Influence of soil-structure interaction on the dynamic behavior of a structure subject to seismic action

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Abstract. The soil-structure interaction (SSI) is present in the structural analysis in the coupling between structure, foundation, and the soil. The consideration of this interaction is important in studies involving seismic events, considering that the structure interacts with the soil, which alters the structural response. Attentive to the damages caused by dynamic loads coming from the ground, the study aims to compare a structure receiving excitation directly at the structure without considering the effects of SSI and another case considering these effects. The excitation would be represented by an already known seism. The structures of the two situations would, firstly, be modeled in discrete spring-mass-dampener systems and solved through the state-space method for a linear time-invariant system. This solution method allows solving problems composed of a set of input, output, and state variables from first-order differential equations in a matrix form. The two models were implemented in Matlab Software. The results were expressed in the time domain via state-space and frequency by applying the Fast Fourier Transform (FFT) in terms of displacement and velocity. The results were compared to verify the influence of SSI on the dynamic response of the structure, which was shown to be beneficial to the structure.

Keywords: Space-State Method, Fast Fourier Transform, Soil-Structure Interaction, Coupled problems, Seismic excitation.

1 Introduction

Soil-structure interaction (SSI) had its first studies in the late nineteenth century, but it was from the emergence of computers between the 1960s and 1970s that it started to gain more attention (Kausel [1]). Recently, problems involving SSI have been gaining attention among researchers, mainly involving the dynamic behavior under seismic excitation's (Liratzakis and Tsompanakis [2], Amini et al. [3], Jiang et al. [4]). According to Ann Sunny and Mathai [5], understand the SSI how the process in which the soil influences the structure's response and the structure's movement influence's the soil's response. Similarly, for Pérez Peña [6], it is the junction between soil, foundation, and structure.

Structures are subject to dynamic loads that propagate through the ground and can occur, for example, through explosions and earthquakes, the latter being the most significant. According to Wolf [7], earthquakes are caused by a sudden release of energy caused by a fault line. Energy is dissipated by waves that can be classified as volume and surface. Volume waves can be primary and secondary, and surface waves can be Love and Rayleigh waves (Datta [8]).

The damage caused by an earthquake can be catastrophic. An example of this is the Northridge earthquake that occurred in 1994 in Los Angeles (USA), leaving 58 deaths and countless people who had to be redeployed from their homes (Todd et al. [9]). According to Eguchi et al. [10], the Northridge earthquake is considered moderate-intensity and has high monetary costs. They point out that excluding the indirect effects can reach $ 40 (US) billion, the event with the most expensive disaster.

According to Wolf [7] in seismic analysis, when the structure's fixed in a rock, the movements at the site are practically the same before and after the structure's allocation. However, the same phenomenon is not observed when the structure is founded on flexible soil. In this case, there are two relevant changes, the first one is that the seismic movement is different in the presence of the structure in the free field, and the second, the structure interacts with the ground around it, consequently modifying the seismic movement at the base.

Among the available methods to solve the problem of SSI are the direct methods, the substructure methods, and the simplified methods, but these are in the frequency domain. Wolf [11] presents time-domain methods, in which he represents the ground using springs and dampeners. In this case, the discrete model of the soil of concentrated parameter is represented by one spring and a damper connected to the structure base and associated with a soil mass, which is then added to the structural mass. To solve the equation of motion of a model under seismic excitation based on Newton's second law, methods that solve ordinary differential equations are necessary. A three-dimensional structure model applying the concepts of mass, spring, and dampers was presented in the study by Grezelle et al. [12]. The analysis was performed in ANSYS software and showed that under the action of the earthquake the last floor presented greater amplitude of acceleration and when verified harmonically to an impulsive force, the greatest vibration in terms of displacement occurred in the last floor and in the first vibrating mode.

The state-space method solves first-order differential equations. This started in control engineering. According to Kristensen [13], in a simple way, the state-space makes it possible through algorithms to verify the behavior of a system and even locate errors. The state-space is composed of two equations, a differential equation of state and another algebraic output equation (Williams and Lawrence [14]). According to Ogata [15], state-space analysis involves road, exit, and state variables, and any state can be represented by a point in state-space, which is presented in the time domain.

By measuring the number of disasters that an earthquake can cause in urban centers, as in the case of the seismic event that occurred in Northridge and that the soil can influence the behavior of the structure, the present study aims to compare the responses of systems with the influence SSI and without it, in addition to verifying the maximum amplitudes of each model. For this, 4 two-dimensional structures are modeled, considering only flexion movements. Models are represented by concentrated masses. 2 systems are considered direct excitation of the earthquake in the structure and the other 2 with the influence of the ground. The structures are composed of 2 floors and 5 floors. The responses of both structures are compared in the time domain in terms of displacement and velocity using the state-space solution implemented in the MATLAB ® [16] software. With the obtained results, the FFT is applied to identify the maximum amplitudes of vibration, in the frequency domain.

2 Methodology

To compare the effect of SSI on structures, the study considered two situations: the first considering the fixed base and receiving direct excitation from an earthquake and another structure with a flexible base in which the soil is coupled to the structure, in both situations it was only wired for flexion movements. To obtain the answers in terms of displacement and velocity in the time and frequency domain, firstly, the models are discretized in concentrated masses systems. Based on the second-order differential equation, the state-space method is used. With the structures answers, the FFT is applied. The calculations were implemented in the MATLAB ® [16] software. Next, the discrete models and the mathematical formulation will be presented.

2.1 Discrete model

Attentive of the proposed objective, four structures were modeled, two considering SSI and the other two without SSI. In this study, were used two-dimensional metallic structures with 2 and 5 floors. Figures 1 and 2 generically represent the structures modeled in this work, the first one is no coupling with the ground, and the earthquake is directly excited in the first mass of the structure (without SSI), and the second is coupled to the ground, where the earthquake propagation occurs through the base (with SSI). As observed in Fig. 1 and Fig. 2 the degrees of freedom is 1-per floor, and the earthquake excitation ($\ddot{x}_g$) is given in the x-direction, considering the XY Cartesian plane.

The equation of motion representing the 4-systems (Fig. 1 and Fig. 2) according to Newton's second law is given by eq. (1).

$$\mathbf{M}\ddot{\mathbf{x}}(t) + \mathbf{C}\dot{\mathbf{x}}(t) + \mathbf{K}\mathbf{x}(t) = \mathbf{F}(t), \tag{1}$$

where $\mathbf{M}$, $\mathbf{C}$ and $\mathbf{K}$ are matrices of mass, damping, and stiffness, respectively. $\ddot{\mathbf{x}}$, $\dot{\mathbf{x}}$ and $\mathbf{x}$ are acceleration, velocity and displacement vectors, in (m/s^2), (m/s) and (m), respectively. $\mathbf{F}$ is the external excitation force and t is the

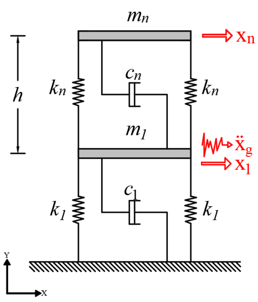


Figure 1. Discrete model without SSI.

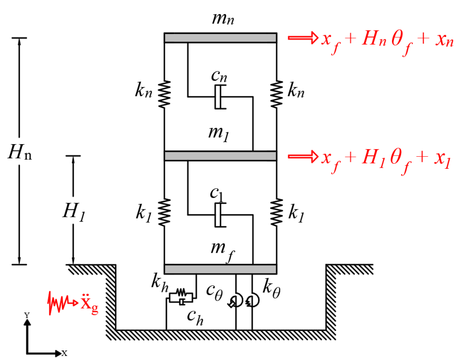


Figure 2. Discrete model with SSI.

time, in (s) and $(Newtons)$, respectively. It is worth noting that for each system the matrices and vectors change. Open matrices for N degrees of freedom can be found in the studies of Chopra [17] and Rao [18].

2.2 Mathematical formulation

The problems presented in section 2.1 can be solved using the state-space method. For this, eq. (1) is derived for a 1st-order differential equation. In state-space is presented in general form by section 2.2 and section 2.2.

$$\dot{\mathbf{z}}(t) = \mathbf{A}\mathbf{z}(t) + \mathbf{B}\mathbf{u}(t) \rightarrow \textit{state equation}, \tag{2}$$

$$\mathbf{y}(t) = \mathbf{C_y}\mathbf{z}(t) + \mathbf{D}\mathbf{u}(t) \rightarrow \textit{output equation}, \tag{3}$$

$\mathbf{A}_{n\times n}$, $\mathbf{B}_{n\times m}$, $\mathbf{C_y}_{p\times n}$ and $\mathbf{D_{p\times m}}$ are state, input, output, and feedforward matrices, respectively. $\mathbf{z}_n$, $\mathbf{u}_m$ and $\mathbf{y}_p$ are state, input and output vectors, respectively. For calculations, the matrix $\mathbf{D}$ is considered zero as it has no input acting on it. Open matrices can be found in the studies by Pérez Peña [6], Williams and Lawrence [14], Ogata [15], and Chen [19]. Soil stiffness and damping are determined by impedance functions. The functions were presented in the study of Gazetas [20].

Figure 3 presents a solution scheme for the solution of the 4-systems. The process starts with the input data, then the mass and stiffness matrices are assembled, from these two matrices they are used to calculate the eigenvalues and eigenvectors to later be used in the Rayleigh method and have the damping matrix. With the 3 matrices, the matrices that make up the state-space are assembled. Next, the system is solved, and the answers are stored in the vector $\mathbf{y}(t)$. From the results, the FFT is applied, and the responses are obtained in the frequency domain. The responses of each structure are stored both in the time and frequency domains to finally confront them.

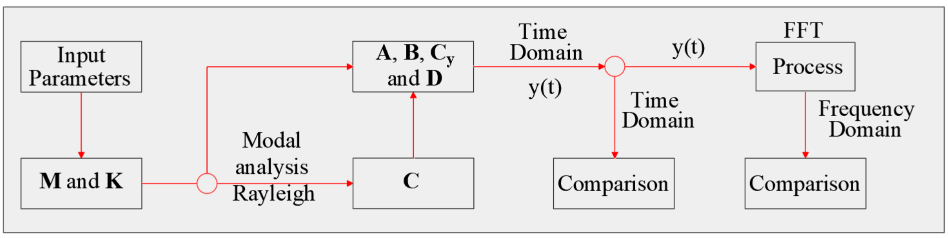


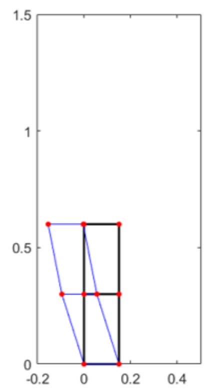
Figure 3. Structure analysis solution scheme.

3 Results

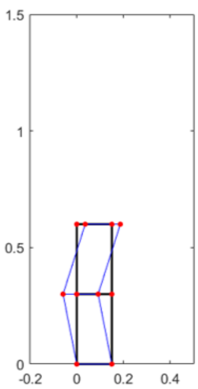
The present study proposes to analyze the responses as a function of a dynamic load for a situation without taking into account the effects of SSI and the other considering. The 4-problems addressed in section 2 were solved via state-space and the parameters adopted for structures with 2-floors are: $m_1 = m_2 = 0.0057$ kg, $k_1 = k_2 = 45.51$ N/m; the height between floors $h = 0.3$ m; slab dimensions = 0.15 m $\times$ 0.006 m $\times$ 8$\times$10^{-4} m; pillar section = 8$\times$10^{-4} m $\times$ 0.006 m; Modulus of elasticity (E) = 2$\times$10^{11} Pa; steel density = 7850 kg/m^3 and the damping factor (ζ) 0.01. For structures with 5 floors, the parameters considered were: $m_1 = m_2 = m_3 = m_4 = m_5 = 0.0053$ kg; k_1 a k_5 = 45.51 N/m; slab dimensions = 0.14 m $\times$ 0.006 m $\times$ 8$\times$10^{-4} m. The other properties are considered to be the same as the 2-storey models.

For models coupled with the ground, the soil parameters must be added, being for 2 floors: $k_h = 1.45 \times 10^7$ N/m and $k_\theta = 3.739 \times 10^6$ N/m; $c_h = 7.632 \times 10^5$ Ns/m and $c_\theta = 5.124 \times 10^4$ Ns/m; $m_f = 0.0057$ kg; foundation dimensions 0.1516 m $\times$ 0.006 m $\times$ 8$\times$10^{-4}. As for the model coupled with 5 floors, the parameters are: $k_h = 1.404 \times 10^7$ N/m and $k_\theta = 3.375 \times 10^6$ N/m; $c_h = 7.128 \times 10^5$ Ns/m and $c_\theta = 4.470 \times 10^4$ Ns/m; $m_f = 0.0053$ kg; foundation dimensions 0.1416 m $\times$ 0.006 m $\times$ 8$\times$10^{-4}. The earthquake considered in the study was the one that occurred in Northridge (1994), o earthquake record was obtained through the *Pacific Earthquake Engineering Research Center - PEER* (Peer Ground Motion Database [21]), the earthquake marking interval time is of 0.005s. The earthquake was recorded at the station LA - Sepulveda VA Hospital, component NORTHR_SPV360.AT2, has a moment magnitude of 6.7 M_w, with an effective peak acceleration (PGA) of -0.932g and the distance from the measurement site to the epicenter of 8.44 Km.

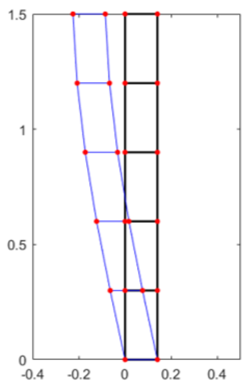
The modal analysis was obtained through the eigenvalues and eigenvectors, the responses obtained for the first two modes considering the structure of 2 and 5 floors in free body is presented in Fig. 4.



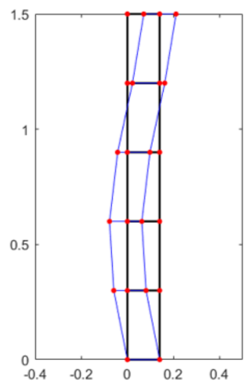
(a) Sca. 10x



(b) Sca. 10x



(c) Sca. 10x



(d) Sca. 10x

Figure 4. Vibration modes of the structure. a) 1st-mode: 8.827 Hz; b) 2nd-mode: 23.108 Hz; c) 1st-mode: 4.207 Hz; d) 2nd-mode: 12.282 Hz.

The results in terms of displacement and velocity for structures with 2 floors in the time-domain in order to compare the influence of SSI are presented in Fig. 5 and Fig. 6, respectively. Frequency-domain responses are presented in Fig. 7 and Fig. 8. The maximum amplitudes obtained under the action of the earthquake were on the last floor in both situations. In the time-domain, the greatest amplitudes without considering the SSI were of -0.04657 m and -1.714 m/s and with SSI were from 7.166$\times$10^{-4} m and 0.02473 m/s. For the frequency domain, the maximum vibration amplitudes without SSI were: 1.835$\times$10^{-3} m and 0.102 m/s and with SSI: 2.713$\times$10^{-5} m and 1.509$\times$10^{-3} m/s. All were in the first mode of vibrating at a frequency of 8.853 Hz. The amplitude differences in the time and frequency domain were 0.0473 m, 1.739 m/s, 1.808$\times$10^{-3} m and 0.1005 m/s, respectively.

The results in terms of displacement and velocity for structures with 5 floors in the time-domain in order to compare the influence of SSI are presented in Fig. 9 and Fig. 10, respectively. Frequency-domain responses are presented in Fig. 11 and Fig. 12. The maximum amplitudes obtained under the action of the earthquake were on the last floor in both situations. In the time-domain, the greatest amplitudes without considering the SSI were of 0.09808 m and -2.599 m/s and with SSI were from -6.541$\times$10^{-3} m and 0.1624 m/s. For the frequency domain, the maximum vibration amplitudes without SSI were: 8.993$\times$10^{-3} m and 0.2353 m/s and with SSI: 5.88$\times$10^{-4} m and 0.01539 m/s. All were in the first mode of vibrating at a frequency of 4.165 Hz. The amplitude differences in the time and frequency domain were 0.105 m, 2.752 m/s, 8.405$\times$10^{-3} m and 0.2199 m/s, respectively.

When observing the structures with 2 and 5 floors, it can be seen that the amplitudes were greater, that is, they became more unstable as the number of floors increased. One of the factors of this occurrence is that as pavements are added, the mass and stiffness matrices change, consequently the dynamic responses of the structure change.

Another point observed in Fig. 6 to Fig. 12 is that when the structure received direct excitation the amplitudes were higher than those considering the SSI. Based on the results, it is noted that the presence of the ground, due to its damping, mitigated the direct impact of the earthquake, in which part of the earthquake's energy was dissipated.

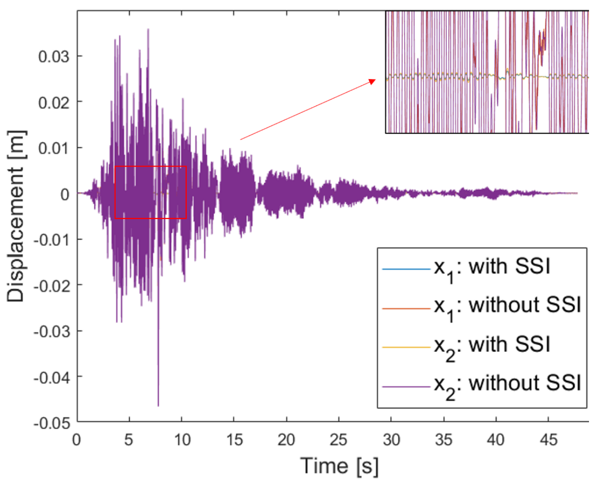


Figure 5. Comparison between structures with and without SSI in terms of time-domain displacement - 2-story case.

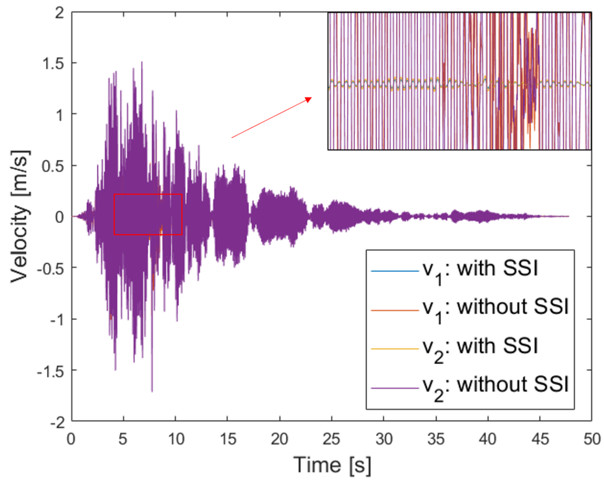


Figure 6. Comparison between structures with and without SSI in terms of time-domain velocity - 2-story case.

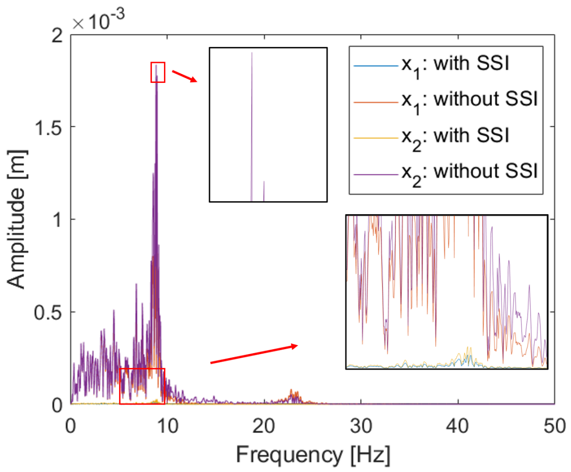


Figure 7. Comparison between structures with and without SSI in terms of frequency-domain displacement - 2-story case.

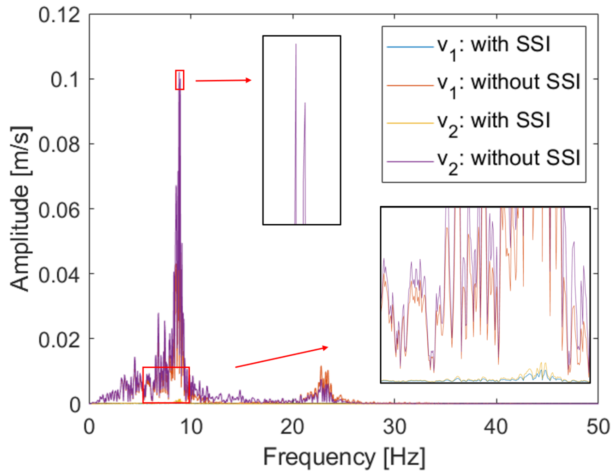


Figure 8. Comparison between structures with and without SSI in terms of frequency-domain velocity - 2-story case.

Yang et al. [22] observed through experimental and analytical results that SSI systems have longer natural periods than the fixed base structure. Furthermore, for the soft soil, when subjected to low-intensity seismic action, there is an amplification effect and under strong seismic excitations, it has an isolation effect. In the research by Pap and Kollár [23], they comment that soil deformability influences the response in seismic projects, they showed that for a soft soil delimited by rock, when in resonance, it tends to significantly amplify the earthquake loads. As the analyzed earthquake has moderate intensity, the ground ended up absorbing part of the earthquake's energy, being beneficial for this type of analysis, adopting only the bending.

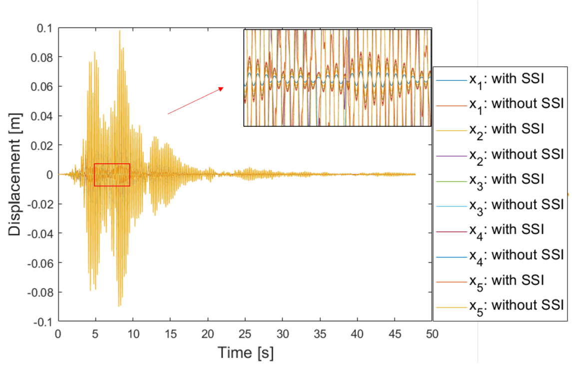


Figure 9. Comparison between structures with and without SSI in terms of time-domain displacement - 5-story case.

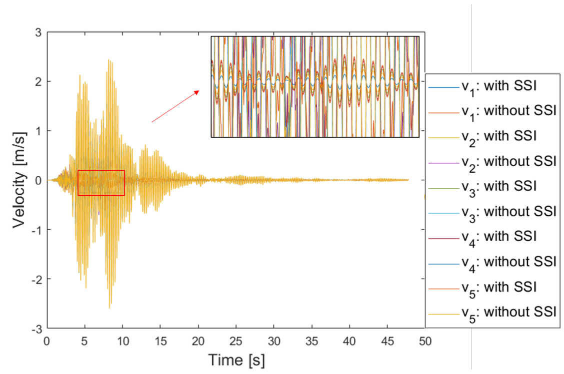


Figure 10. Comparison between structures with and without SSI in terms of time-domain velocity - 5-story case.

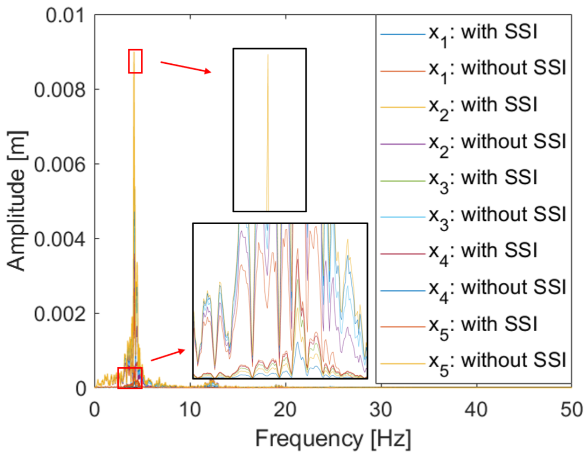


Figure 11. Comparison between structures with and without SSI in terms of frequency-domain displacement - 5-story case.

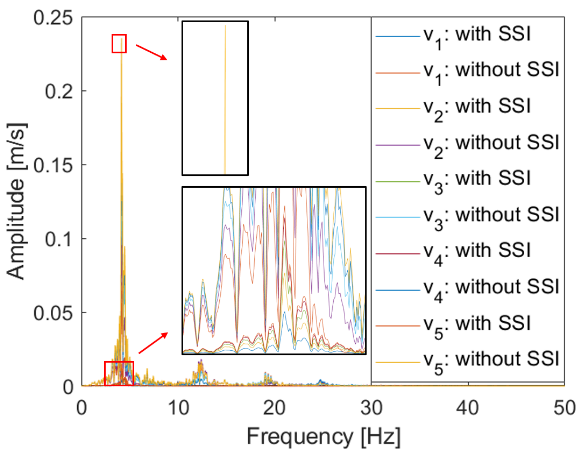


Figure 12. Comparison between structures with and without SSI in terms of frequency-domain velocity - 5-story case.

According to Rao [18] most vibratory systems are very complex and predicting all the variables involved is extremely difficult. Thus, the models were limited to two-dimensional problems, considering bending only. Thus, the results presented are theoretical models in order to identify the influence of SSI and the dynamic behavior of the structure under seismic excitation.

4 Conclusions

The present study sought to analyze the influence of SSI on structures with different sizes and the dynamic behavior of the structure against a seismic excitation, directly in the structure and through the base. When analyzing the results obtained via state-space, it was noted that the largest amplitudes of displacement and velocity in the time domain occurred on the last floor of each structure.

When applied to FFT, the dynamic response of the structure in the frequency domain is obtained and it was observed that all structures had the maximum vibration amplitudes in terms of displacement and velocity in the first vibrating mode and the last floor. Furthermore, when confronting the responses of the structures with and without the influence of SSI, it was noticed that the model considering the soil was beneficial to the structure than the one that did not have it.

As a suggestion for future work, it would be to analyze the same cases, but with different types of seismic intensity, soils, and heights through the state-space solution.

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