Experimental study of the interaction between adjacent structures

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ABSTRACT: This paper reports the results of physical experiments on adjacent structures. Six single degree-of-freedom models were considered to study a wide range of natural frequencies. Effects of an impact-like load and synthetic ground motions were studied. Models were tested in stand-alone condition and several configurations of two adjacent structures on top of a soil container. A rigid container was used for the impact load while a laminar box on a shaking table was used for the synthetic ground motions. The response of a stand-alone structure was observed to be the envelope of the adjacent configurations for the impact load. However, this phenomenon is more complex when models were subjected to ground motions. Finally, the response was compared using the response spectrum approach. Considerable differences were found between the estimation from the response spectra and the actual acceleration recorded.

1 INTRODUCTION

During the last century, soil-structure Interaction (SSI) has intended to study the effects of the support conditions in the structural response. Several closed solutions to standard problems have been developed so far. A compilation of fundamental solutions to classic elastodynamics problems was presented by Kausel (2006). Also, analytical methods as the one presented by Stewart, et al., (1999-a) have been proposed to incorporate SSI in the dynamic analysis of structures. A review of the SSI state-of-the-art can be found in Kausel (2010). However, in common practice it is usually assumed that SSI will produce beneficial effects, therefore, neglect it will lead to a conservative design. This assumption has been questioned by Mylonakis and Gazetas (2000) among other authors. They showed that SSI effects are highly complex and capable of increasing the ductility demand among other design parameters.

Additionally, SSI studies have been commonly focused on a stand-alone structure on soil. However, several authors have exposed significant effects of closely adjacent structures in the soil-structure system. Luco and Contesse (1973) have proposed the Structure-Soil-Structure Interaction (SSSI) concept to address this phenomenon. A complete SSSI literature review can be found in Lou et al. (2011). A dramatically example of the SSSI effects was presented by Lysmer, et al., (1975). The authors studied the behaviour of a nuclear containment concluding that to consider the surrounding buildings increases the response of the main structure 2.5 times. SSI and SSSI effects have also been documented based on field observations. One of the first in situ SSI observations was made by Jennings (1970). Also, Stewart, et al., (1999-b) presented an extended SSI field-study based on registers from about 60 different buildings. Regarding SSSI, the study conducted by Celebi (1993-a; 1993-b) must be the best documented on-site SSSI case.

However, relatively low attention has been paid to experimental work in SSI and SSSI fields. During the last years, some studies have attempted to fill this gap. The works conducted by Negro, et al., (2000) and Biondi, et al., (2015) studied SSI. Regarding SSSI effects, the work presented by Ge, et al., (2016) studied several structural models closely adjacent in a large soil container.

However, large-scale tests have some inconvenient. Firstly, the load is usually applied directly to the structure neglecting the soil inertial effects. Secondly, the soil container dimensions must be much larger than the structural model to represent the soil failure mechanism.

The present study intends to evaluate SSI and SSSI effects in a set of single-degree-of-freedom (SDOF) models. An impact- like load and synthetic ground motions were studied. A rigid soil container and an impact hammer were used to simulate the impact load. A laminar box and a shaking table were used to study the response under synthetic ground motions. Substantial changes in the structural response were observed when an adjacent building was considered. The presented results are focused in the linear range of the soil and structural response. However, it is expected that they serve as benchmark for future research addressing non-linear behaviour.

2 METHODOLOGY

2.1 SDOF models

Six SDOF models were built to represent different natural frequencies. The period-height relation (Eq. 1) proposed by the ASCE 7-10 (2010) was considered to design two main models.

$$T = C_t H^x \tag{1}$$

Where, H is the overall height of the building, $C_T = 0.068$ and $x = 0.8$ are parameters for steel moment resisting frames. Two groups with three models each one were built. The “short” models group (S) considered a height of 400 mm and the “tall” models group (T) considered 550 mm height, both in model scale.

Figure 1. SDOF models

A fixed-base snap-back test was used to obtain the natural frequency of the models. The fast Fourier transformation (FFT) of the acceleration on top of the model was used to obtain the natural frequency. The damping ratio was obtained using the half power bandwidth method (Chopra, 2007). Obtained parameters are summarized in Table 1.

Table 1. SDOF fundamental periods (fixed base condition)

	Model	Natural frequency [Hz]	Damping ratio
Short models H = 400 mm	S1	1.81	1.35
	S2	4.10	1.19
	S3(*)	4.86	2.51
Tall models H = 550 mm	T1	1.86	1.32
	T2	2.57	0.95
	T3(*)	3.71	2.63

(*) Correspond to the main “short” and “tall” models.

A 250 mm x 250 mm acrylic square base plate 9 mm thick was used for each model. Sand paper was glued to the base to properly represent the friction between the footing and the sand. The test configuration considered 50 mm between structures for the adjacent configurations. This distance intended to maximize the interaction avoiding pounding.

2.2 Soil conditions

To simulate soil the SDOFs models were placed on top of a sand container. For the impact test, a rigid soil container was used. The rigid walls allows the input to travel from the base (where the load was applied) to the top of the soil. Dimensions of the container were 900 mm x 800 mm and 550 mm depth. For the shaking table test a laminar box was used. Dimensions of the laminar box were 800 mm x 820 mm and 570 mm depth. The air pluviation technique was used to fill both containers. Rad and Tumay (1987) suggested that to achieve a relatively homogeneous density it is necessary to rain the sand from at least 300 mm height. In this study the minimum distance used to rain the sand was 450 mm, thus the density of the soil is assumed to be homogeneous.

A densification process was conducted in both tests to obtain a medium-dense soil condition. This intended to achieve a stable soil condition restricting possible settlement during the tests. The densification was performed using a series of masses distributed all over the soil surface (Figure 2).

Figure 2. Mass allocated for soil densification

The soil container was excited until no soil’s height variations were observed. For the impact test the box was hit using a massive hammer. For the shaking table test a sine sweep wave with frequencies from 0.01 Hz to 3 Hz and amplitude of 5 mm was used. Properties of the soil, after the densification, are presented in Table 2.

Table 2. Sand properties

Parameter	Impact test	Shaking table	Unit
Density	1536	1562	kg/m^3
Void ratio	0.74	0.71	
Relative density	58	67	%

2.3 Selected inputs

A massive hammer with a soft head was used for the impact test. The hammer was hanged from a crane to produce a similar impact force for each test. The hammer was stooped after the first impact. A general view of the impact test setup is presented in Figure 3.

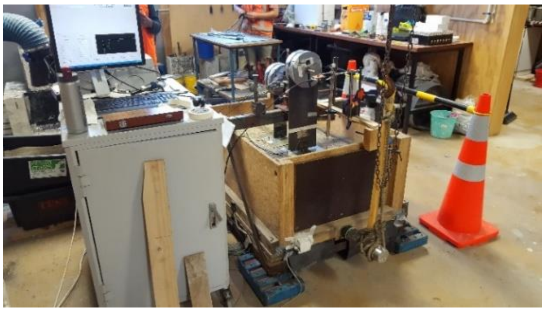


Figure 3. Impact test

For the shaking table test, three simulated ground motions based on the NZ design spectra (NZS1170.5, 2004) were considered. The selected parameters were: Z = 0.4, R = 1.0 and N = 1.0. Registers for soil class A&B (hard soil), C (medium soil) and D (soft soil) were used. The generated registers were corrected to achieve a final zero displacement. The response spectrum of the corrected register are presented in Figure 4.

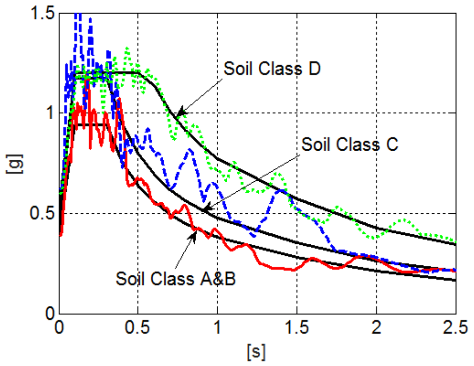


Figure 4. Ground motions response spectra

3 RESULTS

3.1 Impact test

The structural response under an impact-like load is dominated by its natural frequency on free vibration. Therefore, the influence of the natural frequency of the structure can be clearly addressed. Figure 5 shows the displacement recorded at top of model S2 in stand-alone condition and adjacent to other models.

For the case of model S2, the stand-alone condition corresponds to the envelope of all the studied cases. The higher reduction on the displacement was observed when the adjacent model has the higher natural frequency (i.e. S2/S3 and S2/T3). When model S2 was tested adjacent to T1 (low frequency model) the reduction was almost negligible.

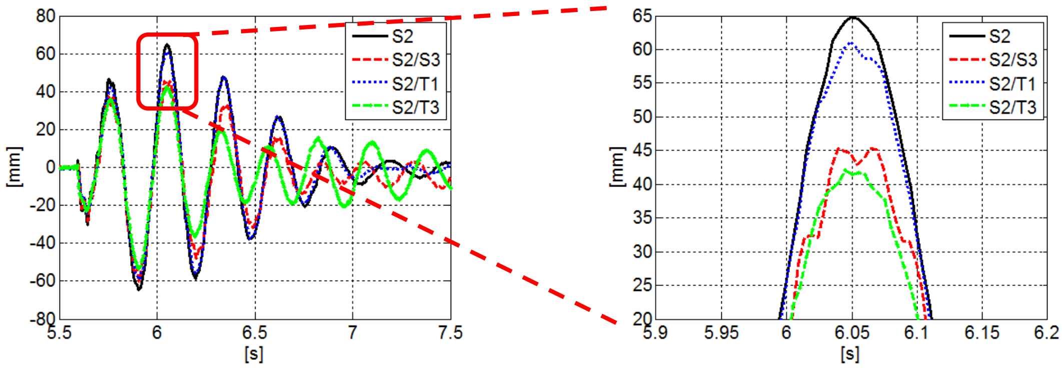


Figure 5. Displacement on top of model S2 (stand-alone and adjacent conditions)

The acceleration recorded on top of model S2 is presented in Figure 6. A slightly higher acceleration was recorded for the adjacent configurations compared with the stand-alone condition.

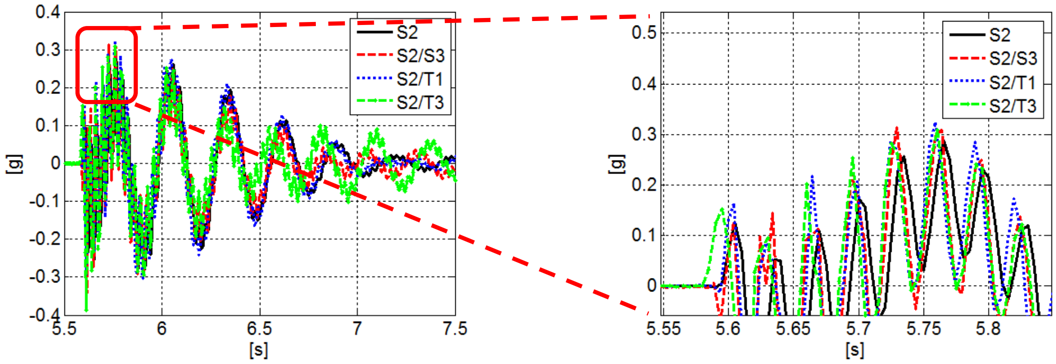


Figure 6. Acceleration on top of model S2 (stand-alone and adjacent conditions)

Commonly, structural damping is represented as a viscous equivalent coefficient. This parameters can be obtained from the decay of the response over time. Figure 7 shows the decay of the response of model S2 for two configuration of adjacent structures.

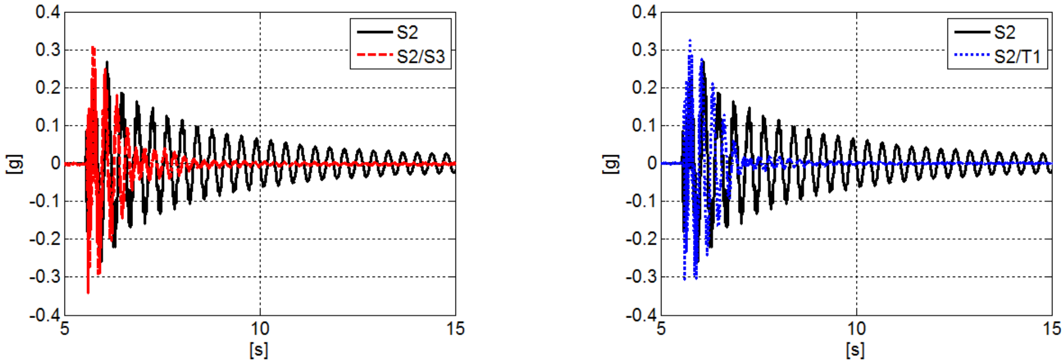


Figure 7. Decay of the response of model S2

Both cases presented in Figure 7 show a clear increment in the damping when an adjacent structure is considered. It is interesting that, even for the S2/T1 test (that presented a minor displacement reduction), a considerable increment in the damping was observed. Damping increased from a 1.2% for the stand-alone condition to about 4.0% for the adjacent configurations.

3.2 Shaking table test

Models subjected to synthetic ground motions were tested in stand-alone and adjacent configurations. Additionally, models were studied on fixed-base condition direct on top of the shaking table. Figure 8 shows the acceleration recorded on top of model S2 for the medium soil (MS) ground motion under fixed base and stand-alone conditions.

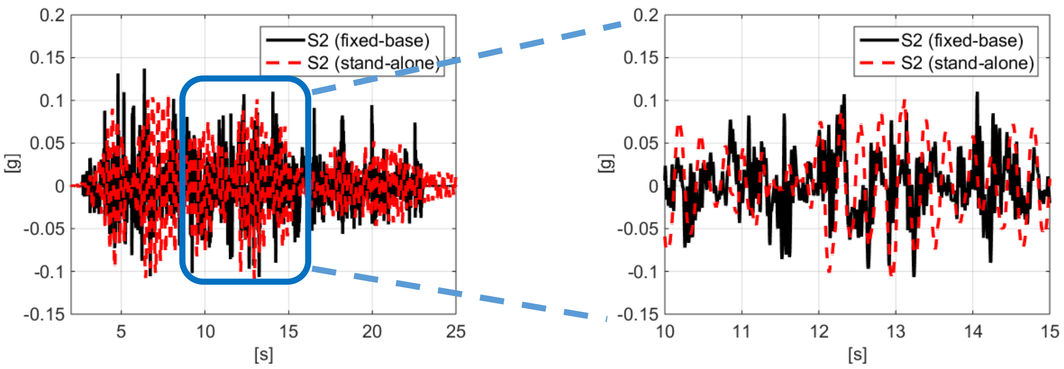


Figure 8. Acceleration on top of model S2 (stand-alone and fixed-base - MS)

Acceleration in model S2 showed areas of both, reduction and amplification. However, a clear filter in the frequency content was observed when the model was tested on soil. To study more in depth the shift in frequency content the FFT of both accelerations (fixed-base and stand-alone) were calculated. Results for all ground motions are presented in Figure 9.

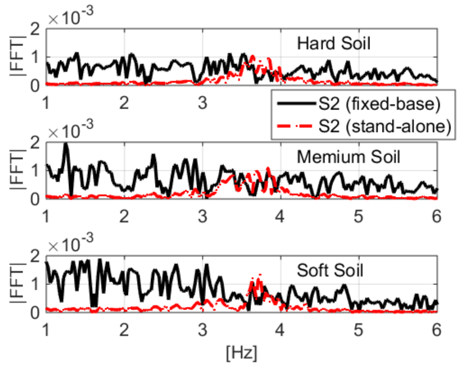


Figure 9. Acceleration on top of model S2 (stand-alone and adjacent conditions)

From Figure 9 is clear to observe that the soil filters most of the frequency that affects the structural vibrations. Therefore, to consider the influence of soil in the analysis can intensify resonance problems.

Back to the acceleration recorded on model S2, Figure 10 shows the acceleration for the MS ground motion. In general, an increment of the acceleration can be observed comparing the stand-alone condition with most of the adjacent configurations. However, if we make a zoom in the central part of the register we observe that some adjacent structures amplify the acceleration while others reduced it. The higher amplification was observed for models S2/T1 and the higher reduction for models S2/T3. As it was showed in the impact load test, when the adjacent structure has the higher natural frequency the influence seems to be beneficial.

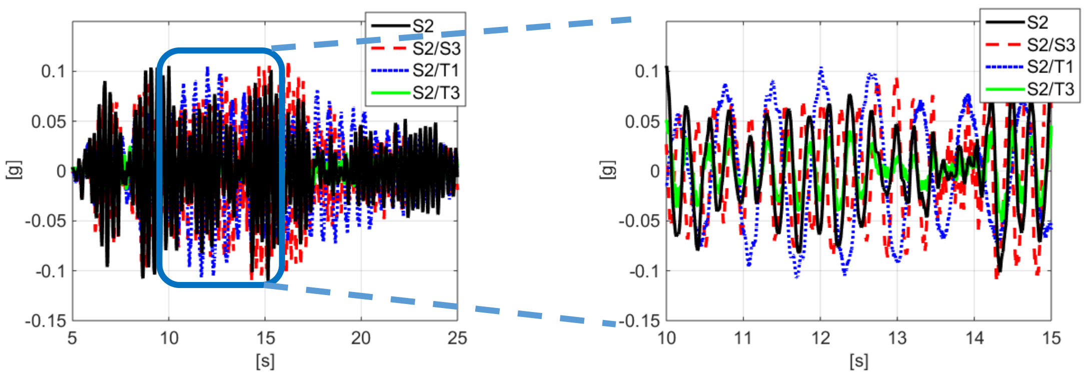
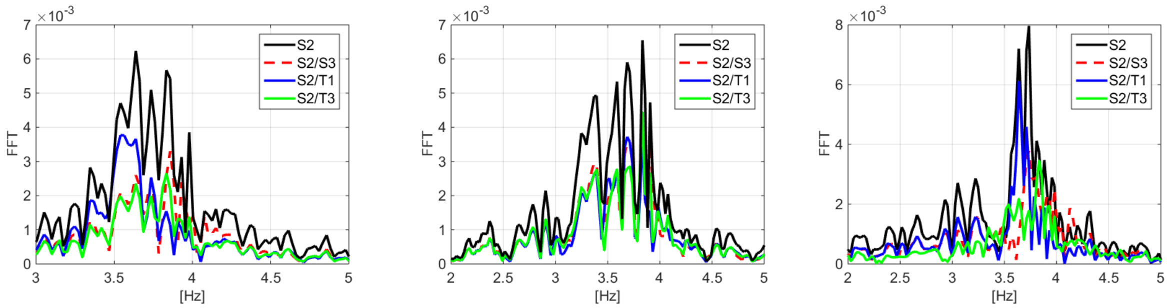


Figure 10. Acceleration on top of model S2 (stand-alone and adjacent conditions – MS)

Finally, SSI effects are commonly considered as a shift in the structural natural frequency. However, this trend has not been studied considering SSSI. Figure 11 shows the ratio in the frequency domain of the acceleration at the top to the acceleration at the base of model S2. Stand-alone and different adjacent configurations are showed for HS, MS and SS ground motions.



a. HS ground motion

b. MS ground motion

c. SS ground motion

Figure 11. FFT of the acceleration at the top of model S2

Only small variations in the main frequency were observed when an adjacent structure was considered. However, a slight reduction was observed for when model S2 was tested adjacent to T1 (S2/T1). Other configurations seems to slightly increase the natural frequency. However, these changes are not strongly significant. Therefore, additional research is recommended to clarify this possible influence.

4 CONCLUSIONS

The interaction between pairs of adjacent SDOF models was investigated. An impact-like load and a synthetic simulated ground motions using a shaking table were studied. Support conditions were simulated using a soil container. The soil considered was a medium-dense sand. Models in stand-alone and several adjacent configurations were tested. The presented results are focused in the linear range of the soil and structural response.

Regarding the impact test, a reduction in the recorded displacement was observed for all the adjacent configurations. This effects was higher when the adjacent structure has the lowest natural frequency. However, regarding the acceleration, an amplifications was observed when an adjacent structure was considered. The natural frequency of the model seems to have a high influence on the observed changes.

The interaction observed during the shaking table was more complex showing both reduction and amplification zones. However, some trends were observed. Firstly a "filter" of the signal was recorded when the structure was tested alone on soil compared to the fixed-base condition. Therefore, resonance effects could be more significant if the soil influence is considered. A slight shift in the natural frequency was observed for some adjacent configurations compared to the stand-alone case.

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