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Dynamic Interaction of a Primary-Secondary System Considering Soil-Structure Interaction

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ABSTRACT

Proper design of secondary structures requires a thorough understanding of the primary-secondary-structure interaction (PSSI). This interaction can affect the response of both the primary and secondary structures. Previous studies on secondary structures focused mostly on elastic linear structures. In reality, however, the primary structure also interacts with the surrounding soil, establishing the soil-foundation-structure interaction (SFSI) that is known to affect the response of the structure in earthquakes. Although many past studies have suggested the benefit of considering SFSI in the seismic analysis of primary structures, not much has been explored on its effect on the response of secondary structures. This work focuses on the response of a coupled primary-secondary structure considering the effect of SFSI. A scaled 4-storey structure with a rigidly attached secondary structure was excited under two different boundary conditions: fixed base and on sand. A laminar box was used to allow shear deformation of sand beneath the structure to simulate a more realistic condition. The response of the primary structure was reduced when SFSI and PSSI was considered separately. When both SFSI and PSSI were considered simultaneously, the effect of PSSI is only significant on the higher mode response.

Introduction

Secondary structures are the non-load bearing members of an infrastructure that are typically attached to the load-bearing elements (Adams, 2001; Villaverde, 1997). Examples of secondary structures include roof-mounted air conditioners, generator sets, and shelving units. These components are generally not designed to withstand seismic loads during earthquake, making them especially vulnerable during such events (Lim and Chouw, 2014a).As a consequence of their non-structural nature, these seismic loads often lead to secondary structure detachment and damage. Hence, property damage and loss of life are realistic threats (Villaverde, 1997; Chen and Soong, 1988).

Proper analysis of secondary structures requires a thorough understanding of the primary-secondary-structure interaction (PSSI) (Naito and Chouw, 2003; Lim and Chouw, 2014a). Previous analysis on secondary structures considering PSSI focused mostly on elastic linear structures (e.g. Igusa and Kiureghian, 1985a-c, Asfura and Kiureghian, 1986). Closed form solutions to estimate the response of the secondary structure has been extensively developed. However, not much has been done for nonlinear cases. In reality, the primary structure could also interact with the surrounding soil, establishing the soil-foundation-structure interaction (SFSI) that has been known to affect the response of structures in earthquakes. Although many past

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studies have suggested the benefit of considering SFSI in the seismic analysis of primary structures (Mylonakis *et al*., 2006; Qin *et al*., 2013a), not much has been explored on its effect on the response of the secondary structure.

This work investigates the response of a coupled primary-secondary structure considering the effect of SFSI through experiments. The effect of SFSI on the response of the secondary structure will be revealed. The contribution of the secondary structure to the response of a subsoil-based primary structure will also be discussed. The outcome will introduce the signficance of considering SFSI in the analysis of secondary structures..

Experimental Setup and Data Acqusition

Experimental Setup

Figure 1 shows the experimental model consisting of an elastic four degree-of-freedom (DOF) primary structure with a single DOF secondary structure affixed to its second floor. The location of the secondary structure is selected at the floor which the response of higher mode of the primary structure is more significant, i.e. the secondary structure was expected to have greater response.

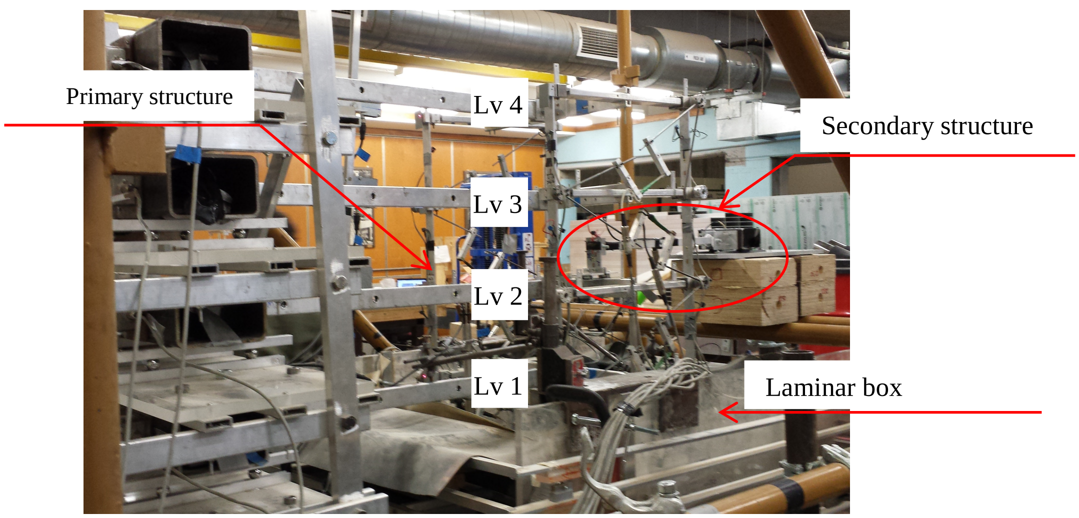

Figure 1. Experimental setup

Prototype and Scaled Model

Primary Structure

The primary structure was a 1:15 scale model of a four storey building prototype. The inter-storey height of the prototype was 3.15 m, resulting in a total height 12.6 m. The mass for each of the first three floors of the structure and the roof floor was 29 tons and 24 tons, respectively. The lateral stiffness of each individual column is 62,100 kN/m. Rigid beam assumption was adopted for the model, thus the natural frequencies of the structure is only governed by the stiffness of the columns. The fundamental frequency of the prototype was 1.46 Hz, i.e. natural period of 0.68 s. This is also the frequency of the model. The damping ratio of the model was calculated as the average decay rate from five free vibration tests. The average damping ratio was 10.5%. This value is within the realistic range for bolted steel structures of 10–13% (Chopra, 2012). The scaled foundation was made of a 470 mm × 470 mm × 22 mm rigid plate.

Secondary Structure

The secondary structure was a single degree-of-freedom system following the same scale as the primary structure. The height was 45 mm, and the mass was 1.95 kg. The secondary structure was rigidly fixed on the rigid beam of the primary structure. This configuration gives the natural frequency of 13 Hz, i.e. natural period of 0.07 s. The damping ratio was 12%. Relative to the primary structure, a higher frequency and lower mass was selected for the secondary structure in order to reflect a more realistic scenario (Lim and Chouw, 2014b). The mass ratio μ, and frequency ratio η, of the primary-secondary system are defined as,

$$\mu=\frac{M_s}{M_p} \tag{1}$$

where, M_s = the mass of the secondary structure and M_p = the mass of the primary structure at the level the secondary structure was attached.

$$\eta=\frac{f_s}{f_p} \tag{2}$$

where, f_s = the natural frequency of the secondary structure and f_p = the fundamental frequency of the primary structure.

Chen and Soong (1988) stated that for PSSI to have a significant effect on structural response, μ must be at least 10%. The mass and frequency of the secondary structure were selected so that μ is 12% and η is 8.90. In actual scale, the selected secondary structure represents possible realistic cases, e.g. generators, computer system, and communication tower.

Laminar Box

A laminar box filled with sand was used to simulate the subsoil. The laminar box consisted of 12 discrete layers of rigid aluminum frame, each of which enclosed an area of 800 mm × 800 mm. These layers were separated by ball bearings to allow relative movement with minimum friction between the layers when ground motion was applied. Compared to a conventional rigid sand box, the vertical propagation of horizontal shear waves from the bedrock to the surface of the soil was more realistically simulated with the laminar box (Qin *et al.*, 2013b). The type of sand used was oven-dried river sand with a unit weight of 15.5 kN/m^3, void ratio of 0.68, and specific gravity of 2.65. The sand particles were “rained” into the laminar box with a drop height between 400–500 mm to ensure a uniform distribution of the sand by the unit weight. The total depth of the sand was 420 mm. Sand paper was placed at the interface between the sand and the base of the laminar box to minimise possible slippage of the sand relative to the box. Sponges on the sides of the box were used to reduce the boundary effect of soil.

Ground Motions

The ground motion applied was simulated based on the Japanese Design Spectrum (JDS) for a hard soil condition (JSCE, 2000; Chouw and Hao, 2004). The scaled target and response spectra and the time history of the earthquake used are presented in Figure 2. The same ground motion was applied to the model for four configurations: (1) Fixed base primary structure, (2) Fixed base primary structure with secondary structure, and (3) Primary structure on a subsoil base, and (4) Primary structure with secondary structure on a subsoil base.

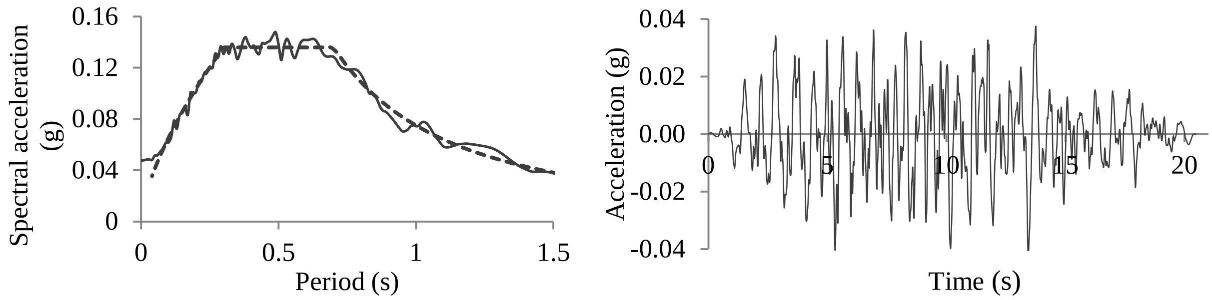

Figure 2. Ground motion characteristics, (a) target and response spectra, and (b) ground acceleration time history

Results and Discussion

Effects of PSSI on Fixed Base Structures

Figure 3 compares the horizontal acceleration of the primary structure at Level 2 with and without the secondary structure. The peak acceleration of the primary structure without the secondary structure was 0.137 g. When the secondary structure was introduced in the system, the peak acceleration was reduced to 0.128 g. This result supports the conclusion found by Lim and Chouw (2014b), in which the presence of a secondary structure reduced the maximum response of an SDOF primary structure.

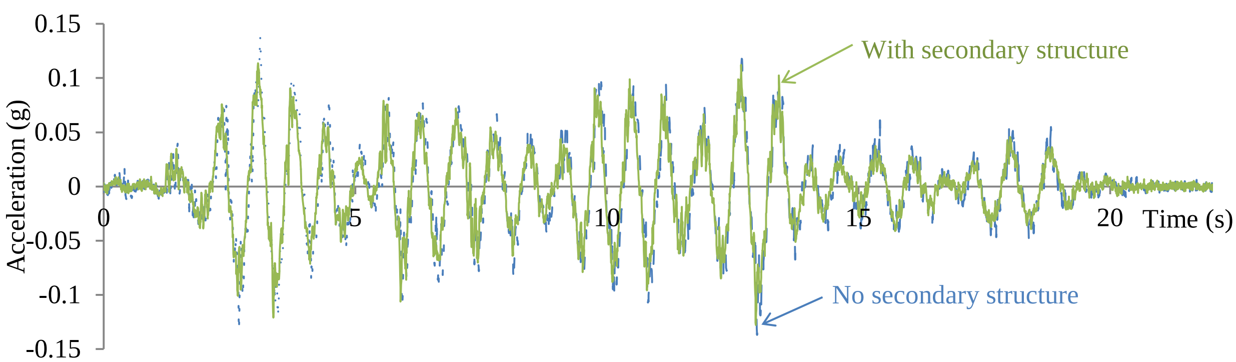

Figure 3. Reduced acceleration of the primary structure when PSSI is considered

Floor response spectra (FRS) were developed from the accelerations of the primary structure shown in Figure 3. The spectral acceleration for a 13 Hz secondary structure were 0.178 g (blue line) and 0.138 g (green line) without and with considering PSSI, respectively (Figure 4(a)). The measured peak acceleration of the secondary structure was 0.136 g. As expected, the measured peak acceleration was closer to the FRS prediction considering PSSI. The acceleration of the secondary structure itself consisted of high frequency cycles within a low frequency response (see Figure 4(b)). The dominant low and high frequencies corresponded to the fundamental frequency of the primary structure and the frequency of the secondary structure, respectively.

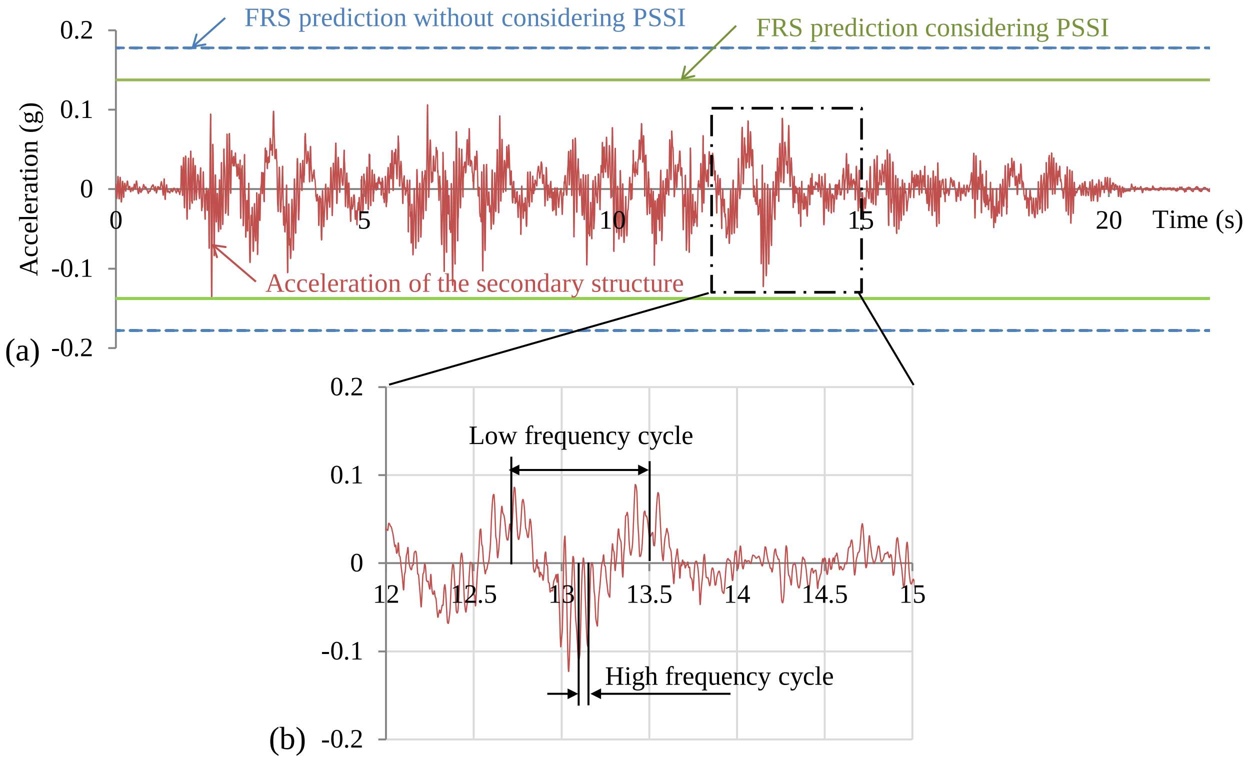

Figure 4. Response of the secondary structure (a) compared to the FRS predictions, and (b) characteristics of the response

Influence of SFSI on the Response of Structures Considering PSSI

Figure 5 compares the acceleration at Level 2 of the primary structure with fixed base and on subsoil base, without secondary structure. The peak acceleration for the fixed base case was 0.137 g while that for subsoil base was 0.084 g (Figure 5(a)). The significant reduction is likely due to the hysteretic damping withing the soil, i.e. the propagation of the earthquake energy to the structure is dissipated through soil deformation. However, the period of the response was found to be increased when SFSI was considered (Figure 5(b)). The period of the response for fixed base primary structure, T_{FB} was 1.46 s, and the period of the response for that of subsoil base, T_{SB} was 1.25 s.

Contrary to the fixed base case, the secondary structure has little effect on the response of the primary structure when SFSI is considered. Figure 6 shows the acceleration time histories of the primary structure at Level 2 on subsoil base with and without the secondary structure, and the corresponding FRS. The peak acceleration at the top of the primary structure were 0.084 g and

0.082 g without and with the secondary structure, respectively. Although the peak value is similar (see also the first peak in Figure 6(b)), the secondary structure reduces the higher mode acceleration of the primary structure (shaded region in Figure 6(b)).

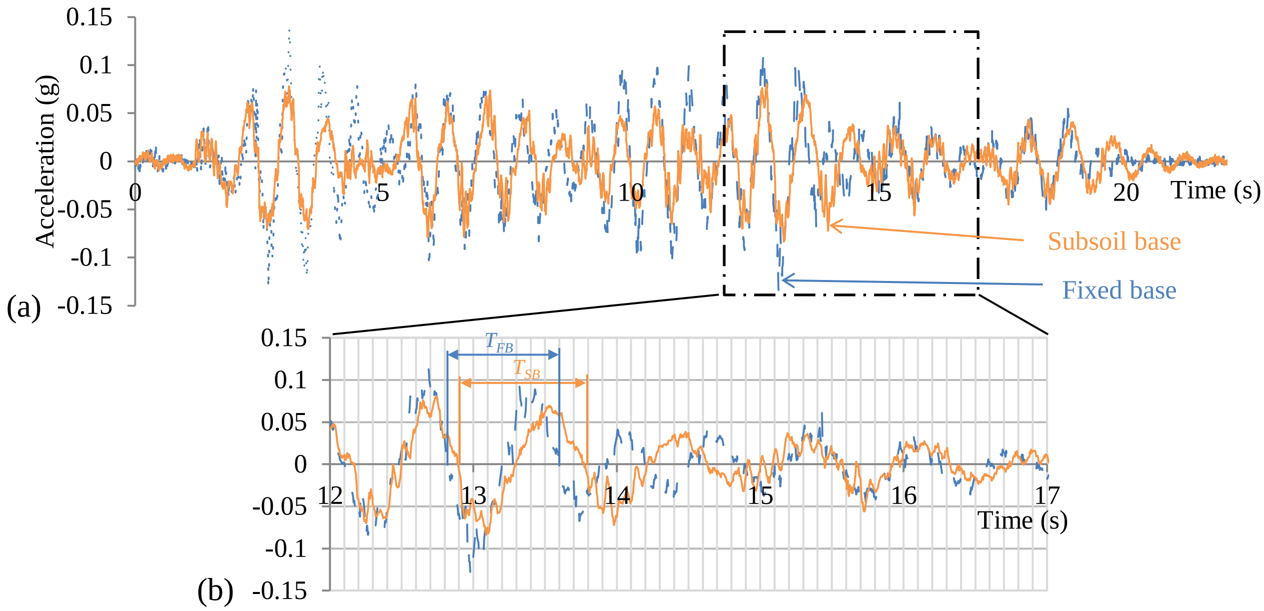

Figure 5. Influence of SFSI on the response of the primary structure, (a) reduced amplitude, and (b) increased period

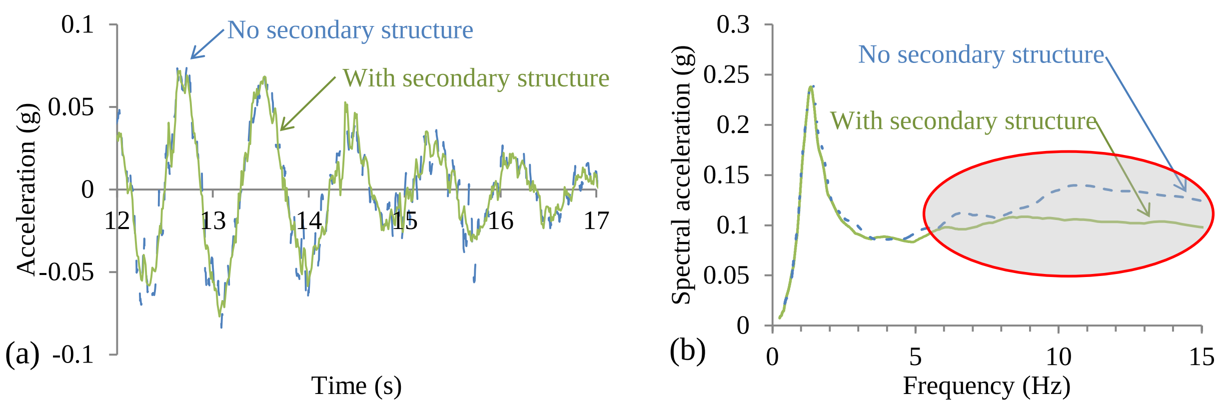

Figure 6. Effects of the PSSI when SFSI is considered on the response of the primary structure (a) Time histories, and (b) FRS

With the reduced higher mode acceleration of the primary structure, the acceleration at the top of the secondary structure was consequently reduced. Figure 7 shows the response of the secondary structure in Fourier domain. The amplitude and period of the response of the secondary structure was reduced when SFSI was taken into account. The peak acceleration of the secondary structure was 0.136 g and 0.082 g without and with SFSI, respectively. The dominant frequency of the secondary structure response for fixed base and subsoil base was 1.46 Hz and 2.44 Hz, respectively. This follows the change in the dominant period of the response of the primary structure shown in Figure 5(b). Supporting the findings in Figure 6(b), the actual high frequency response of the secondary structure was also lower when SFSI is considered compared to that without.

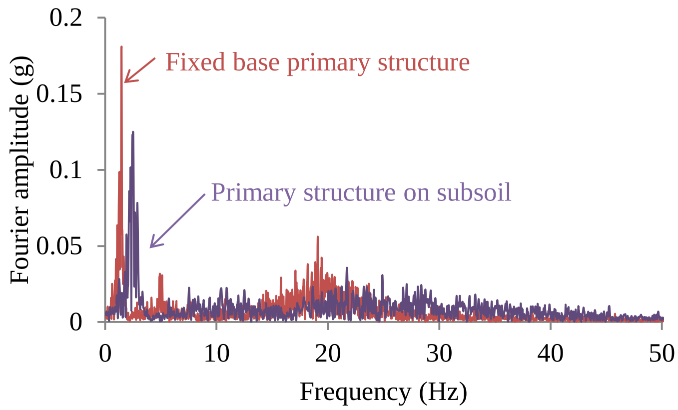

Figure 7. Effects of the SFSI on the response of the secondary structure

Conclusions

This study investigates the effect of primary-secondary structure interaction (PSSI) when SFSI is considered through experimental works. The results confirmed the findings from previous simplified works performed by the authors, and introduced new findings involving SFSI:

1. The presence of a secondary structure reduces the maximum acceleration of the primary structure.
2. FRS prediction calculated using the acceleration of the primary structure considering PSSI appears to be more accurate in estimating the peak acceleration of the secondary structure.
3. The subsoil base dissipates part of the earthquake energy through hysteretic damping, resulting in reduced acceleration of the primary structure.
4. When SFSI is considered, the effect of PSSI becomes less significant in the lower mode. However, PSSI still significantly reduces the higher mode response.
5. As the higher mode response reduces, the response of the secondary structure is also reduced. Thus, considering SFSI could possibly lead to more economical design of secondary structures.

The conclusions were drawn based on an experiment using a simulated earthquake according to the Japanese Design Spectrum for a hard soil condition. It is likely that the findings are valid only when the system is subjected to earthquakes with similar characteristics to that used in this study.

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