Dynamic response of adjacent structures in earthquakes

G. Barrios[1], X. Qin[2] and N. Chouw[3]

1. Corresponding Author. PhD student, Department of Civil and Environmental Engineering, the University of Auckland, Auckland, New Zealand.
   Email: gbar737@aucklanduni.ac.nz

2. Postdoctoral researcher, Department of Civil and Environmental Engineering, the University of Auckland, Auckland, New Zealand.
   Email: xqin009@aucklanduni.ac.nz

3. Associate Professor, Department of Civil and Environmental Engineering, the University of Auckland, Auckland, New Zealand.
   Email: n.chouw737@auckland.ac.nz

Abstract

The response of structures in urban areas is influenced not only by the foundation soil but also by adjacent structures. Recent researches have shown that the interaction between adjacent structures can generate beneficial or detrimental effects depending on the properties of the involved structures. Even though, the interaction between adjacent structures has been addressed in the last years, most of the last research have considered either a numerical approach or a small number of laboratory tests. In this work, different configurations of adjacent structural models were tested using a large laminar box filled with sand. A shake table was use to simulate real ground motions. Recorded ground motions from the Canterbury earthquake sequence (2010 – 2011) were used. Two, and three closely adjacent structures in the direction of the shaking were tested. Results were compared with the same models on stand-alone condition. Changes in the acceleration at the roof height of the models were investigated. Observations are compared to results recently presented by other authors using numerical models and laboratory tests.

Keywords: Adjacent structures, Structure-Soil-Structure interaction, Cross-dynamic interaction

1 INTRODUCTION

A common assumption in structural design is to consider a fixed-base condition. Until the late part of the 20th century, this assumption was considered conservative. However, Mylonakis and Gazetas (2000) exposed the detrimental Soil-Structure Interaction (SSI) effects. Other authors such as Dutta et al. (2004) and Ghosh and Madabhushi (2007) have also exposed the complexity of SSI and its detrimental effects.

During the second part of the 20th century, the rise of nuclear energy encouraged researchers to develop more precise design procedures. One of the main focus was to study structures considering the entire structure-foundation-soil system. Nuclear facilities commonly consist of several critical structures built close to each other. Therefore, the response of closely adjacent structures has also become relevant. Luco and Contesse (1973) were the first authors to address the Structure-Soil-Structure Interaction (SSSI) concept to refer to the interaction between adjacent buildings. The waves generated due to the vibration of the footing of the building interact with the waves generated by closely adjacent buildings. The waves interacting can either be amplified or reduced at different times during the ground motion. One of the first analytical models to study the response of two and three structures was presented the same year by Lee and Wesley (1973). Several researchers have developed other analytical models to estimate the SSSI effects. Recently, Aldaikh et al. (2015; 2016) presented results from both, laboratory tests and a numerical model addressing two and three adjacent structures (see Figure 1). Based on their finding, the authors developed curves to show the possible beneficial or detrimental effect of SSSI compared to the case when the structure is analysed on a stand-alone condition (i.e. the influence of the adjacent structure).

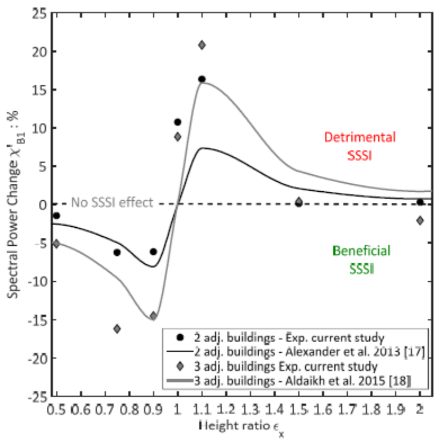


Figure 1. Acceleration amplification (Aldaikh et al. 2016)

Although, great contributions in the SSSI field has been presented in the past years, most of the works have either considered a numerical approach or only a small number of laboratory tests. Even though numerical models are a powerful tool to study Soil-Structure Interaction problems, a high variability in the results can be obtained depending on the modelling assumptions and many other characteristics of the considered software (Regnier et al. 2016). In the laboratory field, using a geotechnical centrifuge, Knappett et al. (2015) showed the differences in the response of a stand-alone structure compared to two adjacent structures. Recently, Ge et al. (2016) presented results from a study considering five single-degree-of-freedom (SDOF) models on top of large soil container subjected to different type of ground motions. Despite the valuable contribution and the complexity of the exposed works, further research is necessary to validate, contrast and extend results from the existing studies.

To help filling this gap, the response of single-degree-of-freedom (SDOF) models on top of a large laminar box was studied. The models presented different heights to achieve different natural frequencies, other characteristics (i.e. column cross-section, footing dimensions and top mass) were the same across all the models to reduce the number of variables involved. Two and three models closely adjacent (in the direction of the shaking) were studied. Results from the adjacent configurations were compared with the response of the model alone on the centre of the soil container. Obtained results are compared with curves presented by other authors (Aldaikh et al. 2016).

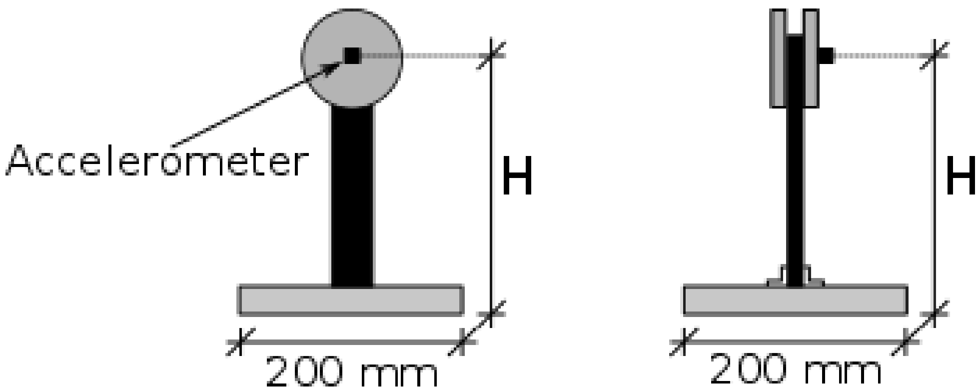
2 METHODOLOGY

A large laminar box with 2 m x 2 m of cross-section and 1.5 m height was used. The box was filed with Waikato river sand (Table 1). After filling the box, a white noise low-amplitude ground motion was applied to obtain a stable soil condition during the test. The white noise was filtered using a band-pass Butterworth filter between 0.1 to 10 Hz. Consecutive shakes were performed until no variation in the sand height was recorded. A final density of 1.57 kg/cm3 (Dr=51%) was obtained. Additionally, the shear wave velocity (V_s) was measured by impacting a rigid steal plate on top of the soil. The delay on the recorded acceleration at different depths were used to estimate V_s obtaining an average value of 147 m/s and 151 m/s at the beginning and the end of the test respectively.
The small change in V_s indicates that the soil conditions keeps relatively constant across the tests. Data was recorded at 200 Hz. Records from accelerometers were filtered using a bandpass Butterworth filter between 0.1 and 50 Hz.

Table 1. Sand properties

Property	Mixed sand
Specific gravity	2.65
e_{max}	0.79
e_{min}	0.59
D_{50}	0.67

Three SDOF models were built using a single steel column 50 mm width and 5 mm thick. A total weigh of 275 N of mass were located on top of every model. A 200 mm x 200 mm steel plate 25 mm thick was used as the base of the models (Figure 2). Three different height were used to obtain different natural frequencies. Models M1, M2 and M3 have a height of 600 mm, 450 mm and 350 mm respectively. Properties of the models are presented in Table 2.



a. Frontal view b. Lateral view

Figure 2. Acceleration amplification (Aldaikh et al. 2016)

Table 2. Models properties

Model	Height (m)	Frequency (Hz)
M1	0.60	1.54
M2	0.45	2.29
M3	0.35	3.79

A total of four identical M2 models were built to study the response of models with the same frequency. The models were firstly tested in stand-alone condition (test SSI), later two (test SSSI-2), and three (tests SSSI-3) closely adjacent models were tested. All the configurations considered the structures closely adjacent in the direction of the shaking. The configurations tested are presented in Table 3.

Table 3. Test configurations

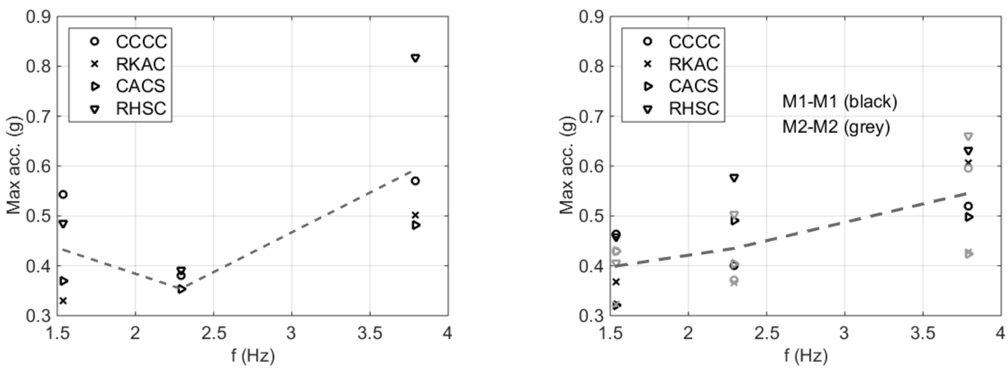
Main test	Configurations			
Stand-alone (SSI)	M1	M2	M3	
Two adjacent models (SSSI-2)	M1-M2	M1-M3	M2-M2	M2-M3
Three adjacent models (SSSI-3)	M2-M1-M2	M2-M1-M3	M2-M2-M2	M2-M2-M3

The acceleration was recorded on top and at the footing of each model. The displacement at the roof height of the models was also measured (roof height corresponds to the height indicated in Table 2). Additionally, the rocking of the models was measured using LVDTs. However, due to the extension limit of this report, results are only focused on the acceleration at the roof of the models.
Records from the Christchurch Cathedral (CCCC) and Rakaia School (RKAC) stations (4th September, 2010) and stations Christchurch Canterbury A (CACS) and Riccarton High school (RHSC) (22th February, 2011) were used as ground motions.

3 RESULTS

3.1 Two adjacent models (SSI)

Figure 3-a and Figure 3-b show the maximum acceleration recorded the models for the stand-alone (SSI) and two adjacent models (SSSI-2) respectively. Results are plotted for the natural frequency of each model.



c. Maximum acceleration for Stand-alone cases

d. Maximum acceleration for two adjacent models

Figure 3. Maximum acceleration for stand-alone and two adjacent models

In both graphs, a grey dashed line presents the average values. For the low frequency (M1 – 1.54 Hz) and high frequency (M3 – 3.79 Hz) models values obtained are fairly similar in both tests. However, the middle frequency (M2 – 2.29 Hz) showed a lower response under stand-alone condition compared to the two adjacent models.

In order to study the influence of the natural frequency of both (adjacent) models, the maximum acceleration ratio (χ) was study (Eq. 1).

$$\chi = \frac{max\ acc\ (2\ adj.)}{max\ acc\ (Stand-alone)} = \frac{max\ acc\ SSSI}{max\ acc\ SSI} \quad (1)$$

The maximum acceleration ratio is presented in Figure 4. Results are shown in terms of the ratio of the natural frequency of the adjacent model to the natural frequency of the model where the acceleration was measured (f_{ad}/f). The grey horizontal line splits the amplification (detrimental) and reduction (beneficial) zones over and under the line respectively. The grey dashed line shows the average values for the studied frequency ratios.

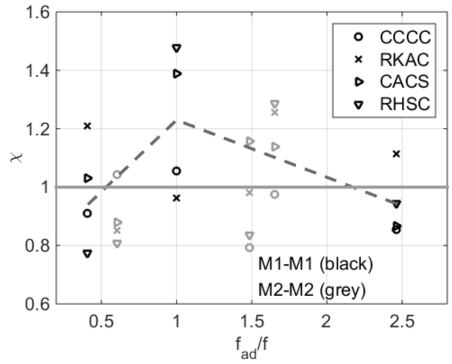


Figure 4. Acceleration amplification for two adjacent models compares to stand-alone case

For frequency ratios f_{ad}/f lower than 0.5 and larger than to 2.5 a reduction on the response was observed. However, for values between 1.0 and 1.5 the acceleration for the SSSI-2 tests was amplified compared to the stand-alone case (SSI). Therefore, models with fairly similar natural frequencies seem to have a detrimental behaviour when they are tested closely adjacent.

3.2 Three adjacent models (SSSI-3)

The tested configurations of three adjacent models were the same as the two adjacent models but considering an additional M2 model (see Table 3). This is intended to fix the effects of the natural frequency of the additional adjacent model. The average of the maximum accelerations recorded for the stand-alone, 2 adjacent (SSSI-2) and 3 adjacent (SSSI-2) test are presented in Figure 5. The response of model M1 (low frequency) and M3 (high frequency) for the configurations of two and three adjacent models presented a reduction compared to the stand-alone condition. However, model M2 presented an amplification in the acceleration. This amplification was lower for SSSI-3 than for SSSI-2.

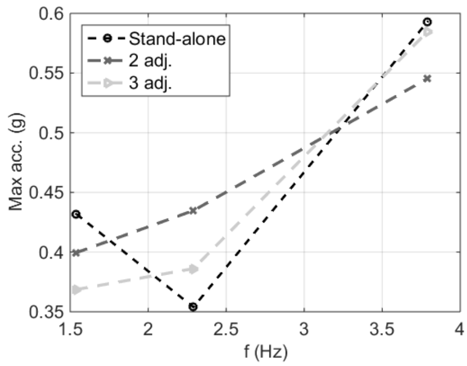


Figure 5. Average maximum acceleration for all the tests

Figure 6 shows the maximum acceleration ratio (χ) for the SSSI-3 tests. The general shape is similar to the one for the SSSI-2. However a lower amplification in the central area and a larger reduction at high frequency ratio were observed.

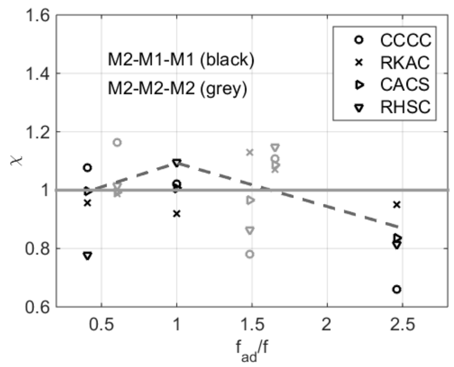


Figure 6. Acceleration amplification for three adjacent models compares to the stand-alone case

Finally, the average curves for SSSI-2 and SSSI-3 tests are presented in Figure 7. The acceleration amplification is presented in terms of the f_{ad}/f ratio. Both curves presented a similar shape. However, SSSI-3 presented a lower maximum amplification.

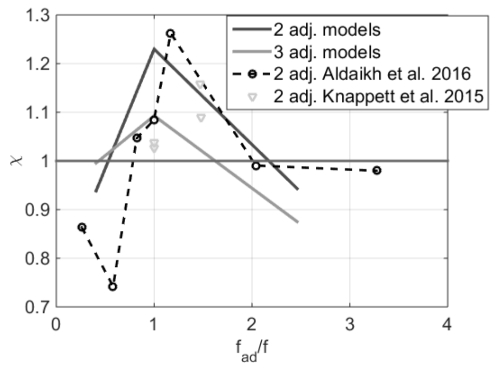


Figure 7. Amplification for two and three adjacent buildings

Results are compared with the curve presented by Aldaikh et al. (2016). The authors considered a similar type of structures (SDOF models) but the soil was represented using a foam block. The models also covered the entire direction perpendicular to the shaking direction.

The Results for two adjacent models are fairly similar to the curve presented by Aldaikh et al. (2016). Zones of reduction were observed for values of f_{ad}/f lower than 0.5 and larger than 2.2. The region between 0.8 to 2.2 presented amplification with a peak value close to 25%. When three adjacent models were tested the amplification zone was reduced to f_{ad}/f between 0.5 to 1.8. Additionally, the maximum amplification reduced from close to a 25% to a 10%. When three adjacent models were considered, the reduction was larger for large values of f_{ad}/f (larger than 1.8) compared to those from the two adjacent models.

4 CONCLUSIONS

The presented research studied the response of single-degree-of-freedom (SDOF) models on top of a large laminar box under different configurations of two and three closely adjacent models. The models presented different heights to achieve different natural frequencies. Records from the Canterbury earthquake sequence were used. Results from two and three closely adjacent models (in the direction of the shaking) were compared to the results from the same models on a stand-alone condition. Obtained results are also compared with curves proposed by other authors.

The low (M1) and high frequency (M3) models under a SSSI-2 configuration presented similar acceleration than the stand-alone condition. However, model M2 presented an amplification in the acceleration. The acceleration amplification was also presented in terms of the ratio of the frequency of the adjacent model to the main model (f_{ad}/f). This intended to study the influence of both natural frequencies (i.e. the main and the adjacent model). A zone of amplification was observed for values of f_{ad}/f between 0.8 to 2.2, whereas outside this range there was a reduction in the maximum acceleration. This curve presented a similar shape compared to the curve previously proposed by other authors.

The maximum acceleration recorded for three adjacent models (SSSI-3) presented the smallest acceleration for the low frequency model (M1). Model M2 presented an intermediate value between the stand-alone condition (lowest value) and the SSSI-2 tests (highest value). Model M3 showed a similar acceleration compared to the stand-alone condition. The amplification curve obtained for SSSI-3 had the same shape as the one for SSSI-2. However, the maximum amplification was lower and the region of amplification was reduced.

REFERENCES

Aldaikh, , Alexander, A, Ibraim, & Knappett, J 2016, 'Shake table testing of the dynamic interaction between two and three adjacent buildings (SSSI)', *Soil Dynamics and Earthquake Engineering*, vol 89, pp. 219-232.

Aldaikh, , Alexander, , Ibraim, & Oddbjornsson, O 2015, 'Two dimensional numerical and experimental models for the study of structure-soil-structure interaction involving three buildings', *Computers & Structures*, vol 150, pp. 79-91.

Dutta, , Bhattacharya, & Roy, R 2004, 'Response of low-rise buildings under seismic ground excitation incorporating soil-structure interaction', *Soil Dynamics and Earthquake Engineering*, vol 24, no. 12, pp. 893-914.

Ge, , Xiong, , Zhang, & Chen, J 2016, 'Shaking table test of dynamic interaction of soil-high-rise buildings', *European Journal of Environmental and Civil Engineering*, pp. 1-23.

Ghosh, B & Madabhushi, S 2007, 'Centrifuge modelling of seismic soil structure interaction effects', *Nuclear Engineering and Design*, vol 237, no. 8, pp. 887-896.

Knappett, JA, Madden, P & Caucis, K 2015, 'Seismic structure-soil-structure interaction between pairs of adjacent building structures', *Geotechnique*, vol 65, no. 5, pp. 429-441.

Lee, TH & Wesley, DA 1973, 'Soil-structure interaction of nuclear reactor structures considering through-soil coupling between adjacent structures', *Nuclear Engineering and Design*, vol 24, no. 3, pp. 374-387.

Luco, J & Contesse, L 1973, 'Dynamic structure-soil-structure interaction', *Bulletin of the Seismological Society of America*, vol 63, no. 4, pp. 1289-1303.

Mylonakis, & Gazetas, G 2000, 'Seismic soil-structure interaction: beneficial or detrimental?', *Journal of Earthquake Engineering*, vol 4, no. 3, pp. 277-301.

Qin, X 2016, 'Experimental studies of structure-foundation-soil interaction effect on upliftable structures', Doctoral thesis, The University of Auckland, Auckland, New Zealand.

Regnier, , Bonilla, L-F, Bard, P-Y, Bertrand, , Hollender, , Kawase, , Sicilia, , Arduino, , Amorosi, & Asimaki, 2016, 'International benchmark on numerical simulations for 1D, nonlinear site response (PRENOLIN): Verification phase based on canonical cases', *Bulletin of the Seismological Society of America*, vol 106, no. 5, pp. 2112-2135.