CONSIDERATION OF SOIL-STRUCTURE INTERACTION IN SEISMIC ANALYZING OF STEEL STRUCTURES BY USING OF HYBRID DAMPER –ACTUATOR BRACING CONTROL (HDABC) SYSTEM

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ABSTRACT

The traditional dynamic analysis of the structures has accomplished on the fixed-base models. In general, the response of structures subjected to earthquake excitations are involved by three main components: structure, foundation, and the soil site layers. Seismic analysis of structural systems with the fixed-base model is suitable for structures built on the bedrock. If the structure has constructed on soft soil, both the control algorithm and the structural system shall include the Soil-Structure Interaction (SSI) that covers the flexibility of the soil and the displacement of the foundation. This leads to an increase in the number of the system's degrees of freedom that is changes the structural response behavior and accordingly control actions. This paper used a new type of hybrid control, combining passive and active systems, the Hybrid Damper-Actuator Bracing Control (HDABC), that is an effective protection system. In the structures which used the closed-loop control system whose utilities by Linear Quadratic Regulator (LQR) techniques to identify the structure with hybrid control. In this study, the effects of SSI on the seismic response of the steel structures under strong earthquakes who has built on shallow foundation and supplied with HDABC system, as energy absorber elements has been investigated. For this purpose, the moment resistant steel frames are considered and the time history analysis of them has treated on the structural models with either considering the SSI or without. The smart structure modeling and control design is carried out using MATLAB software in the state space form. The substructuring method achieved from SSI software such as SASSI2000 has used to evaluate the SSI dynamic response. Based on the analysis response, they are shown in the SSI cases, control forces result are more reduced of the structural response than without SSI. The control forces sequence in without SSI are smaller than with SSI case and SSI is effective for the hybrid control, needs to be included in the design of hybrid system as well as other types of the control for buildings on soft soil.

INTRODUCTION

Structural control is a relatively new technology for building protection under a severe environmental disturbance such as strong winds or earthquakes. These systems have categorized such as active, passive, hybrid and semi-active controls. The passive control technique including base isolation is the earliest and most widely used application for its simplicity, and it does not require an external power. The active control system put control forces on the building structure through employment of actuators with external power input, which may exclude the inelastic deformation for considered earthquakes. The hybrid control system combines the passive and active control devices to reduce the input power required by the active system (Cheng et al., 2008). A hybrid control system has utilized in this paper. The system is composed of visco-elastic dampers and hydraulic actuators mounted on a chevron brace between adjacent floors, called hybrid actuator-damper-bracing control (HDABC) it is shown in figure 1.

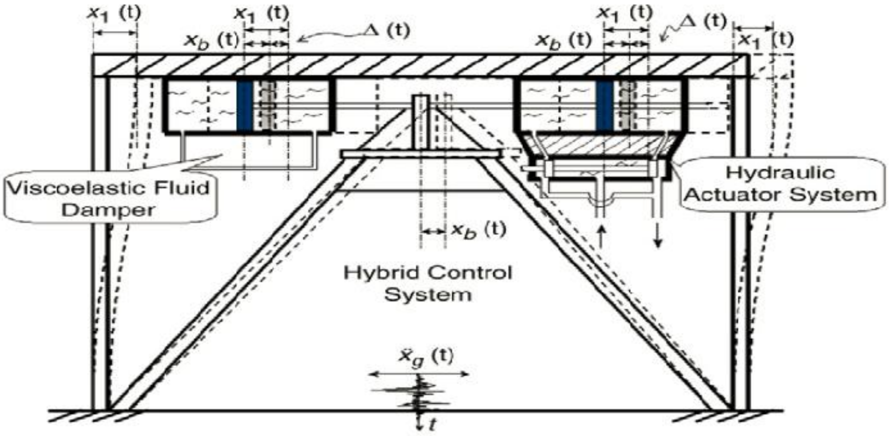

Figure 1. One-story structure with HDABC system

It has recognized suitably that the seismic response of a structure could be influenced by its supporting conditions such as fixed base and soil–structure interaction (SSI). Considering SSI in structural control to evaluate the effects of SSI on the response of structures with the control design based on the fixed base assumptions (Zhang et al., 2006, Wolf, 1985). There are two kinds of SSI interactions: Inertial and kinematic. Inertial interaction refers to displacements and rotations at the foundation level of a structure that result from inertia-driven forces such as base shear and moment. Kinematic interaction results from the presence of stiff foundation elements on or in soil, which causes motions at the foundation to deviate from free-field motions, which describes the ground motion at site without existence of a structure (NEHRP SSI for building structures, 2012). The inertial interaction is more significant than the kinematic interaction for the case of foundation without huge, rigid base slab or deep embedment. The inertial interaction has therefore considered in this study with the impedance function to model the soil–foundation dynamic characteristics.

DEFINITION OF THE HYBRID CONTROL SYSTEM (HDABC)

The motion equations for an *n*-story shear building structure equipped with a hybrid control device under a horizontal earthquake acceleration input can derived (Spencer and Chang, 2013; Cheng et al., 2008) as:

$$[M]\{\ddot{x}\}+[C]\{\dot{x}\}+[K]\{x\}=[¢_a]\{f_a\}+[¢_p]\{f_p\}+\{¢_r\}\ddot{x}_g \qquad (1)$$

Where $\{x\}=[x_1,x_2,\cdots,x_n;x_{b1},x_{b2},\cdots,x_{bm}]^T$ is the vector of floor and bracing displacements are denoted by x_1 and x_b, respectively; $[M]$, $[C]$ and $[K]$ are mass, damping and stiffness matrices, respectively; $[¢_a]$, $[¢_p]$ and $\{¢_r\}=-[M]\{I_n\}$ are the input location matrices for active, passive forces and the coefficient vector for earthquake ground acceleration inputs, $\ddot{x}_g$, respectively. $\{I_n\}$ is unit vector in order of *n*. As shown in Fig. 1, the hybrid control system is composed of visco-elastic dampers as the passive part and hydraulic actuators system as the active part. Cylinders of the damper and actuator have connected to a structural floor and the piston bar of both damper and actuator have connected to the Chevron-brace. The displacement difference between the floor and brace $\Delta_1(t) = x_1(t) - x_{b1}(t)$ is the piston's relative movements. The dynamic behaviour of the damper follows the constitutive relationship of visco-elastic fluids, which could be described by the Maxwell Model as:

$$\text{ª}_0 \dot{f}_p(t) + f_p(t) = C_0 \dot{\Delta}_p(t) \qquad (2)$$

Where $f_p(t)$ and $\Delta_p(t)$ are the passive force and the piston displacement, respectively. C_0 is the passive damping coefficient and ª_0 is the relaxation time (Zhang et al., 2006).

The hydraulic actuator system consists of an actuator, a servo-valve and a fluid pumping system. The actuator and the servo-valve have modelled as:

$$f_a(t) = \left(\frac{2\ \ A^2}{V}\right)\dot{\Delta}_a(t) + \left(\frac{A K_v}{V}\sqrt{2P_s}\right)c(t) \qquad (3)$$

And

$$\text{²}\dot{c}(t) + c(t) = u(t) \qquad (4)$$

Where, in Eq.3, $f_a(t)$ and $\Delta_a(t)$ are the active force supplied and the actuator piston displacement, respectively. P_s is the fluid input pressure, which is generated by the pumping system and supposed to be a constant. A, V, and K_v are actuator cylinder cross-section area, half cylinder volume, fluid bulk modulus and servo-valve pressure loss coefficient, respectively. Where in Eq. 4, u (t) is the control command and c (t) represents servo-valve piston displacements; $\text{²} = 1/(2\text{®} f_b)$ and f_b is servo-valve bandwidth (Cheng et al., 2008; Zhang et al., 2006).

The state space representation of the motion equation can be obtained by choosing a state vector as:

$$\{Z(t)\}_{N\times 1} = \left\{ \{x(t)\}^T \quad \{\dot{x}(t)\}^T \quad \{f_a(t)\}^T \quad \{f_p(t)\}^T \quad \{c(t)\}^T \right\}^T \qquad (5)$$

If r actuators and s dampers are supported by m bracings on a structural building model with n d.o.f., there are $(n + m)$ elements in either $\{x\ (t)\}$ or $\{\dot{x}(t)\}$, r elements in either $\{f_a(t)\}$ or $\{c\ (t)\}$, and s elements in $\{f_p(t)\}$. Thus, the order of $\{Z\ (t)\}$, vector of state variables, is:

$$N = 2n + 2m + 2r + s \qquad (6)$$

$$\{\dot{Z}(t)\} = [A]\{Z(t)\} + [B_u]\{u(t)\} + \{B_r\}\ddot{x}_g \qquad (7)$$

Where $[A]$ of $N \times N$ is plant matrix; $[B_u]$ of $N \times r$ is coefficient matrix for control commands; and $\{B_r\}$ of $N\times 1$ is coefficient vector for earthquake excitation.

$$[A] = \begin{bmatrix} [0] & [I] & [0] & [0] & [0] \\ -[M]^{-1}[K] & -[M]^{-1}[C] & [M]^{-1}[\text{¢}_a] & [M]^{-1}[\text{¢}_p] & [0] \\ [0] & [B_x] & [0] & [0] & [B_c] \\ [0] & [P_1] & [0] & [P_2] & [0] \\ [0] & [0] & [0] & [0] & [C_c] \end{bmatrix}, \quad [B_u] = \begin{bmatrix} [0] \\ [0] \\ [0] \\ [0] \\ [C_u] \end{bmatrix}, \quad [B_r] = \begin{bmatrix} [0] \\ [M]^{-1}\{\text{¢}_r\} \\ [0] \\ [0] \\ [0] \end{bmatrix} \qquad (8)$$

Parameter matrices $[B_x]$ of $r\times(n+m)$, $[B_c]$ of $r\times r$, $[C_c]$ of $r\times r$, and $[C_u]$ of $r\times r$ are determined by coefficients in Equation (3) and (4). Elements in $[B_x]$ are zero except $B_x(k,i) = -2(\ \ A^2/\mathrm{V})_k$ and $B_x(k,i+n) = 2(\ \ A^2/V)_k$; $[B_c]$, $[C_c]$ and $[C_u]$ are diagonal with elements $B_c(k,k) = (\ \ AK_v\sqrt{2P_s}/V)_k$, $C_c(k,k) = -1/\text{²}_k$, and $C_u(k,k) = 1/\text{²}_k$; parameter matrices $[P_1]$ of $s\times(n+m)$ and $[P_2]$ of $s\times s$ can be easily obtained from Equation (2). Elements in [P1] are zero except that

$P_1(k,j) = -(C_0/\text{ª}_0)_k$ and $P_1(k,j+n) = (C_0/\text{ª}_0)_k$; $[P_2]$ is a diagonal matrix with elements $P_2(k,k) = -1/\text{ª}_{0k}$ (Cheng et al., 2008; Zhang et al., 2006).

The optimal control has obtained through full state-feedback with a control law defined as follows:

$$\{u(t)\} = -[G]\{Z(t)\} \tag{9}$$

$[G]$ is expresses as the control gain in the above equation. Consequently:

$$\{\dot{Z}(t)\} = ([A]-[B_u][G])\{Z(t)\} + \{B_r\}\ddot{x}_g \tag{10}$$

Linear quadratic regulator (LQR) in the sense of optimal control theory have used to determine the control gains (Ghaffarzadeh and Younespour, 2014; Spencer and Chang, 2013). A performance index has used to find a compromise between the need to reduce structural response and the need to minimize control forces. The feedback control system has designed to minimize a cost function or a performance index, which is proportional to the required measure of the response of system. The cost function used in this case has given by:

$$J = \int_0^\infty \left(\{Z(t)\}^T [Q]\{Z(t)\} + \{u(t)\}^T [R]\{u(t)\}\right) dt \tag{11}$$

Where [Q], [R] are weighing matrices. Magnitudes of [Q], [R] represent the relative importance to the structural response and to the control forces. This influence has decided by the ratio of two matrix magnitudes. The assignment of larger values for elements in [Q] relative to those in [R] indicates the response reduction is given priority over the control force and larger control forces will be generated to cause more response reduction. The gain matrix $[G]$ can obtained by solution of Riccati equation given by:

$$[P][A]+[A]^T[P]-[P][B_u][R]^{-1}[P]+[Q]=0 \tag{12}$$

$$[G]=[R]^{-1}[B_u]^T[P] \tag{13}$$

Where $[P]$ is the Riccati matrix (Ghaffarzadeh and Younespour, 2014).

INVOLVING THE SSI ON THE CONTROL STRATEGIES

For the inertia interaction formulation, the foundation–soil interaction stiffness and damping characteristics have quantified by the impedance function, which provides a frequency dependent stiffness-damping model (Wolf, 1985). In the time domain analysis, the model has simplified as a set of frequency independent springs and dashpots. Their stiffness, K_s , and damping coefficients, C_S have taken from the corresponding impedance function items at the fundamental frequency of the SSI system (Amini and Shadlou, 2011; NEHRP SSI for building structures, 2012). The motion equation for the hybrid controlled SSI system (an n-story shear building) under the input of ground horizontal accelerations, $\ddot{x}_g$ as shown in Figure 2, can written (Zhang et al., 2006) as:

$$[M_{SSI}]\{\ddot{X}\}+[C_{SSI}]\{\dot{X}\}+[K_{SSI}]\{X\} = [\text{¢}_a^s]\{f_a\}+[\text{¢}_p^s]\{f_p\}+[\text{¢}_r^s]\begin{Bmatrix}\ddot{x}_g \\ \ddot{\text{¤}}_g\end{Bmatrix} \tag{14}$$

Where $[M_{SSI}]$, $[C_{SSI}]$ and $[K_{SSI}]$ are the mass, damping, and stiffness matrices of the SSI system, respectively. They can be derived by assembling structural matrices of *M* (mass), *K* (stiffness), *C* (damping), foundation property matrices M_f , and the impedance matrices of K_s and C_s , as shown in Eq.(15):

$$[M_{SSI}]=\begin{bmatrix} M & 0 \\ 0 & M_f \end{bmatrix}, \qquad [C_{SSI}]=\begin{bmatrix} C & -C\Gamma \\ -\Gamma^T C & \Gamma^T C\Gamma + C_s \end{bmatrix}, \qquad [K_{SSI}]=\begin{bmatrix} K & -K\Gamma \\ -\Gamma^T K & \Gamma^T K\Gamma + K_s \end{bmatrix} \tag{15}$$

Where $M_f=\begin{bmatrix} m_0 & 0 \\ 0 & I_0 \end{bmatrix}$ and m_0, I_0 are the foundation mass and the foundation's mass moment of inertia,

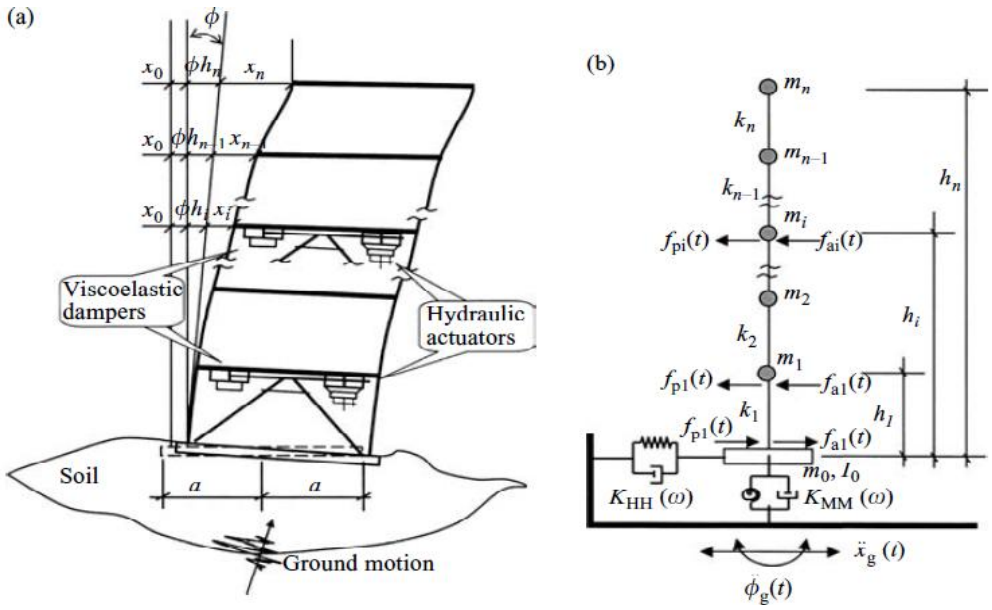

Figure 2. HDABC SSI structure system: (a) multiple-story structure, (b) mathematical model

respectively. The centroidal moment of inertia of the superstructure can ignored in the seismic response of simple building-foundation systems, so there is I_0 rather than I_T in this model. The input location matrices in Eq. (14) has expressed as:

$$[¢_a^s]=-\begin{bmatrix} -¢_a \\ \Gamma^T ¢_a \end{bmatrix}, \qquad [¢_p^s]=-\begin{bmatrix} -¢_p \\ \Gamma^T ¢_p \end{bmatrix}, \qquad [¢_r^s]=-[M_{SSI}]\begin{bmatrix} \Gamma \\ I_2 \end{bmatrix} \tag{16}$$

Where subscripts a, p and r signify the active, passive, and earthquake inputs, respectively; the superscript s is used for the case with SSI. The information matrix $\Gamma=\begin{bmatrix} 1 & \cdots & 1 & 1 & \cdots & 1 \\ h_1 & \cdots & h_n & h_{1b} & \cdots & h_{mb} \end{bmatrix}^T$ gives the floor height, h and brace height, h_b as shown in Fig 2. The number of braces, m can be various from the number of stories, n. $[I_2]$ is an identify matrix with order of two. The floor displacements have expressed as $\{X(t)\}=\left[\{x_t(t)\}^T \quad \{X_f(t)\}^T\right]^T$ with $\{x_t(t)\}=\{x(t)\}+[\Gamma]\{X_f(t)\}$, where $\{x(t)\}$ is the relative floor displacement with respect to the foundation and $\{X_f(t)\}=[x_0(t) \quad ¤(t)]^T$ is the foundation motion vector with x_0, ¤ of its horizontal displacement and rotation, respectively. The state space representation of the soil–structure system can similarly obtained, as with the fixed base case, using the state vector composed of the displacement and velocity for both the superstructure and the foundation, $\{Z^s(t)\}=\left[\{X(t)\}^T \quad \{\dot{X}(t)\}^T \quad \{f_a(t)\}^T \quad \{f_p(t)\}^T \quad \{c(t)\}^T\right]^T$, (Zhang et al., 2006).

NUMERICAL STUDY ON THE RESPONSE OF MODELS

A six-story building has utilized in this study with all parameters for the structural model, hybrid system model, foundation and soil. Table 1 summarizes all the parameters:

Table 1. System parameters for numerical examples

model	parameter	value	unit
structure	Floor mass M_s	110	ton
	Brace mass M_b	0.75	ton
	Column stiffness k_s	$k_1 = 3.51e5,\ k_2 = 2.25e5,\ k_3 = 1.7e5$ $k_4 = 1.24e5,\ k_5 = 8.8e4,\ k_6 = 6e4$	KN/m
	Brace stiffness k_b	2×10^5	KN/m
	Story height h	3.75	m
Hydraulic Actuator	Fluid Bulk modulus	6.9033×10^5	KN/m^2
	Supply pressure P_s	2.071×10^4	KN/m^2
	Frequency bandwidth f_b	53.63	Hz
Passive Damper	Damper coefficient C_0	3500	KN/m^2
	Relaxation time $^{a}{}_{0}$	0.05	-
Foundation	Half side length	7	m
	Mass m_0	220	ton
	Moment of inertia I_0	300	$ton.m^2$
Soil	Mass density $^{\circ}{}_{s}$	1700	kg/m^3
	Shear velocity V_s	160	m/s

At a first step, the computation of SSI state vector has conducted. Since the stiffness and damping are the impedance function in the frequency domain, in order to apply them to control, they must expressed in the time domain. This can done by using the structural system's fundamental frequency of 9.70 rad/s in the impedance function curves achieved by the computer software such as SASSI2000 (Lysmer et al., 2000) shown in Figure 3. The coefficients are then:

$$k_{HH} = 1.5e9 \text{ N/m};\quad k_{MM} = 5.6e10N;\quad c_{HH} = 4e7N.s/m;\quad c_{MM} = 1.3e8N.s \tag{17}$$

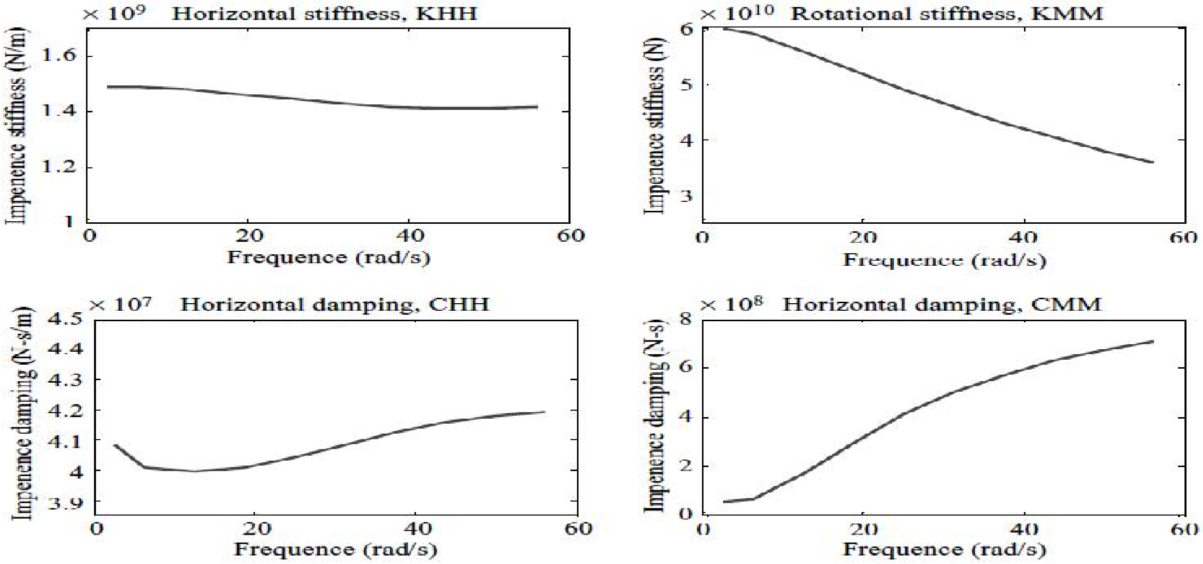

Figure 3. Impedance function curves.

In this paper, the Kobe (1995) earthquake ground motion has used for the dynamic time history analysis of these models. The controlled and uncontrolled roof displacement and acceleration time responses have shown as bellow:

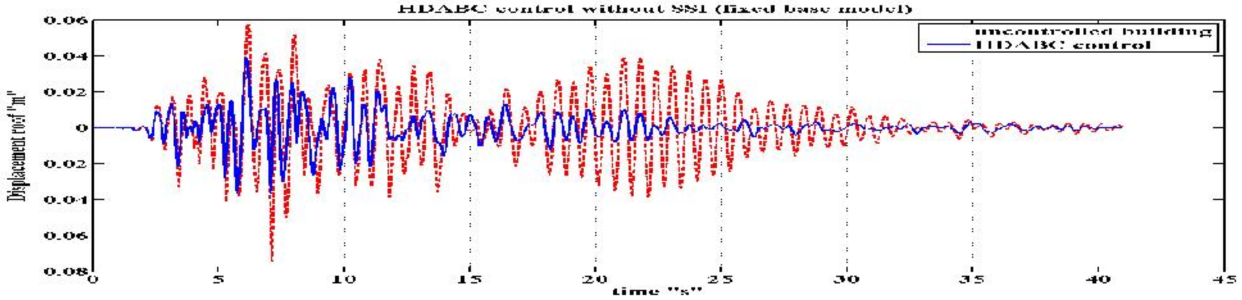

Figure 4. Comparison of response time history of 6th floor, HDABC system without SSI considered

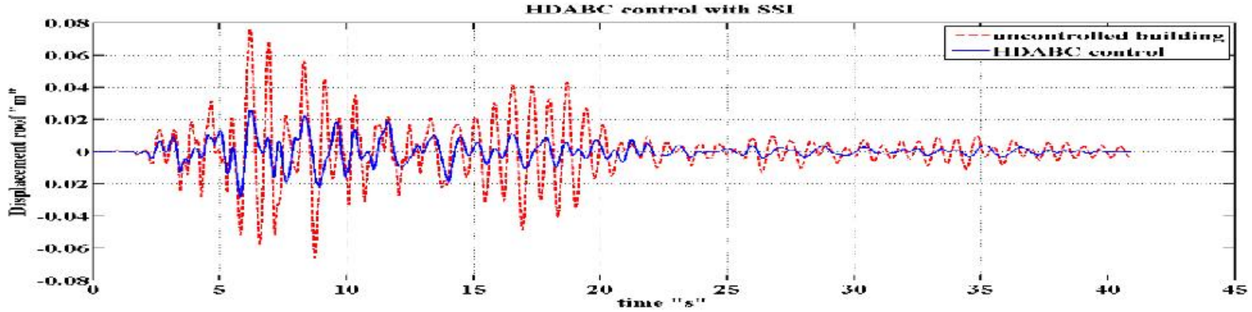

Figure 5. Comparison of response time history of 6th floor, HDABC system with SSI considered

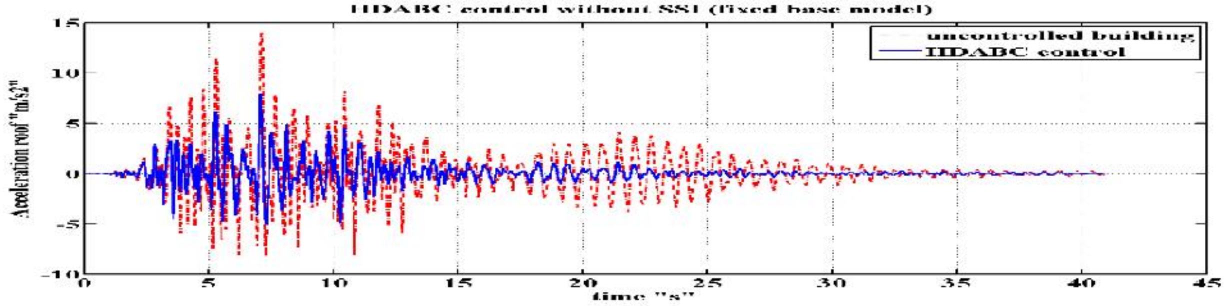

Figure 6. Comparison of acceleration of 6th floor, HDABC system without SSI considered

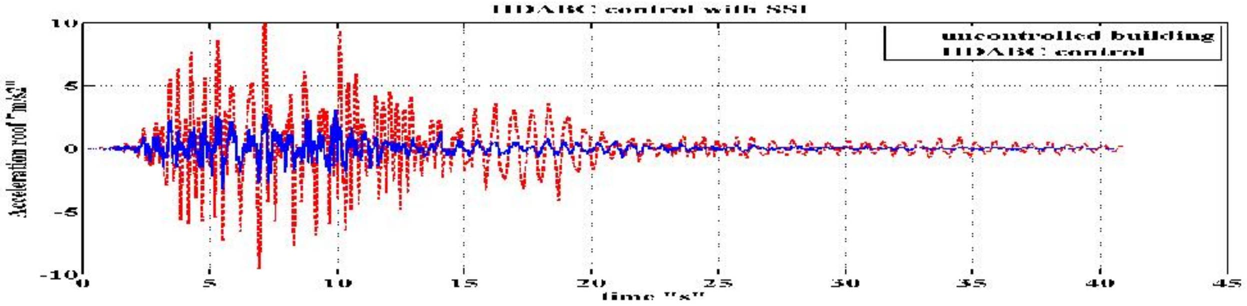

Figure 7. Comparison of acceleration of 6th floor, HDABC system with SSI considered

CONCLUSION

Dynamic soil-structure interaction under earthquake loads is a complicated phenomenon. Unless the fundamental frequency of the structure is near that of its supporting soil strata, SSI generally results in a reduction of the structural deformation and shear force at base. In this study, it has shown that assuming fixed-base for a structure with shallow foundation is not conservative. This study has focused on the evaluation of LQR controller considering Soil-Structure Interaction effects. It has shown that the applied system identification in this study is useful for other analyses of structure considering SSI effects. They have shown in the SSI cases, control forces result have more reduced of the structural response than without SSI. The result shows that the reduction of SSI-controlled model is about 66 percent of peak response. In addition, as the acceleration response of SSI-controlled model is about 69 percent of peak response reduction calculated. On the other hand as shown as results has seen that the control effort of HDABC devices is 118 percent is more economical to suppress the lateral displacement of the structural model in this research.

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