1 \to x_r \\ z_2 \to 0 \Rightarrow x_2 \to \dot{x}_r + \alpha \Rightarrow x_2 \to \dot{x}_r - c_1 z_1 \\ \Rightarrow x_2 \to \dot{x}_r \end{cases} \tag{15}$$

In summary, we have:

Control force

$$f_c := -c_2 m_s z_2 + k_s x_1 + c_s x_2 - \frac{\gamma_1}{\gamma_2} m_s z_1 - c_1 m_s x_2 - m_s \hat{d} \tag{16}$$

Adaptive law to find $\hat{d}$

$$\dot{\hat{d}} := \frac{\gamma_2}{\gamma_3} z_2 \tag{17}$$

Where,

$$\begin{cases} z_1 = x_1 - x_r \\ z_2 = x_2 - \dot{x}_r + c_1 (x_1 - x_r) \end{cases} \tag{18}$$

3.2. Implementation of the proposed control

Design for SSI system

As mentioned in problem statement in section 2.2, SSI system has two DOFs. The equation of motion for the whole structure with a single degree of freedom is,

$$\ddot{x}_s = -\frac{1}{m_s} k_s (x_s - x_b) - \frac{1}{m_s} c_s (\dot{x}_s - \dot{x}_b) + \frac{1}{m_s} f_c - a_g \tag{19}$$

x in Equation (19) is taken as the relative displacement with respect to the ground. Indices s and b specify the parameters related to structure and base-isolator, respectively.

Now rewrite Eq. (19) and compare it with Eq. (6). One can conclude that in the SSI system the external disturbance applied to the structure is,

$$d = -a_g + \frac{1}{m_s} (k_s x_b + c_s \dot{x}_b) \tag{20}$$

Notice that structural mass, stiffness and damping, m_s, k_s and c_s, are all known parameters. Following the steps illustrated in section 3.1 and applying adaptive law obtained in Eq. (17), control force is calculated from Eq. (16),which guarantees dynamic responses of the structure, x, act like reference signal, $x_r=0$.

4. Numerical results

To investigate the effect of soil-structure interaction on the backstepping control method, the performance of control design on the SSI system and the system without any soil interaction effect are compared. Numerical example deals with a base-isolated system with the SSI effect, as mentioned in section 2.2. Table 1 shows soil and structural properties. Lateral stiffness of the structure is supposed to be 1e8 (N/m). Structural damping is obtained from Rayleigh damping as,

$$c_s = 0.004 k_s + 0.001 m_s \tag{21}$$

Shear wave velocity (V_s) is a representative of soil condition; the larger the value of shear wave velocity varies, the relatively stiffer the soil becomes. Therefore, to investigate the effect of soil condition on the structural response, four different shear wave velocities are defined (V_s =70,100,150 and 200 m/s) to demonstrate numerical results.

The SSI system is supposed to be excited by Elcentro earthquake with maximum amplitude of 0.35g. Figure. 2 represents the ground motion considered in the study.

The relevant controlled results of displacement for the fixed-base structure and soil-structure interaction system, due to

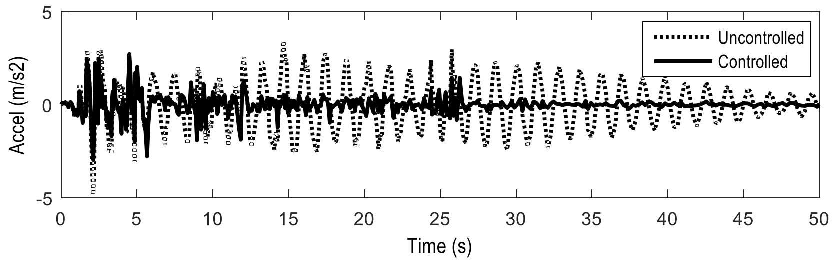
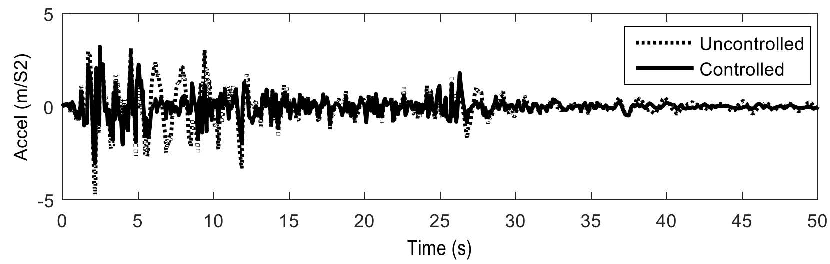


Fig. 5. Uncontrolled and controlled acceleration response for fixed-base structure.



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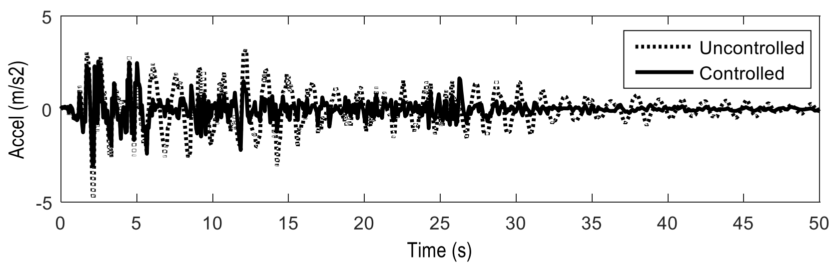

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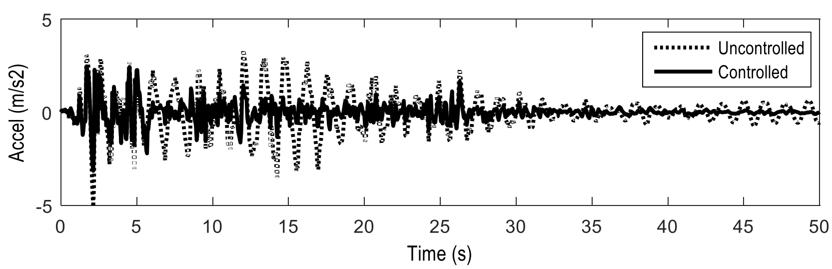

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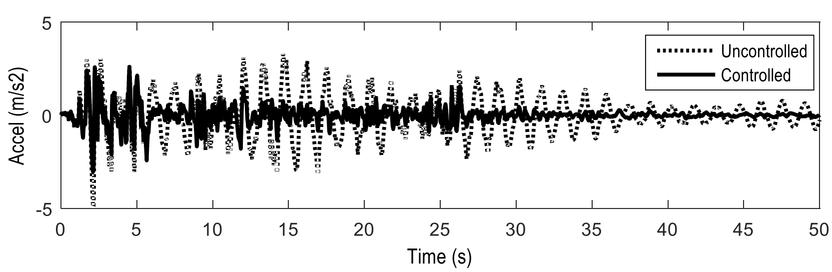


(d)

Fig. 6. Uncontrolled and controlled acceleration response for SSI system with (a)Vs=70m/s (b)Vs=100m/s (c)Vs=150m/s (d)Vs=200m/s.

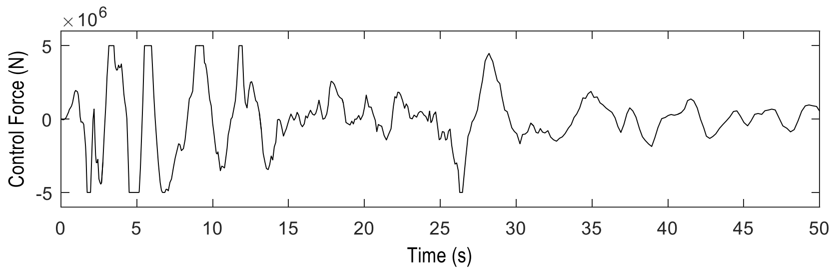
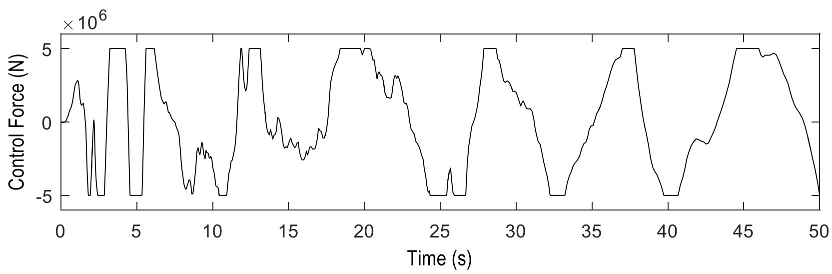


Fig. 7. Control forces for fixed-base structure.



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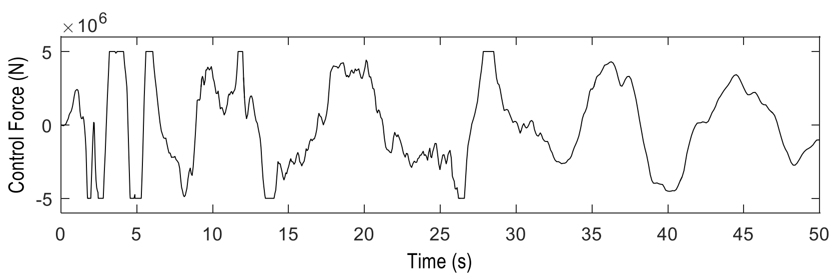

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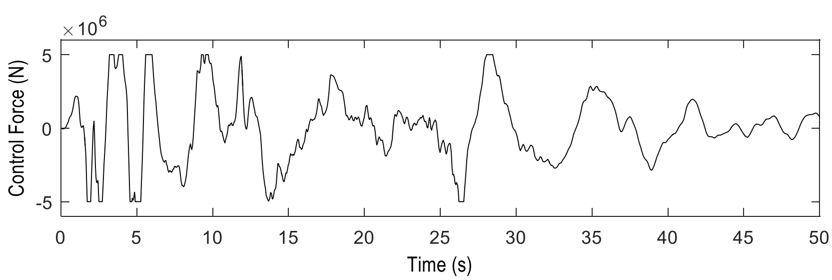

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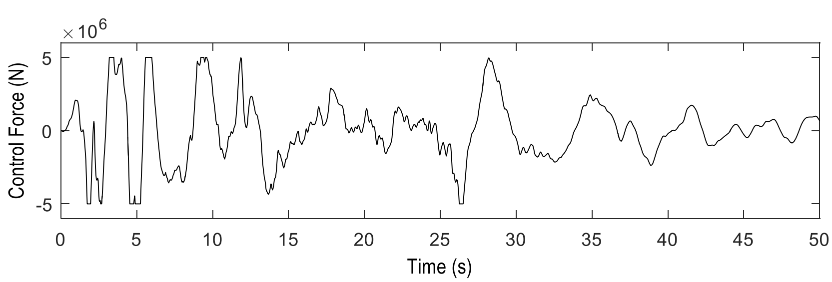

(d)

Fig. 8. Control forces for SSI system with (a)Vs=70m/s (b)Vs=100m/s (c)Vs=150m/s (d)Vs=200m/s.

Elcentro earthquake are compared with the corresponding uncontrolled ones in Figures. 3 and 4. The results of different shear wave velocities (V_s=70,100,150,200 m/s) are shown in Figure. 4.

Figure. 4 demonstrates that for stiffer soil with larger values of shear wave velocity (Vs=200 m/s), the behavior of control system is more similar to the fixed-base structural system. In these systems, displacement responses are approximately the same as fixed-base structure and backstepping control design can reduce values of displacement responses effectively. However, for the soil-structure interaction systems with softer soil, which have lower shear wave velocities (Vs=70,100), backstepping control design is not effective enough in reducing peaks of displacement responses. It is highly recommended to investigate soil condition before using fixed base model for structural control by backstepping design. In soft soil condition, the effect of soil-structure interaction leads to larger peaks of displacement responses for controlled SSI system compared to the uncontrolled one. Therefore, it is necessary to consider soil-structure interaction effect for the SSI system with very soft soil. Figures. 5 and 6 show acceleration responses of controlled and uncontrolled system for fixed-base and soil-structure interaction system with various shear wave velocities due to the different soil conditions.

Similar to displacement responses, as the soil becomes stiffer the control behavior of the SSI system will be more similar to the fixed-base structure. For the SSI system with very soft soil (Vs=70 m/s), the diagrams of acceleration for controlled and uncontrolled structure are approximately the same. Therefore, in SSI system with soft soil, the control design cannot reduce the acceleration responses properly. As the soil becomes stiffer, the performance of backstepping control design is improved.

However, the control results of acceleration responses for SSI system with soft soil are not as bad as displacement responses. It means that soil structure interaction for systems with soft soil has more undesirable effects on displacement responses than the acceleration ones.

To improve economic efficiency of the control design, the amount of control force has been limited to 5E6 N (10 percentage of structural weight). Figures. 7 and 8 represent the corresponding control forces for the fixed-base structure and SSI system with different soil condition.

5. Summary and conclusion

This paper deals with active control of a base-isolated building under earthquake excitation considering the effects of soil structure interaction. A recursive lyapanov-based method known as backstepping design was employed to control the structure. For studying the effect of soil condition on control design, different shear wave velocities (Vs=70,100,150,200m/s) were considered for the soil. The control strategy was applied on the structure with and without SSI effect and the response reduction results were compared. The numerical results showed that the control performance of the structure rested on stiffer soil (Vs=150 and 200m/s) and fixed-base structure are very similar in terms of displacement and acceleration responses. In fact, for relatively stiffer soil, ignoring the effect of soil structure interaction may not cause noticeable change in structural response. However, for the structure rested on soft soil with less shear wave velocity (Vs=70 and 100 m/s), some peaks of displacement responses were intensified after the control process. The control system was also not able to reduce acceleration responses of the SSI system with soft soil. The undesirable effect of soft soil on backstepping control design was more obvious in displacement responses rather that acceleration ones.

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