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Experimental Analysis of the Seismic Response of Cluster Structures

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Abstract

Structures in densely populated areas are commonly built close to one another. When these structures are subjected to a dynamic load, the small separation generates cross-interaction effects via the common soil. This study investigates the seismic response of structures with and without the presence of adjacent structures using a shake table and a large laminar box. The laminar box was filled Waikato river sand. A total of four records form the Canterbury earthquake sequence (2010-2011) were applied. Three single-degree-of-freedom (SDOF) models with different natural frequencies were considered. The models were tested on top of the laminar box in different configurations. Firstly, three adjacent models in the direction of shaking were studied. Later, clusters of six models (two rows of three models in the direction of shaking at a short distance in the perpendicular direction) were tested. Accelerometers were placed on the top part of the models to measure the seismic response. Results indicate that the configuration of building models can have a beneficial or detrimental influence depending on the properties of the models.

Keywords: SSSI, clustered structures, cross-dynamic interaction, large shake-table

1 INTRODUCTION

The continuous rise in the global population is placing increased demands on the construction of buildings in densely populated urban areas. To meet these demands, structures have been built close to each other, generating large clusters of buildings. However, current design methods do not consider the influence of nearby structures during earthquakes. Kitada et al. (1999) studied of the effects of an adjacent building in the natural frequency of nuclear facilities. Knappett et al. (2015) showed changes in the structural drift and other parameters due to the presence of an adjacent structure. More recently, Mirzaie et al. (2017) showed the effects of the foundation soil on the ductility demand of structures using a probabilistic approach.

The concept of Structure-Soil-Structure Interaction was proposed by Luco and Contesse (1973) to address the seismic response of adjacent structures. The authors concluded that the seismic response of low frequency structures was more sensitive to the presence of an adjacent structure. However, limited experimental research regarding the effect of adjacent structures is available. Boutin et al. (2014) studied the response of a large number of models subjected to dynamic loads using a polyurethane block to represent the soil. A similar approach was used by Aldaikh et al. (2016) to study the response of two and three adjacent models. The authors also developed a macro-element model to estimate the response of adjacent structures. Even though these works have provided valuable insight into the response of adjacent structures, a proper representation of the soil is crucial to validate their results. The work of Bolisetti (2015) provides an updated framework on the performance building assessment considering the interaction between multiple structures. Geotechnical centrifuges have also been used to study SSSI. The work presented by Knappett et al. (2015) remarked the importance of adjacent buildings in the permanent deformation of structures under earthquake loads. Chen, et al. (2010) also studied the building-foundation response under dynamic loads emphasising the need to recognise the influence of adjacent structures in the design practice.

Other approaches to study soil-foundation systems include the use of large (1g) shake tables and flexible soil containers. These facilities have the advantage of a lower cost and less geometric (and size) restrictions compared to geotechnical centrifuges. However, limited experimental studies using large shake tables are available. The work presented by Ge et al. (2016) has been one of the few studies to utilise a large shake table and a big soil container to study SSSI. The authors compared the response of a stand-alone model, with the same model but surrounded by four identical models (one at each side).

This study evaluates the response of three closely adjacent models in the direction of the shaking and in clustered configurations (total of six models), using a large shake table and a laminar box. Three different natural frequencies are considered through varying the height of the models. Four ground motions from the Canterbury earthquake sequence (2010-2011) are considered. The response of the models was compared to the response on a stand-alone condition. Changes in the maximum acceleration and spectral acceleration are presented.

2 METHODOLOGY

Experiments were conducted using a laminar box (2 m x 2 m x 1.5 m), no a large shake table. The laminar box was filled with Waikato river sand. The sand was clean and poorly-graded with angular particles. Table 1 shows the parameters of Waikato river sand.

Table 1. Sand parameters

Parameter	Impact test	Shaking table	Unit
Density	1.59	1.60	Kg/m3
Void ratio	0.66	0.65	
Dr	50.4	56.2	%
Specific gravity	2.64		
Minimum void ratio	0.55		
Maximum void ratio	0.78		

Ground motions from the Canterbury earthquakes sequence (2010-2011) were utilised. A total of four registers were considered, two from September 2010 and two from the subsequent February 2011 earthquake. Some parameters of the selected ground motions are presented in Table 2.

Table 2. Ground motions parameters

	4/9/2010		22/2/2011	
Station	CCCC	RKAC	CACS	RHSC
Mw	7.1		6.3	
PGA (g)	0.22	0.21	0.19	0.30
PGV (m/s)	34.5	16.0	28.4	28.4
PGD (mm)	14.8	9.21	3.30	14.6

Three single-degree-of-freedom (SDOF) models were studied. Models were built using a single steel column fixed to a rigid base (inverted pendulum). The models varied only in height to achieve different natural frequencies. Properties of the models are listed in Table 3. Additional four intermediate frequency model (M2) were built to generate the different configurations.

Table 3: Model Features

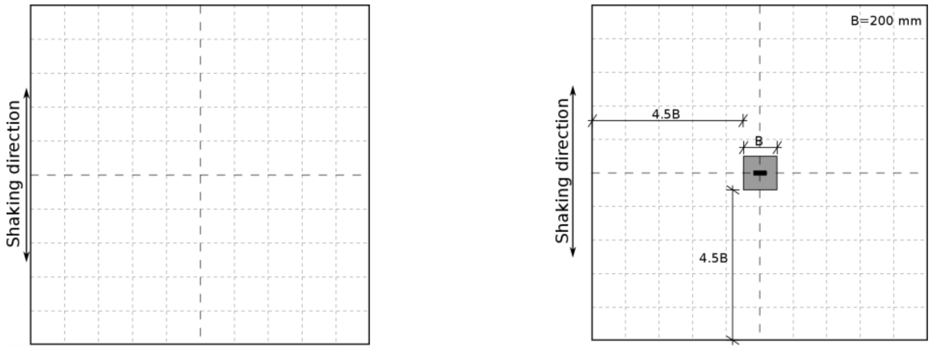
	M1	M2	M3
Height (m)	0.6	0.45	0.35
Frequency (Hz)	1.37	2.29	3.79
Mass (N)	275	275	275

A total of nine configurations were tested. Firstly, free-field (FF) tests (no structures) was conducted as a benchmark. Secondly, the models were tested on a stand-alone condition at the centre of the laminar box. These results provided a baseline reference for comparisons to other configurations. Thirdly, models were tested in groups of three closely adjacent in the direction of the shaking. Finally, two rows of three models (as in the previous case) were tested closely adjacent in the perpendicular direction of shaking. Table 4 summaries the tested configurations and a schematic top view of the tests can be seen in Figure 1. A total of four configurations of three adjacent and two of six clustered models were tested.

Table 4. Test configurations

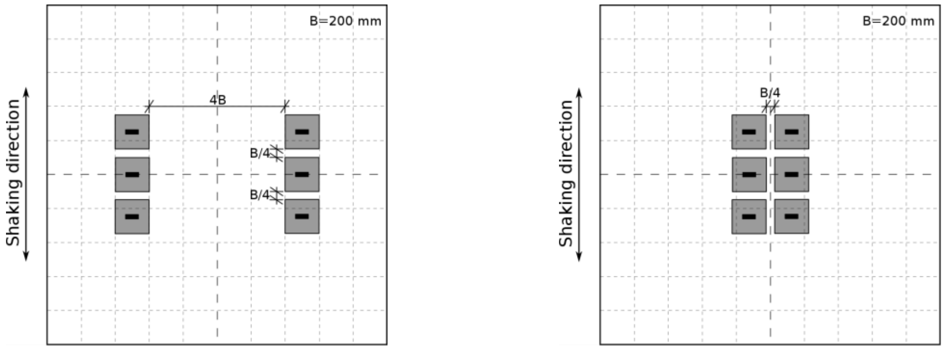
Test	**Configuration**			
	1	2	3	4
Stand-alone (SSI)	M1	M2	M3	
Three adjacent models (SSSI-3)	M2-M3-M1	M2-M2-M2	M2-M3-M2	M2-M1-M2
Six clustered models (SSSI-6)	M2-M3-M1 & M2-M2-M2	M2-M3-M2 & M2-M1-M2		

Figure 1-a shows the FF condition; Figure 1-b the stand-alone case; Figure 1-c the three adjacent models. Two adjacent configurations of three models were tested simultaneously at a large distance in the perpendicular direction of the shaking. This distance is intended to minimise any interaction between the two rows of models. Finally, Figure 1-b shows the configuration of six clustered models.



a. Free-field condition

b. Stand-alone condition



c. Three adjacent models

d. Six clustered models

Figure 1. Different configurations tested.

Two accelerometers were placed on each model, one on the mass at the top and one on the base. Two LVDTs were located on the extremes of each model base (0.17 m apart) to measure rocking movements. A strain gauge was fitted to each model at the column. Lasers were pointed horizontally towards the top masses to measure the lateral displacement of the models. Due to the limited extension of this report, the presented results are based on records from the accelerometers on the top mass and the footings of the models.

3 RESULTS AND DISCUSSION

3.1 Response spectrum

The response spectrum from an accelerometer located 0.05 m beneath the surface at the centre of the soil container is presented in Figure 2. The values for free-field, stand-alone (for model M2) and the two clustered configurations are presented. Results corresponds to the RKAC ground motion.

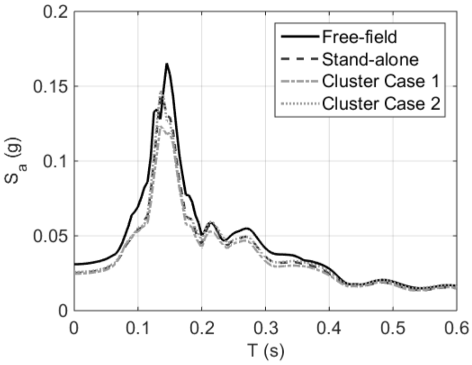


Figure 2: Response spectrum of acceleration 0.05 m beneath the surface at the centre of the laminar box

The spectral acceleration of all the configurations presented a lower value than that for the free-field case. The cluster configurations presented a lower acceleration than the stand-alone condition. The response spectrum for the same cases, but from the acceleration at the base of model M2, is presented in Figure 3. Only the case when model M2 was at the centre of the cluster was considered.

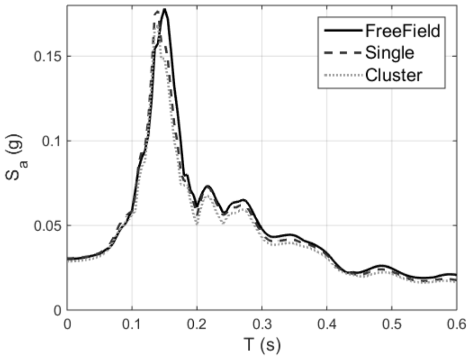


Figure 3: Response spectrum for model M2 (RKAC)

In this case, the maximum spectral acceleration was similar for all the studied cases. No reduction was observed like it was when the acceleration was recorded beneath the surface (see Figure 2). However, the peak slightly shifts to a lower period. This shift can significantly affect the response of the structure if it is located close to the peak zone.

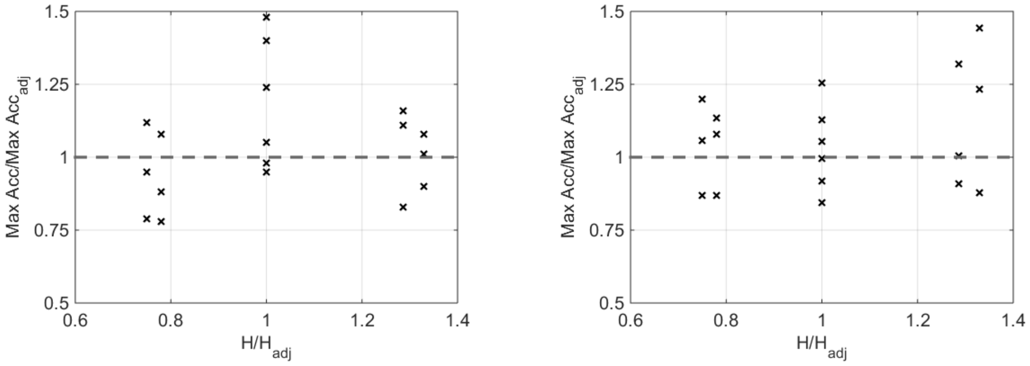
3.2 Acceleration amplification

The actual response of the models was addressed in terms of the peak acceleration ratio. The acceleration ratio was defined as the maximum acceleration of a model for the adjacent or clustered configuration divided by the maximum for the stand-alone condition (Eq. 1). Results are presented in terms of the ratio of the height between adjacent models (Eq. 2).

$$Acceleration\,ratio = \frac{\max(acc_{adj/cluster})}{\max(acc_{stand-alone})} \quad (1)$$

$$Height\,ratio = \frac{H_{main}}{H_{adj/cluster}} \quad (2)$$

Figure 4-a, and b show the acceleration ratio for the three-adjacent and six clustered configurations respectively. A grey line divides the detrimental (above the line) and beneficial (under the line) areas.



a. Three adjacent models

b. Six clustered models

Figure 4: Peak Acceleration ratio for adjacent and clustered configurations

For the three adjacent models cases (Figure 4-a), an amplification can be seen in the centre region (where both models have the same height). Other regions show data distributed close to the non-influence line (value of 1). Figure 4-b (clusters) shows an incremental amplification with increasing height ratio. However, the height ratio was obtained considering only the models adjacent in the direction of the shaking. Therefore this parameter seems not be the most adequate to represent configurations with models in the direction perpendicular to that of the shake.

As it was expected, the influence of adjacent structures cannot be fully addressed using the concept of response spectrum. The response of the structures and amplification areas were only observed when the actual acceleration was measured on the models.

4 CONCLUSIONS

Configurations of adjacent and clustered models were tested using a large laminar box on a shake table. Records form the Canterbury earthquake sequence (2010-2011) were applied. The response of the models was compared in terms of the recorded acceleration at different locations. The different configurations were compared to the stand-alone condition. The main conclusions of this report are listed below.

- When three adjacent models with the same height were tested, the response was amplified compared to the stand-alone case. When the models had different heights (height ratios different than one) the response was close to the stand-alone case. However, for the cluster configurations, the larger the height ratio the larger the maximum acceleration amplification.
- The height ratio definition must be modified to properly address the effect of adjacent structures in the direction perpendicular to that of the shake.

- A reduction on the spectral accelerations beneath the soil was recorded for all the tested configurations compared to the free-field condition. The cluster configuration presented the larger reduction.
- When the spectral acceleration was obtained from the accelerometer at the base of the model, all the cases presented a similar peak value. However, the tested configurations presented a shift in the period where the peak value is generated.
- A low influence of the models was observed on the spectral acceleration away from the vicinity of the peak value.
- The response spectrum does not properly represent the response of adjacent structures under dynamic loads.

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