Impact of existing structures on soil response during earthquakes

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ABSTRACT: Soil-structure interaction is a process where the soil response affects the structural response and vice versa. The vibrating structure interacts with the surrounding soil through the forces activated at the interface between footing and foundation soil. These forces generate waves from the interface which interfere with the waves arriving from below and transmit part of the vibration energy of the structure. Consequently, the ground motions at the footing-soil interface are not the same as those under free-field conditions at the same depth. However, in current design practice, the response of a structure to earthquakes is estimated using the free-field ground motions, i.e. the structural response are obtained using incorrect loading. This study focuses on the investigation of soil-structure interaction effects on the soil response. Experiments are conducted using a shake table. A laminar box is used to simulate a more realistic soil stress-strain field. Two different single degree-of-freedom structures with shallow foundations were considered. Experimental results show the rotation of the shallow foundation can play a significant role. This finding confirms that the loading of the structure during an earthquake cannot be accurately estimated using free-field ground motions.

1 INTRODUCTION

Following the recent Christchurch earthquakes, much research has been carried out to improve the seismic resistance of structures. A particular issue that has long been overlooked in structural design is the lack of consideration of soil-structure interaction (SSI). It is common to assume that the seismic motions at the base of a structure are the same as the free-field ground motions. Consequently, free-field ground motions are used to estimate the response of a structure. However, this is only true when the supporting soil is rigid and the structure is fixed to the ground. In reality, the supporting soil is deformable. Consequently, the structural response with SSI can be significantly different from that estimated using free-field ground motions. Foundation rocking and sliding may also occur and contribute to the difference (Poland et al. 2000).

In current design practice, structures are designed under a fixed-base assumption. However, as mentioned earlier, structures are flexibly supported. The structure-soil system has a longer natural period than that of the structure with an assumed fixed base (e.g. Larkin 2008).

To investigate SSI, a laminar box was used to simulate the behaviour of soil during shaking. Qin et al. (2013) constructed a uniaxial laminar box using a stack of aluminium laminar layers. Rollers were fitted between each laminar layer to allow relatively frictionless horizontal movement. A comparison was made between the response of soil with a structure placed on the soil surface and the response of soil under free-field conditions. The results showed the free-field soil response was greater than when SSI was taken into account. This means SSI interfered with the incoming seismic waves to produce a reduced wave field. However, only one structure was considered by Qin et al. (2013), thus a general conclusion on the effects of SSI from a cluster of structures could not be derived.

Another uniaxial laminar box was constructed by Turan et al. (2013). The box consisted of 24 laminar layers each made of solid high strength aluminium alloy box sections. Each layer was supported individually by linear bearings and steel guide rods connected the box sections to an external frame. The objective was to investigate the SSI effect using a structure with embedded basements. A single degree-of-freedom (SDOF) model represented the structure and a rigid box assembly composed of four segments simulated the embedded basements. Their results showed the structure-soil system had a lower natural frequency than a fixed base surface mounted structure.

The aim of this study is to investigate how SSI affects the soil response. Two different structures were considered. A laminar box, constructed by Qin et al. (2013), was used to simulate the shear behaviour of soil during an earthquake on a shake table. Two different SDOF models (structure 1 and structure 2) each with a surface mounted shallow foundation were considered. Experiments both with a structure and without a structure (free-field) were conducted using a laminar box filled with dry sand.

2 METHODOLOGY

2.1 Laminar box setup

When conducting the experiments, the soil in the laminar box should be of uniform relative density. To achieve this objective, the sand specimen was rained into the laminar box from a height of 1m above the base. The laminar box had dimensions 800 x 800 x 700 mm.

In research conducted by Rad and Tumay (1987), it is suggested that sand should be rained through a height larger than the terminal falling height, i.e. the sand grains reach terminal velocity before impact, to avoid significant differences in relative density (D_r). It is also suggested that the sand be rained from a height of at least 300 mm. In this study the sand was rained from an initial height of 1m, it is reasonable to assume the entire soil volume has a reasonably constant D_r. The overall height of sand in the laminar box after raining is 450 mm. Table 1 shows the sand properties.

Table 1. Sand properties

Parameters	Values
Density	1503 kg/m^3
Unit weight	14.7 kN/m^3
Specific gravity of particles	2.67
Void ratio	0.78
Minimum void ratio	0.6
Maximum void ratio	0.93
Relative density	46.70%

2.2 SDOF models

The two models, structure 1 and structure 2, were based on the SDOF model considered by Qin et al. (2013). The properties of the model was derived from a four storey prototype and scaled using the Buckingham π theorem. The process of obtaining the scale factors are described by Qin et al. (2013). The models had a lumped mass of 20 kg and height of 590 mm and a foundation consisting of a flat piece of plexi-glass, with dimension 475 x 475 mm. Model structure 1 and model structure 2 had fundamental frequencies of 2.3 Hz and 3.3 Hz, respectively. Experiments utilising models structure 1 and structure 2 are henceforth named S1 and S2, respectively, and tests without a model are designated FF.

2.3 Instrumentation

For each experiment, two accelerometers of dimension 19.8 x 44.5 x 27.2 mm and mass of 46 g were used. To measure the soil response, the accelerometers were embedded beneath the centre of the SDOF model at different depths. The embedment was achieved by temporarily fixing the accelerometers to a rod at the correct height inside the laminar box. The rod was then removed after the sand was rained in, leaving the accelerometers embedded. As stated in Larkin (2008), for simplicity, the shear strain in an element of soil at a depth of one eight the width of the foundation was assumed to be representative of the strain in the zone of influence of SSI. With a foundation width of 475 mm, the depth of the representative element is 59 mm beneath the soil surface. Accordingly the accelerometers were embedded at a depth of 50 mm and 150 mm beneath the soil surface to investigate the influence of depth on the recorded accelerations.

To measure the amount of foundation rotation, two LVDTs were installed. The experimental setup is as shown in Figure 1.

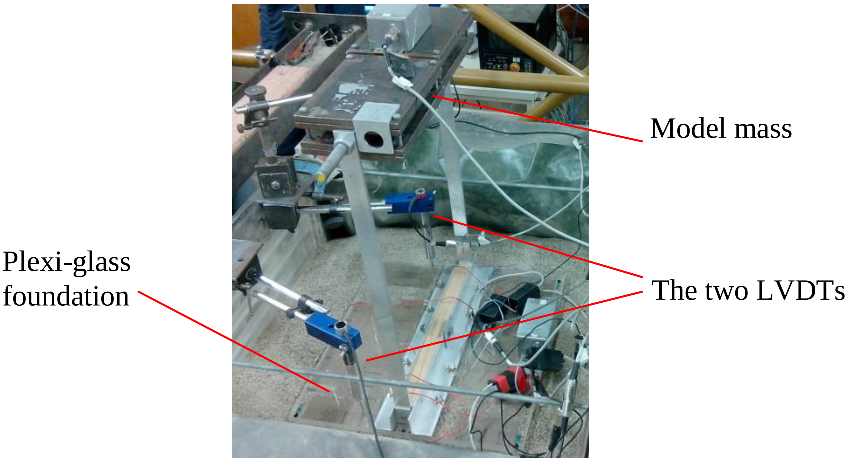

Figure 1. Experimental setup

The LVDTs were placed at the two ends of the foundation, see Figure 1, to measure vertical displacements.

2.4 Ground excitations

The simulated base acceleration applied was based on the Japanese design spectrum for hard soil conditions (JSCE 2000). It was selected due to its clearly defined frequency content (Chouw and Hao 2005). The acceleration time history of the ground excitation is shown in Figure 2.

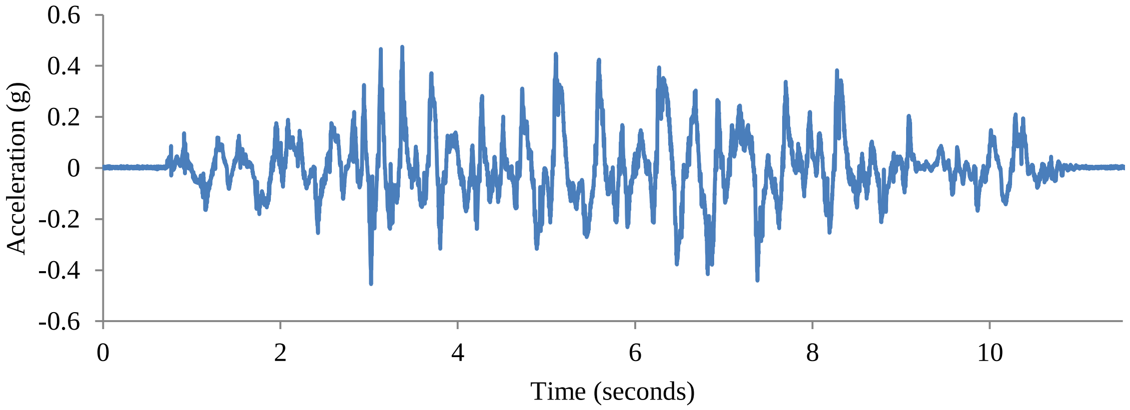

Figure 2. Applied base acceleration

3 RESULTS AND DISCUSSION

3.1 Soil response at 50 mm beneath the surface

The accelerometer embedded at 50 mm beneath the surface measured the soil accelerations during the FF, S1 and S2 experiments. Figure 3 shows the acceleration time histories recorded in the soil for all three experiments. The dashed line represents the FF experiment. The dotted and solid lines indicate the S1 experiment and the S2 experiment, respectively. It is observed that there are two obvious pulses in the S1 experiment at 5.72 seconds and 6.57 seconds. There was also a minor pulse in the S2 experiment at 5.72 seconds. Apart from these pulses, the responses of the soil from all three experiments are similar.

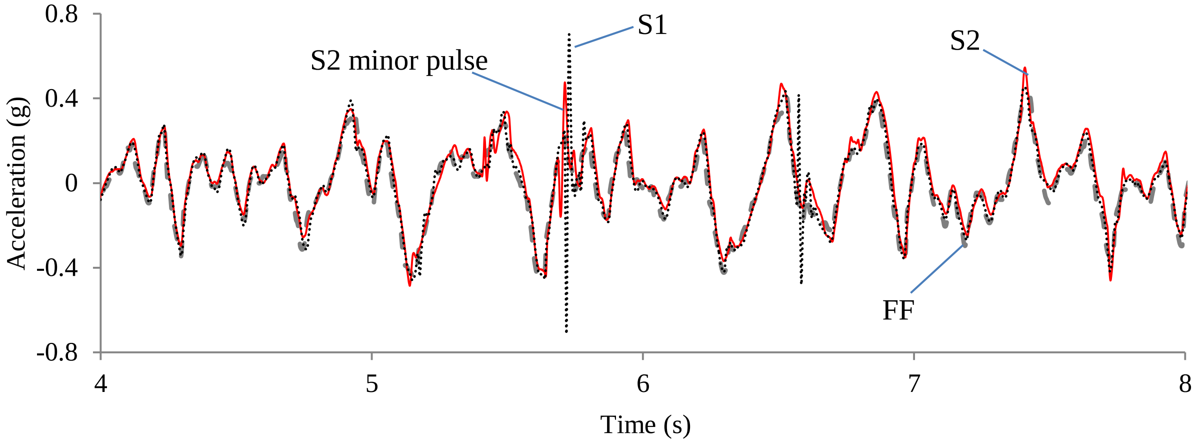

Figure 3. Soil accelerations at 50 mm depth

By closely examining the soil acceleration pulses, Figures 4 and 5 shows an impact-like response (dotted line) in the case of S1. In particular, the pulse in Figure 5 contains the highest peak soil acceleration of all three experiments, with a magnitude of 0.71 g. This pulse response was caused by the rotation of the footing, as described below.

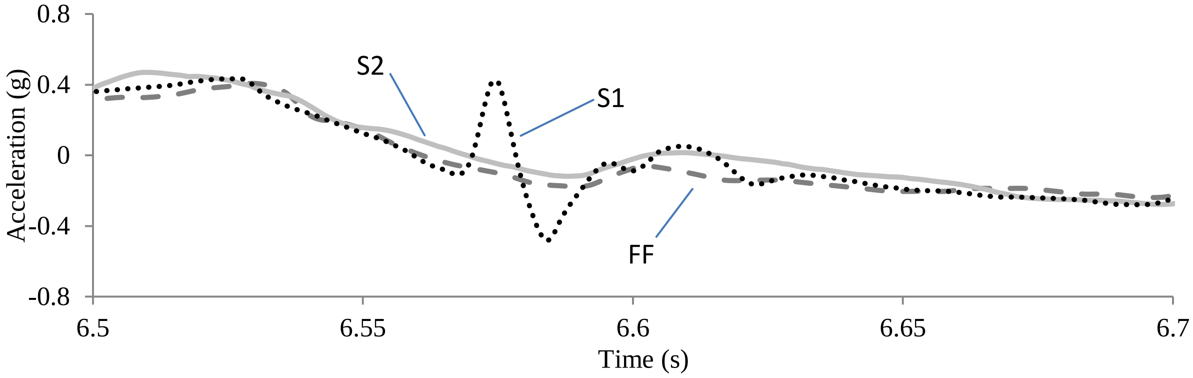

Figure 4. Pulse in soil accelerations at 50 mm depth

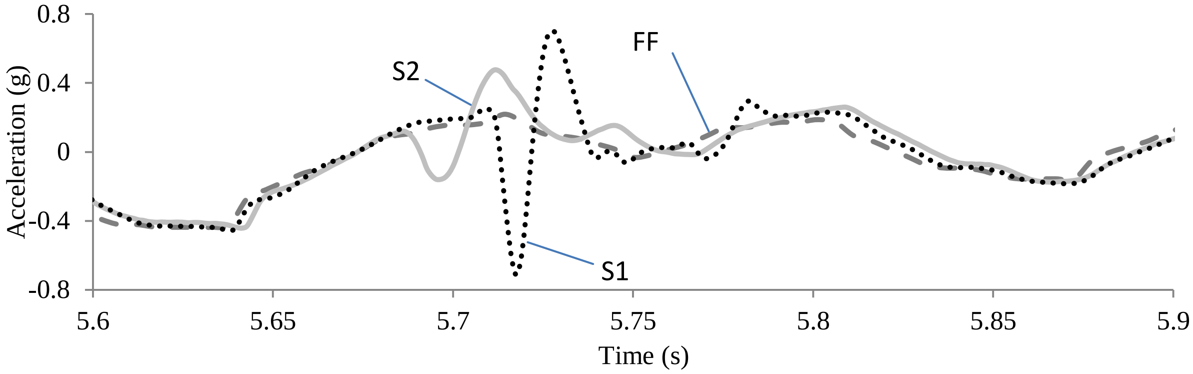

Figure 5. Pulse in soil accelerations at 50 mm depth

Figure 6 shows the foundation rotation time history of the S1 experiment. From 1.1 seconds, the foundation begins to rotate by small amounts, indicating the supporting soil beneath the foundation is being deformed. A large rotation cycle occurs between 5 and 6 seconds with a peak rotation of -2.7

degrees. This large rotation indicates a relatively large deformation of the supporting soil. The large deformation causes permanent soil deformation and the structure becomes more prone to foundation rotation. This can be clearly observed as cycles of foundation rotation occur more frequently after 6 seconds compared with the occurrences before 6 seconds. Furthermore, the foundation is resting at an angle of -0.5 degrees after the experiment ends. Consequently, the supporting soil has permanent deformation after the shaking, resulting from a ratcheting effect and leading to a leaning structure.

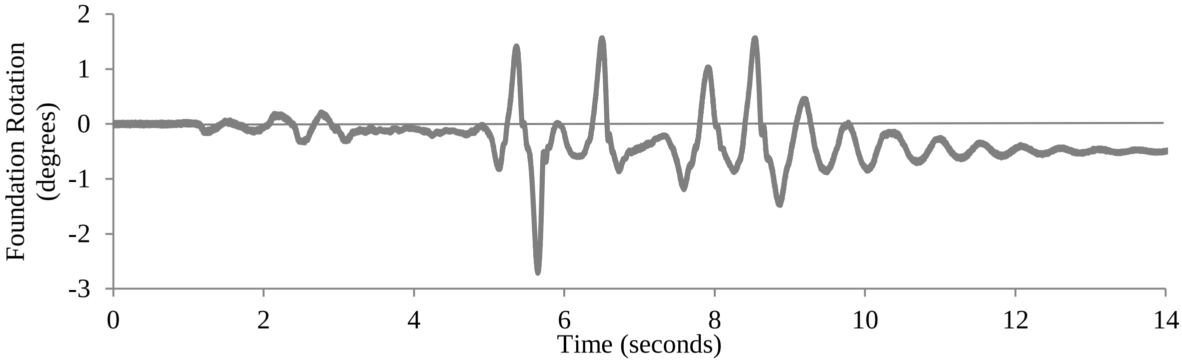

Figure 6. Foundation rotation during S1 experiment

The pulses found in the soil acceleration time histories are thought to result from an impact on the soil. This is reinforced when the foundation rotation and the soil acceleration are synchronised. Figures 7 and 8 show the foundation rotation and soil acceleration respectively from the S1 experiment between 4.7 and 6.7 seconds.

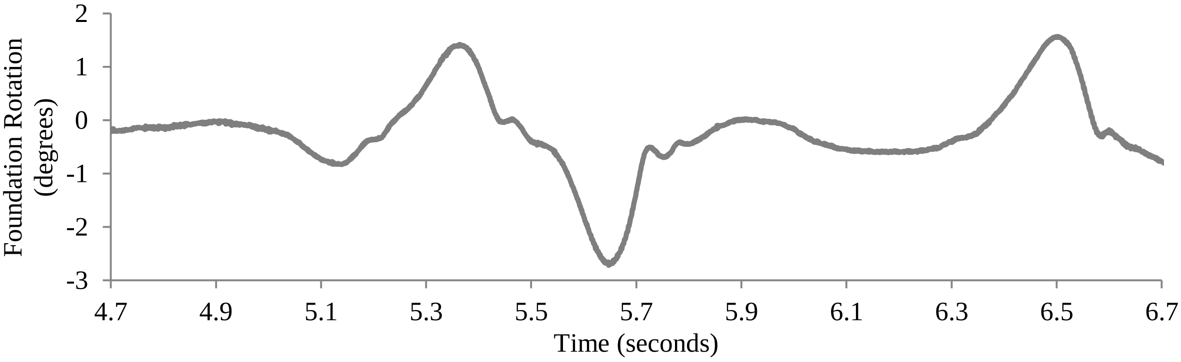

Figure 7. Foundation rotation during S1 experiment

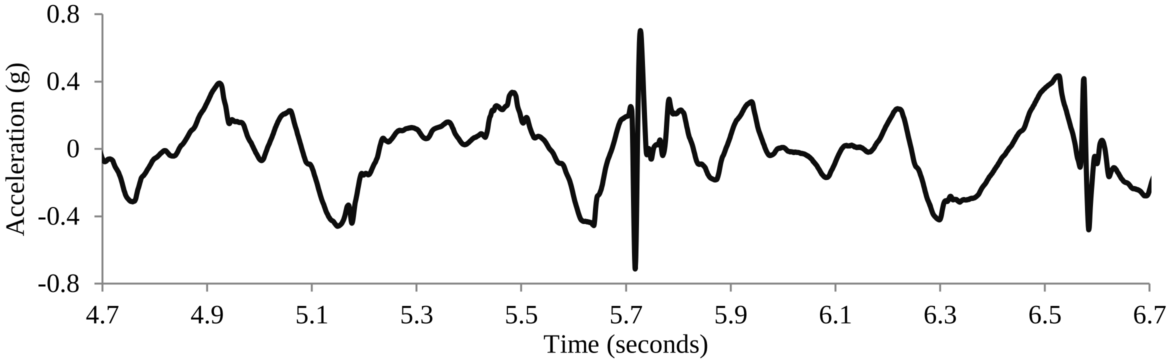

Figure 8. Soil acceleration at 50 mm depth during S1 experiment

At 5.1 seconds, a rotation cycle with relatively large amplitude begins. The cycle ends at 5.72 seconds. However, instead of smoothly continuing onto the next rotation cycle after 5.72 seconds, the rotation ends abruptly with approximately flat response, i.e. 0 degrees of rotation. The rate of change (gradient) of rotation in Figure 7 signifies the rotational velocity of the foundation. Since the gradient immediately before 5.72 seconds is relatively large, i.e. the foundation is rotating at a high velocity. Immediately after 5.72 seconds, the gradient becomes very small, indicating that the foundation stops rotating. For the velocity of the foundation rotation to go from large to almost zero suggests an impact force was exerted by the foundation onto the supporting soil. In other words, the supporting soil ceased to deform, resulting in a discontinuation in foundation rotation. Instead, the soil was subjected to an impact force imposed by the foundation's rotational movement. This impact force created acceleration which was then detected by the embedded accelerometer and is displayed as the high amplitude pulse in Figure 8.

This finding shows that SSI creates significant soil response.

3.2 Soil response at 150 mm beneath the surface

The accelerometer embedded at 150 mm beneath the surface measured the soil accelerations during the FF, S1 and S2 experiments. Figure 9 shows the acceleration time histories recorded in the soil. For the majority of the recordings, the responses of soil from all three experiments are fairly similar. However, there is one obvious pulse in the S1 experiment at 5.72 seconds. This pulse occurred at the same time as the high amplitude pulse seen in Figure 5. This suggests this pulse is a result of the same foundation rotation impact as discussed previously. The peak to peak amplitude in Figure 5 is 1.4g while in Figure 9 it is 1.15g. This suggests the soil response at 150 mm beneath the soil surface was less affected by the foundation rotation.

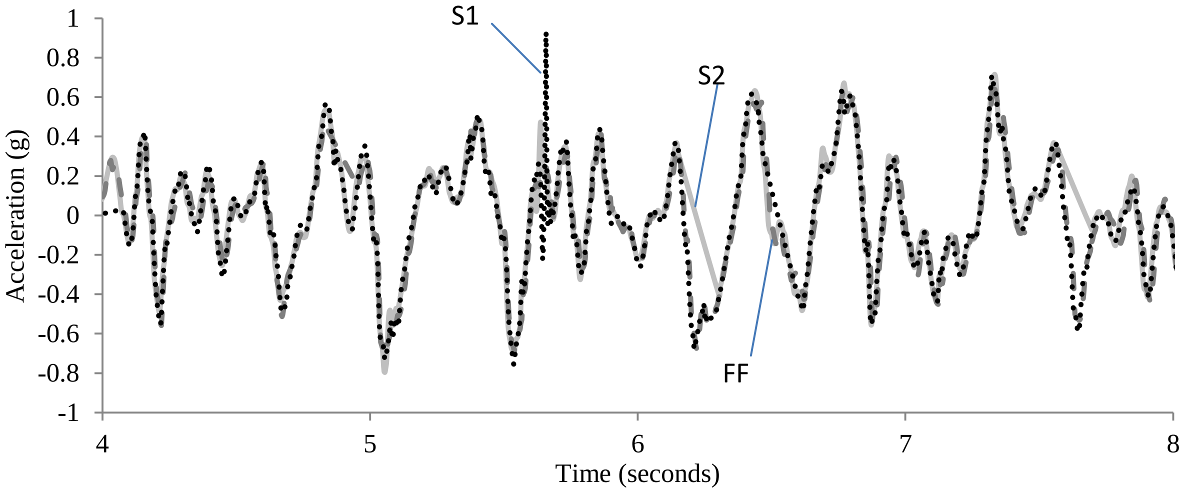

Figure 9. Soil accelerations at 150 mm depth

4 CONCLUSIONS

This study was carried out to reveal how SSI can affect seismic soil response. A laminar box was used to simulate the shear behaviour of soil during shake table tests. Two different SDOF models with shallow foundations were considered. The experiments were conducted on a laminar box filled with dry relatively uniform sand. Two LVDTs were fixed at each end of the foundation and vertical displacements were measured. From those measurements, foundation rotation was derived. An accelerometer was embedded 50 mm and 150 mm beneath the surface of the soil to measure the soil acceleration during shaking.

The results showed that

- in the case of the stiffer structure with the fundamental frequency of 3.3 Hz, SSI had little impact on the soil response.
- for the structure with a lower fundamental frequency of 2.3 Hz, SSI can significantly influence the soil response due to a high magnitude pulse.
- For a shallow foundation, foundation rotation can significantly impact the soil response.

5 ACKNOWLEDGEMENT

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