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# CONTROL METHOD FOR ADJACENT BUILDINGS CONSIDERING SOIL STRUCTURE INTERACTION

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**Abstract.**
*In recent years a vibration control technique, called structural coupling, has been studied. This technique consists on linking two neighboring buildings, through a coupling device, with the purpose of reducing dynamic response. It is possible to control both structures response simultaneously, which is precisely the attractiveness of the technique. Several researchers explored the effectiveness of various seismic control devices, in connecting two adjacent buildings, considering they are supported on a fixed base. However, in general, all structures interacts with the surrounding soil, what substantially affects the dynamic response, it is called soil-structure interaction (SSI). Considering SSI on structural coupling is still incipient in literature. This work aims to evaluate SSI influence on the performance of this control technique, besides of presenting a simple analysis methodology to this type of problem. The results found show that SSI effects cannot be neglected on dynamic analysis of coupled structures. It was verified that changes on system natural frequencies due to SSI are important since, depending on earthquake frequency components, it modifies also the dynamic response of the system. All analysis were performed using MATLAB software.*

## 1 INTRODUCTION

The impact between two neighboring high buildings, during severe earthquakes in the past, caused significant damages and loss of lives. In order to avoid these impacts, in the beginning of seventies various researchers proposed to connect neighboring structures using cable connecting devices. This technique called structural coupling [1] has proved to be effective on minimizing impact possibilities between two neighboring structures, besides of mitigating it dynamical responses.

From the 90s, it has been performed theoretical, numerical and experimental approaches of coupled structures using various control strategies, which showed positive results [1-11]. One of the main conclusions was that the connecting devices are effective if the two adjacent structures have different dynamic properties. In addition, these elements can increase the energy dissipation capacity of the structural system according to its mechanical properties and its position between adjacent structures.

Every structure generally interacts with the surrounding soil. This process is known as soil-structure interaction (SSI) [12]. During earthquakes, structures interact with soil in its surroundings, imposing strains to it. These deformations, however, cause movements in the supports or in the interface region between the ground and the structure, which are different from the movement of the free ground surface.

These interactions change significantly the structural response. In order to a correct evaluation of the dynamic response, taking into account the SSI effects, it is necessary to incorporate the soil dynamic properties on the mathematical formulation of the adopted physical model. There are several methods to solve this kind of problem. Noteworthy are the Direct Method and the Substructure Method, the latter being more computationally efficient [13].

There are still few studies in the literature about SSI influence on the coupling technique. Recently Farghaly [14] analyzed SSI effects on coupling technique performance, through finite element method. The author proposed to link two buildings with fixed mechanical properties using as connecting device like a viscous damper with known properties. All the analyses were performed with SAP2000 [15]. The results showed that the coupled system response is critical for soft soils, considering the types of soils taken into account on the study.

Given that the coupling technique considering SSI has been little studied, this work aims to evaluate SSI influence on the performance of this technique, besides of proposing a simple analysis methodology to this problem. For this purpose it is compared a two structure connected model supported on a fixed and flexible base. The structures are linked through a spring-dashpot device.

The numerical analysis was performed in two stages. On the first stage it was performed an optimization study, using the Particle Swarm Optimization (PSO) [16], in a way to set the connecting device properties, calculating the minimum dynamic responses of the coupled system on a fixed base.

A second stage is performed, now considering a flexible basis to the coupled system and setting the optimum properties calculated previously. Finally, all the results are compared in a way to evaluate SSI influence on coupled structures dynamic behavior. The El Centro earthquake is considered and all analyses are performed with MATLAB [17]. The results obtained in this study show how it is important to consider SSI effects on coupled structures dynamic analysis. Changes in the system natural frequencies were observed due to SSI, it affects the structure dynamic behavior depending on the earthquake frequencies components.

# 2 MATHEMATICAL FORMULATION

## 2.1 SSI Model

Consider the single degree-of-freedom (SDOF) system showed in Figure 1(a), supported through a rigid base on an elastic homogeneous isotropic medium [12]. Structure and foundation masses are, respectively, $m_b$ and $m_f$ and $I_b$ e $I_f$ are structure and foundation moments of inertia, respectively.

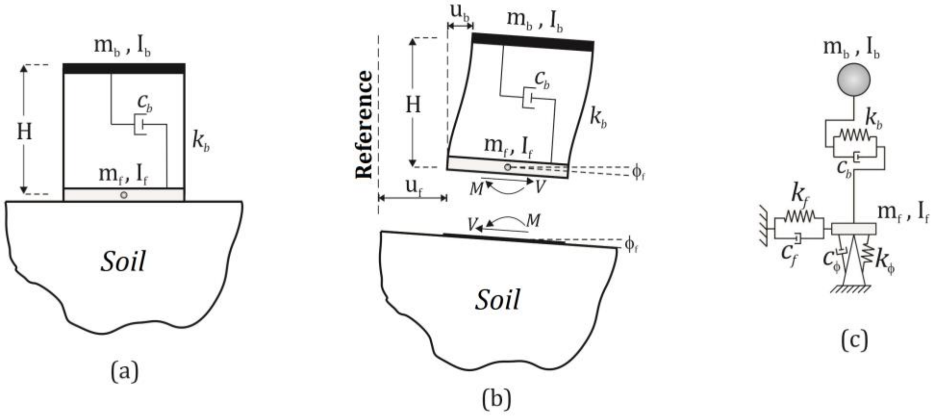


Figure 1: Soil interaction models

It can be observed on Figure 1(b) that structure induces occurrence of two forces at the base, a horizontal shear force (*V*) and a rocking moment (*M*). These forces generate a horizontal displacement ($u_f$) and a rotation ($\phi_f$). Thus, in addition to the structure equilibrium equation, two additional equations must be satisfied due to these additional quantities. Thereby the equations of motion of the system of Figure 1(b) are given by

$$\mathbf{M}_{bs}\,\ddot{\mathbf{u}}_{bs}(t)+\mathbf{C}_{bs}\dot{\mathbf{u}}_{bs}(t)+\mathbf{K}_{bs}\,\mathbf{u}_{bs}(t)=-\mathbf{v}_{bs}\,\ddot{\mathbf{u}}_{g}(t) \tag{1}$$

$$\begin{bmatrix} m_b & m_b & m_bH \\ m_b & m_b+m_f & m_bH \\ m_bH & m_bH & I_f+m_bH^2 \end{bmatrix}\begin{Bmatrix} \ddot{u}_b \\ \ddot{u}_f \\ \ddot{\phi}_f \end{Bmatrix}+\begin{bmatrix} c_b & 0 & 0 \\ 0 & C_f & 0 \\ 0 & 0 & C_\phi \end{bmatrix}\begin{Bmatrix} \dot{u}_b \\ \dot{u}_f \\ \dot{\phi}_f \end{Bmatrix}+\begin{bmatrix} k_b & 0 & 0 \\ 0 & K_f & 0 \\ 0 & 0 & K_\phi \end{bmatrix}\begin{Bmatrix} u_b \\ u_f \\ \phi_f \end{Bmatrix}=-\begin{Bmatrix} m_b \\ m_s+m_f \\ m_bH \end{Bmatrix}\ddot{\mathbf{u}}_g(t) \tag{2}$$

In this work SSI is represented by Winkler discrete model, presented on Figure 1(c). In this model, the soil stiffness is represented by springs with constants $K_f$ and $K_\varphi$ and damping soil effect is modeled by dampers with constants $C_f$ e $C_\varphi$. These coefficients are called impedance coefficients and can be obtained through the solution of a boundary value mixed problem in elastodynamics. In general it depends on soil properties, base dimensions and excitation frequency.

It can be found in literature several correlations to consider impedance coefficients in time domain [18-19]. One of the advantages of modeling the problem in time domain is that $K_f$, $K_\varphi$, $C_f$ e $C_\varphi$ values can be calculated through soil mechanical problems, lixe shear modulus (*G*) and Poisson´s ratio (*ν*). In this way Gazetas [18] and Mulliken and Karabalis [19] provide various graphics and tables to estimate impedance coefficient values to different types of foundations and soil conditions.

## 2.2 Coupled models with fixed base

The model presented on Figure 2 consists of two SDOF structures with fixed base, with masses ($m_{b1}$, $m_{b2}$), stiffness ($k_{b1}$, $k_{b2}$) and damping ($c_{b1}$, $c_{b2}$) associated to each structure, and a spring and a dashpot ($k_3$, $c_3$) placed between the two structure masses, acting as a connection device. When the two structures are connected, it represents a two degree of freedom system.

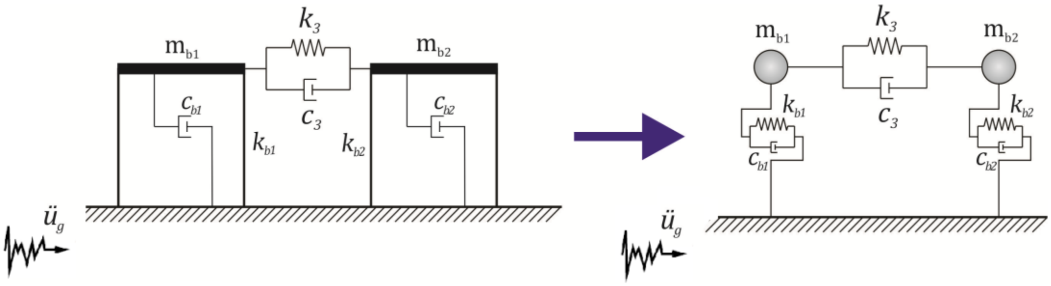


Figure 2: Two degree of freedom coupled system.

The coupled system motion equation, when it is subjected to a seismic base acceleration base $\ddot{\mathbf{u}}_g(t,)$ is given by Eq. (3) where $\mathbf{M}_{bb}$, $\mathbf{C}_{bb}$ *e* $\mathbf{K}_{bb}$ are respectively the mass, damping and stiffness matrices of the coupled system (Eq. (4)), $\mathbf{u}_{bb}(t)$ is the structure displacement vector.

$$\mathbf{M}_{bb}\ddot{\mathbf{u}}_{bb}(t)+\mathbf{C}_{bb}\dot{\mathbf{u}}_{bb}(t)+\mathbf{K}_{bb}\,\mathbf{u}_{bb}(t)=-G\,\ddot{\mathbf{u}}_g(t) \quad (3)$$

$$\mathbf{M}_{bb}=\begin{bmatrix} m_{b1} & 0 \\ 0 & m_{b2} \end{bmatrix},\mathbf{K}_{bb}=\begin{bmatrix} k_{b1}+k_3 & -k_3 \\ -k_3 & k_{b2}+k_3 \end{bmatrix},\mathbf{C}_{bb}=\begin{bmatrix} c_{b1}+c_3 & -c_3 \\ -c_3 & c_{b2}+c_3 \end{bmatrix},G=\mathbf{M}_b\begin{Bmatrix} 1 \\ 1 \end{Bmatrix} \quad (4)$$

In order to reduce the data processing time, real models of multiple degrees of freedom (MDOF) can be reduced to a two degree of freedom model (2DOF) using modal analysis techniques. For each one of the coupled buildings, natural frequencies, associated vibration modes, modal effective mass ($M_i^*$), not considering coupling are calculated. With mass $M_i^*$value, effective stiffness ($K_i^*$) and effective damping ($C_i^*$) can be calculated, those are the properties of the reduced SDOF system.

## 2.3 Coupled models considering SSI

Consider now the 2DOF system of Figure 2, supported by an elastic homogeneous isotropic medium, as shown in Figure 3. Thus the system motion equation can be written:

$$\mathbf{M}_{bsb}\,\ddot{\mathbf{u}}_{bsb}+\mathbf{C}_{bsb}\,\dot{\mathbf{u}}_{bsb}+\mathbf{K}_{bsb}\,\mathbf{u}_{bsb}=-(\mathbf{M}_{bsb}\mathbf{v}_{bsb}+\mathbf{v}_{fbsb})\ddot{\mathbf{u}}_g(t) \quad (5)$$

where: $\mathbf{M}_{\text{bsb}}$, $\mathbf{C}_{\text{bsb}}$ e $\mathbf{K}_{\text{bsb}}$ are mass, damping and stiffness matrices of the coupled system considering SSI effects (Eq. 6); $\ddot{\mathbf{u}}_{\text{bsb}}$, $\dot{\mathbf{u}}_{sbs}$ e $\mathbf{u}_{\text{bsb}}$ are 4x1 vectors with accelerations, velocities and displacement of the structures and surrounding soil; $\mathbf{v}_{\text{bsb}}$ is the soil influence vector and $\mathbf{v}_{\text{fbsb}}$ is the mass foundations vector.

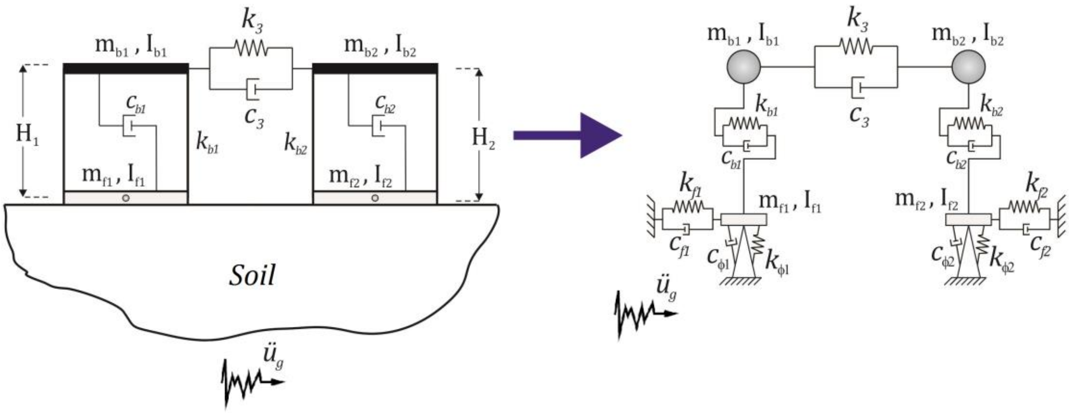


Figure 3: 2DOF coupled system

$$\mathbf{M}_{bsb}=\begin{bmatrix}\mathbf{M}_{bs1} & 0\\ 0 & \mathbf{M}_{bs2}\end{bmatrix},\mathbf{v}_{bsb}^{T}=\{1\quad 0\quad 0\quad 1\quad 0\quad 0\},\mathbf{v}_{fbsb}^{T}=\{0\quad 0\quad m_{f1}\quad 0\quad 0\quad m_{f1}\}$$

$$\mathbf{C}_{bsb}=\begin{bmatrix}c_{b1}+c_3 & 0 & 0 & -c_3 & 0 & 0\\ 0 & C_{f1} & 0 & 0 & 0 & 0\\ 0 & 0 & C_{\phi 1} & 0 & 0 & 0\\ -c_3 & 0 & 0 & c_{b2}+c_3 & 0 & 0\\ 0 & 0 & 0 & 0 & C_{f2} & 0\\ 0 & 0 & 0 & 0 & 0 & C_{\phi 2}\end{bmatrix},\mathbf{K}_{bsb}=\begin{bmatrix}k_{b1}+k_3 & 0 & 0 & -k_3 & 0 & 0\\ 0 & K_{f1} & 0 & 0 & 0 & 0\\ 0 & 0 & K_{\phi 1} & 0 & 0 & 0\\ -k_3 & 0 & 0 & k_{b2}+k_3 & 0 & 0\\ 0 & 0 & 0 & 0 & K_{f2} & 0\\ 0 & 0 & 0 & 0 & 0 & K_{\phi 2}\end{bmatrix} \quad (6)$$

## 3 NUMERICAL ANALYSIS

The structural system studied in this work is shown in Figure 4(a) [1,2]. On both buildings it was considered a mass of 30000 kg per floor. The steel columns have a height of 3,0 m with the same stiffness in all floors $k_1^1 = k_1^2 = k_2^2 = k_3^2 = 12{,}58$ MN/m. A damping ratio of 3% was taken into account. El Centro base acceleration (North-South component) was considered. Widely used in literature, this earthquake has a frequency range varying from 0,14 Hz to 2,1 Hz.

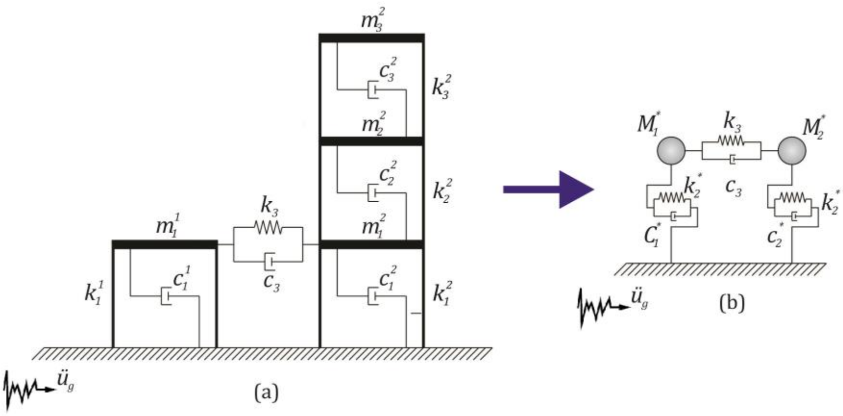


Figure 4: (a) MDOF model; (b) Equivalent reduced model.

In order to reduce computational cost, the MDOF system of Figure 4(a) was reduced to a two degree of freedom model (2DOF), shown in Figure 4(b), using modal analysis techniques. For each one of the uncoupled buildings, natural frequencies, associated vibration modes, modal effective mass ($M_i^*$) are calculated. According to Paz and Leigh [20] the more influent vibration modes are those, which the adding of its effective masses reach about 90 % of the total structure mass. With mass $M_i^*$value, effective stiffness ($K_i^*$) and effective damping ($C_i^*$) can be calculated, they are shown on Table 1.

| Structure | Vibration Mode | $\omega_i$ [rad/s] | $f$ [Hz] | $M^*_i$ [kg] | % mass | $K_i^*$ [N/m] | $C_i^*$ [Ns/m] |
|---|---|---|---|---|---|---|---|
| 1 | 1 | 20.478 | 3,2592 | 30000 | 100 | $1.25800.10^7$ | $3.68604.10^4$ |
| 3 | 1 | 9.1137 | 1.4505 | 82267.154 | 91.4 | $6.83307.10^6$ | $4.49855.10^4$ |
| | 2 | 25,5352 | 4,0641 | 6738.928 | 98.9 | | |
| | 3 | 36,8994 | 5,8727 | 993.918 | 100 | | |

Table 1: Natural frequency, modal mass, effective stiffness and effective damping of uncoupled structures.

## 3.1 First stage

On this stage it was performed an optimization study, using PSO method [16] in a way to set up connection device properties, calculating minimum coupled response with a fixed base.

The first step was to calculate the dynamical response of each reduced structure alone, *rms* values are shown on Table 2.

| Structure | $x_{rms}$ [m] | $v_{rms}$ [m/s] | $a_{rms}$ [m/s²] |
|---|---|---|---|
| 1 floor | 0.00437 | 0.08573 | 1.73199 |
| 3 floors | 0.02409 | 0.22198 | 2.10129 |

Table 2: Reduced structures *rms* response

Following, $k_3$ and $c_3$ values were optimized though PSO technique, with an objective function of the summation of coupled model *rms* accelerations. Stiffness value $k_3$ varied from zero to $6.10^6$ N/m. The same way, damping coefficient $c_3$ varied from 0 to $6.10^6$ Ns/m. These values were based on passive dampers properties available commercially (Taylor Device, Inc.).

One of the advantages of PSO algorithm is that the processing time needed to minimize the objective function is small. In this work various simulations were performed in a way of testing PSO technique and obtain suitable $k_3$ and $c_3$ values. On Table 3 it is presented results obtained with three different PSO numerical simulations.

| $c_3$ [Ns/m] | $k_3$ [N/m] | $f_{objective}$ [m/s²] | $a_{rms\_E1}$ [m/s] | $a_{rms\_E2}$ [m/s²] |
|---|---|---|---|---|
| 3.30675x10$^5$ | 9.58930x10$^{-7}$ | 1.7197 | 0.75990 | 0.95982 |
| 3.30359x10$^5$ | 3.72651x10$^{-4}$ | 1.7197 | 0.75989 | 0.95982 |
| 3.31336x10$^5$ | 3.18925x10$^{-4}$ | 1.7197 | 0.75990 | 0. 95982 |

Table 3: Connection device properties and *rms* response.

It can be observed on the above table that $k_3$ and $c_3$ had a very little variation. It also can be noticed that to control dynamic response on both structures, it is necessary to use a connection device with $c_3 = 3.30359 \times 10^5$ Ns/m and $k_3 = 0$. It can be said that the best connection device to the analyzed model is using only a viscofluid damper.

Next, the *rms* response is obtained to the coupled system, using the optimized values of $k_3$ and $c_3$. These values are compared with those from Table 1, in order to verify response reduction. The results are presented in Table 4.

It is also compared time history of displacements, velocities and accelerations of coupled and uncoupled systems, the results are shown on Figure 5.

| ***Structure 1*** | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| *uncoupled* | | | *coupled* | | | *Reduction* | | |
| $x_{rms}$ [m] | $v_{rms}$ [m/s] | $a_{rms}$ [m/s²] | $x_{rms}$ [m] | $v_{rms}$ [m/s] | $a_{rms}$ [m/s²] | *x [%]* | *v [%]* | *a [%]* |
| 0.00437 | 0.08573 | 1.73199 | 0.0040 | 0.0517 | 0.7599 | 8.5 | 39.7 | 56.2 |

| ***Structure 2*** | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| *uncoupled* | | | *coupled* | | | *Reduction* | | |
| $x_{rms}$ [m] | $v_{rms}$ [m/s] | $a_{rms}$ [m/s²] | $x_{rms}$ [m] | $v_{rms}$ [m/s] | $a_{rms}$ [m/s²] | *x [%]* | *v [%]* | *a [%]* |
| 0.02409 | 0.22198 | 2.10129 | 0.0083 | 0.0832 | 0.9598 | 65.6 | 62.5 | 54.3 |

Table 4: *Rms* response of coupled and uncoupled systems.

Analyzing the above results it is possible to notice that all responses presented a significant reduction due to the connection device installation. It can also be observed that the better response reductions occurred on structure 2, being displacement the parameter with greater reduction. However, in structure 1 displacement presented a low reduction, being acceleration the parameter with a better response control.

It is noteworthy that PSO optimization presented good performance, however to optimize $k_3$ and $c_3$ values it is necessary to define a proper objective function depending on the design and construction conditions, besides the type of response to be reduced.

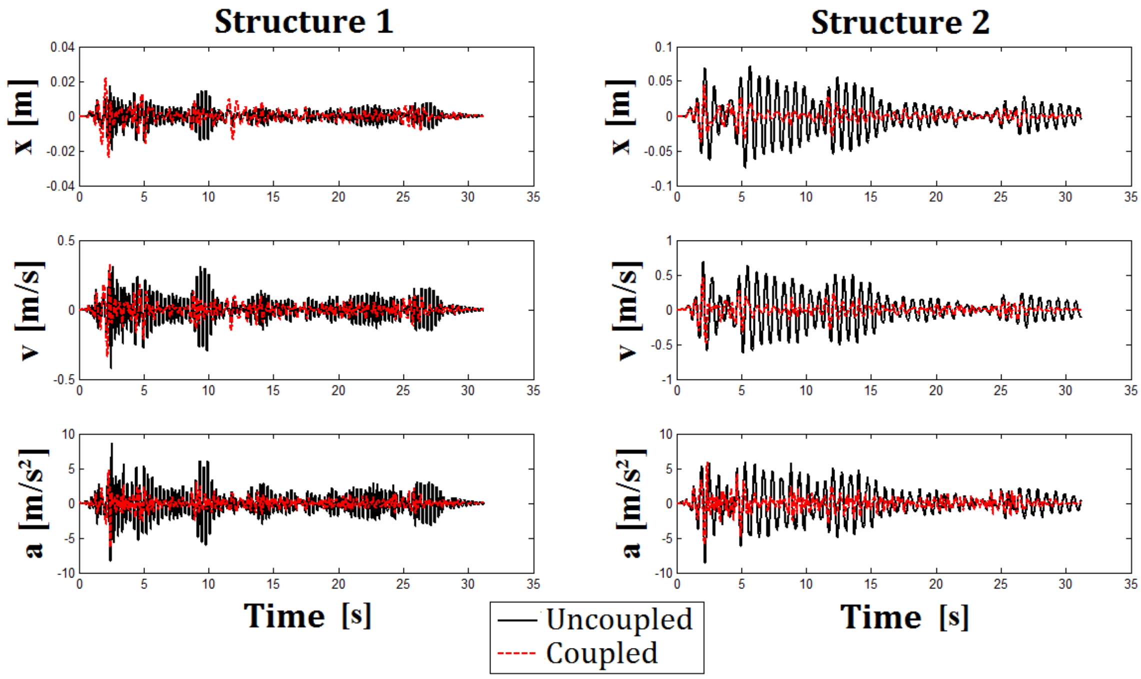


Figure 5: Displacement, velocity and acceleration time histories of coupled and uncoupled systems

### 3.2 Second stage

At this stage the coupled model with flexible base dynamical responses are obtained making use of the optimum parameters of the connecting device calculated before. Next, the responses obtained on the first and second stages are compared, in order to evaluate SSI effects on coupled structures analysis.

The coupled model considering SSI is similar to the one shown on Figure 3. The optimum values of $k_3$ e $c_3$ and only the soil mechanical properties are varied.

Consider the buildings supported on circular superficial foundation or 1.0 m of radius ($a$ = 1.0 m). It is considered three types of soil with different mechanical properties, shown on Table 5. The more resistant the soil is, higher the velocity of propagation of seismic waves $V_s$ is. Thus, it can be said that these soils presented in Table 5 can be classified as: soft (No.1), semi-rigid (No. 2) and rigid (No. 3).

| *Soil* | *Es[Mpa]* | *G [Mpa]* | *ρ [t/m³]* | *Vs [m/s]* | *ν* |
|---|---|---|---|---|---|
| No. 1 | 0.3 | 0.11 | 1.3 | 9.20 | 0.3 |
| No. 2 | 15 | 5.76 | 1.9 | 55,10 | 0.3 |
| No. 3 | 30 | 10.71 | 1.9 | 75.09 | 0.4 |

Table 5: Soil mechanical properties [21].

Soil impedance coefficients proposed by Kennedy and Eberhart [16] are considered and shown on Table 6, they are valid for rigid foundations supported on an homogeneous elastic linear soil.

| | *Mass* | *Damping* | *Stiffness* |
|---|---|---|---|
| Horizontal | $m_f = 4.37 \frac{(1-\nu)}{(7-8\nu)} \frac{Ga^3}{V_s^2}$ | $C_f = 1.50 \frac{1}{(2-\nu)} \frac{Ga^2}{V_s}$ | $K_f = 9.2 \frac{1}{(2-\nu)} Ga$ |
| Rocking | - | $C_\phi = 2.40 \frac{1}{(1-\nu)} Ga^4$ | $K_\phi = 4.0 \frac{1}{(1-\nu)} Ga^3$ |

Table 6: Damping impedance coefficients [16].

Following, the responses considering SSI are compared with those with rigid base. On Table 7 natural frequencies and corresponding periods for both cases are presented.

| *Natural frequencies and vibration periods* | | | | |
|---|---|---|---|---|
| *Coupled fixed base* | | *Coupled (SSI)* | | |
| *f [Hz]* | *T [s]* | *Soil* | *f [Hz]* | *T [s]* |
| 1,4504 | 0,6894 | No. 1 | 0.1254 | 7.9747 |
| | | No. 2 | 0.7759 | 1.2889 |
| | | No. 3 | 0.9985 | 1.0015 |

Table 7: Natural frequencies and vibration periods of coupled system with and without SSI

It can be observed that SSI affects the dynamics behavior of the coupled system, reducing its frequencies and consequently increasing vibration periods. The coupled model based on soil No 1 (soft soil) presented the greater reduction on frequency value, it was about 91,3 %. In the same way, the models based on soils No. 2 and No. 3 (semi-rigid and rigid soils) reduced its frequencies on 46,5% and 31,2%, respectively.

Next, displacement, velocity and acceleration time histories for the three cases, using optimum values of $k_3$ e $c_3$ were obtained, they are presented on Figures 6 to 8.

Soil characteristics influence frequency and duration of the earthquake. In general, rock foundations are exposed to high frequency excitation (low periods), but if they are on a weak or soft soil, they will be exposed to low frequency excitation (long periods). Knowing that El Centro earthquake frequency band varies from 0,14 to 2,4 Hz and taking into account the above said, it can be deduced that the coupled model when based on soil No. 1 won't suffer considerable shock since the frequency of this model is outside the earthquake frequency band. In this case, it can be observed on Figure 6 that the response considering SSI has lower amplitudes than the fixed base model.

Coupled models based on soils No. 2 and 3 presented frequencies within the El Centro earthquake frequency band. Observing Figures 7 and 8 that show displacement, velocity and acceleration time histories for both cases, it can be observed that response amplitudes for soil 2 were reduced compared to those of the fixed base model. Finally for soil No. 3 responses considering or not SSI were very similar, what was expected since this soil is considered rigid according to Table 5 classification.

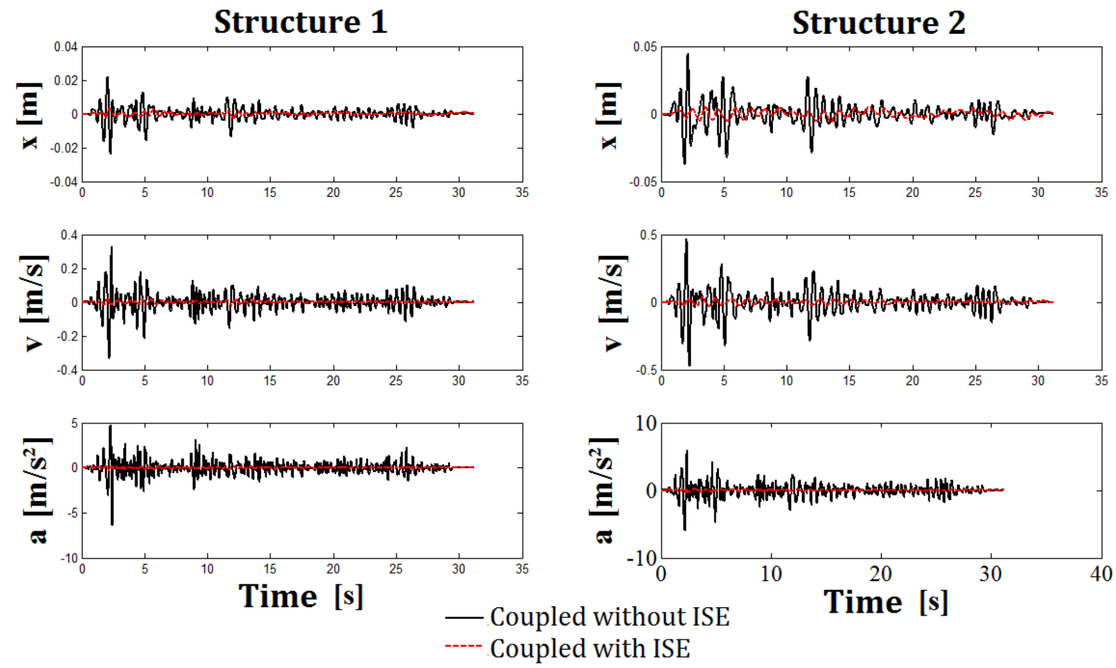


Figure 6: Displacement, velocity and acceleration time histories of coupled structures with and without SSI consideration – Soil No. 1.

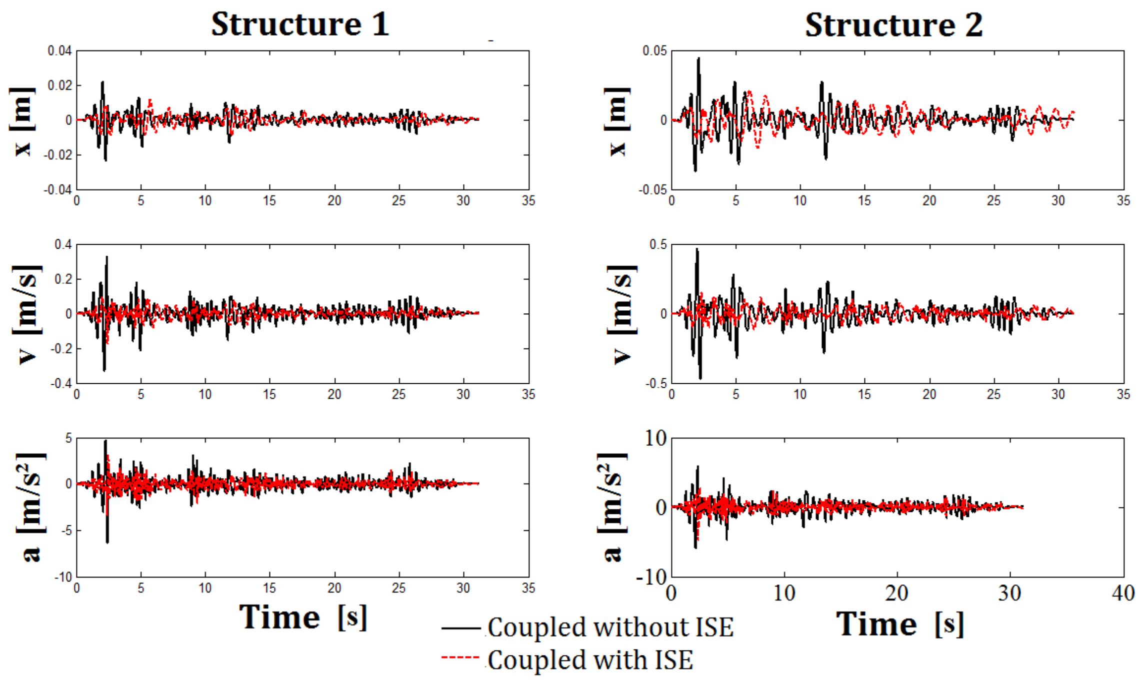


Figure 7: Displacement, velocity and acceleration time histories of coupled structures with and without SSI consideration – Soil No. 2.

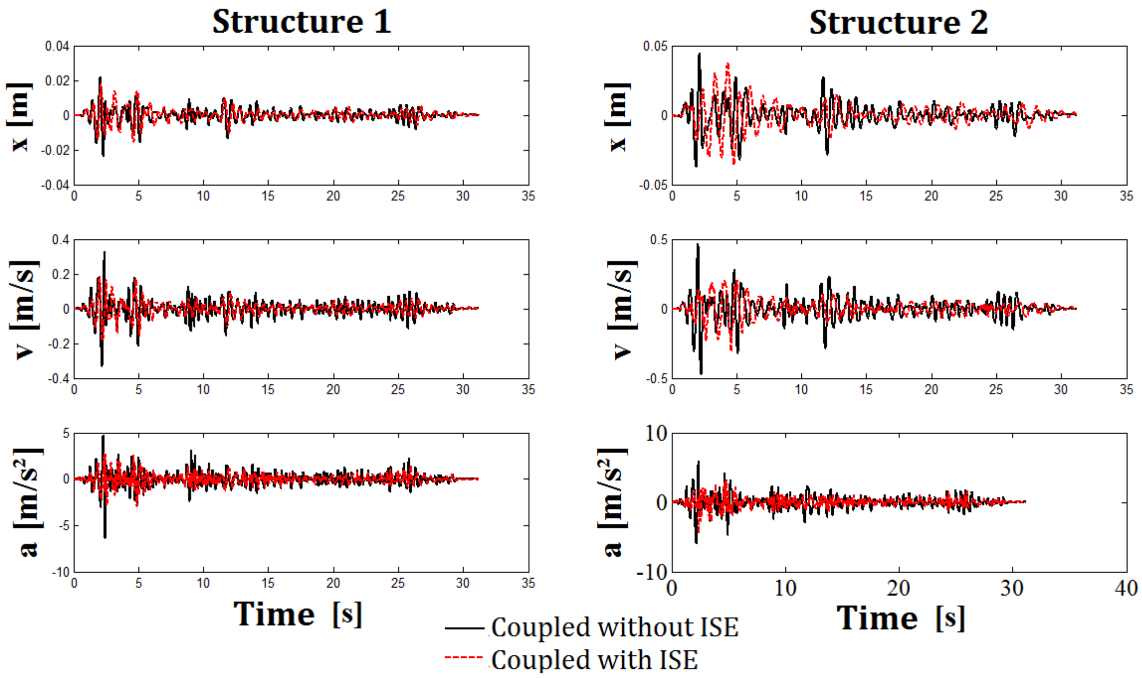


Figure 8: Displacement, velocity and acceleration time histories of coupled structures with and without SSI consideration – Soil No. 3.

## 4 CONCLUSIONS

It was presented the influence of soil structure interaction on the behavior of two connected structures by passive dampers. Two structures with known and fixed mechanical properties were considered. The SSI was expressed by the discrete model of Winkler and considered that the structures were supported by circular superficial foundations.

On SSI problems the dynamics responses depend on the type of structure and also on the foundation base type. It was verified that considering SSI effects modifies the system natural frequencies. This change affects the structural response to earthquakes, depending on the seismic frequency components associated.

As the soil stiffness decreases, the frequencies of the coupled system with SSI decrease considerably comparing to those of the coupled model with fixed base.

The more rigid the soil is, the behavior of the coupled model resembles to that of the fixed base model.

The results found in this paper show the importance of considering SSI effects on dynamic analysis of coupled structures. It can be verified that changes on system natural frequencies due to the soil stiffness is important since it modifies its response depending on earthquake frequencies. It was observed that models based on soft soils collaborate on reducing amplitude response acting as an energy dissipator. Additional studies on setting connecting device properties are necessary, considering on optimization procedures the SSI effects.

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