Study of soil-structure interaction effect on ground movement using a laminar box

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2013 NZSEE Conference

ABSTRACT: In current design practice, the response of a structure subjected to earthquakes is estimated using the free-field ground motion records. During an earthquake the superstructure interacts with the supporting soil and thus alters the excitation characteristics. Hence, depending on the degree of soil-structure interaction (SSI) a consideration of the seismic action of structure using free-field ground motion may not be appropriate. This study focuses on the determination of more realistic excitation experienced by the superstructure during earthquakes. The difference between ground motions under two configurations, i.e. soil with and without the structure, will be discussed. A laminar box that allows shear deformation of soil was utilized in a series of shake table tests. The excitation applied to the laminar box was simulated based on the Japanese design spectrum. The structure considered represents a scaled model of a multi-storey building. Wireless accelerometers were embedded within the sand to measure the response of the soil during shaking for the two considered configurations. The effect of SSI on the ground excitation of the structure will be discussed.

1 INTRODUCTION

During an earthquake, a building experiences large lateral forces at the base of the structure. These forces will activate the inertia forces of the building which in turn lead to large bending moments and deformation of the supporting soil. In most current design practice the effect of soil-structure interaction (SSI) has not been incorporated. The structure is designed with an assumed fixed base condition. The design action is computed based on the earthquakes recorded from free-field soil sites.

SSI can affect the dynamic response of structures. For example the stiffness of the supporting soil can lengthen the period of the structure and could result in a variation of force development when compared to analyses performed without considering SSI (e.g. Larkin 2008). A structure supported on soft soil has more degrees of freedom and therefore different dynamic characteristic than a fixed base structure (e.g. Veletsos and Meek 1974). As Veletsos and Meek mentioned a flexible ground can act as a damper. This can reduce the design action imposed on a structure. This effect is not evident in fixed base structures as most of the energy is transmitted to the structure.

Previous studies by Malhotra and Veletsos (1994) concluded that storage tanks supported on a flexible ground were less prone to buckling at the junction of the tank wall and base plate. The beneficial effect of SSI was acknowledged to the energy dissipation due to the supporting soil plastic deformation. In addition, research has shown that SSI can lead to favourable reduction in the plastic hinge development of structure (Qin et al. 2013). In studies on SSI by Shirato and Kouno (2008), they examined the nonlinear foundation response of a large scale model with pier footings on sand. The experiment was carried out using a laminar box on a shake table. The results showed that the residual displacement of the footing is dependent on the number of loading cycles during an excitation as well as the base excitation intensity; and the uplift of the model significantly affects the foundation behaviour. The combined effect of vertical and horizontal displacement with footing rotation contributed to the nonlinear response of shallow foundations to strong earthquakes.

Most of the previous study on SSI mainly focused on the performance of the super-structure. The seismic response of soil has not been considered. In fact, the structural response can interact with the soil behaviour during earthquakes. The excitation of the structure could be altered significantly depending on this interaction. Designing a structure using excitation obtained from free-field ground motion would lead to incorrect estimation of the seismic action on the structure. However, this phenomenon was not much considered in previous studies. Most study of SSI in the past was conducted using free-field ground motion records.

To simulate the shear behaviour of soil, laminar box is commonly applied. In a research on centrifuge modelling of earthquake induced lateral spreading in sand; a laminar box was constructed from using 39 thin rings (Taboada-Urtuzuastegui and Dobry 1998). These rings were used to provide flexibility and to approximate a continuous shear strain field in the soil during shaking. Bearings were inserted between each ring to facilitate vertical and shear forces as well as lateral displacements. From the experiment they concluded that as the input acceleration increase, the permanent shear strain and settlement of soil would either stay constant or increase. However, as the input frequency was increased, the pore pressure, thickness of liquefied soil, soil acceleration, permanent lateral displacement, settlement and shear strain all decreased. Another laminar box was designed by Wu and Sun (2002) which had dimensions of 2 m long by 1.5 m wide by 2 m high, consisting of 100 mm steel square hollow sections for each laminate. Bearing tracks were fitted externally to each layer to create a sliding mechanism. Steel walls were used to confine the laminates such that movement was allowed only in the longitudinal direction. The internal walls were lined with 2 mm rubber membrane to contain the soil and for waterproofing. The purpose of the experiment was to investigate the performance of the laminar box. Free vibration tests were conducted on the empty laminar box and produced a frequency response of 1.4 Hz. When the laminar box with sand was tested the frequency obtained was approximately 10 Hz. The disparity between the natural frequencies suggested that the resonance of the laminar box had negligible effects on the response of the soil.

The aim of this study is to investigate the effect of SSI on the horizontal movement of soil. A laminar box was constructed to simulate the shear behaviour of soil during earthquake. A SDOF model was used to represent the superstructure. Two different boundary conditions, i.e. with and without structure, were considered on a laminar box filled with dry sand. Accelerometers were instrumented at different location of the sand to measure the acceleration in the soil during excitation. Simulated ground motion based on the Japanese design spectrum was utilized. The development of ground acceleration in soil is discussed. The difference between the excitation induced to the soil-structure interface and that obtained from free-field condition was discussed.

2 LAMINAR BOX AND SHAKE TABLE TEST

2.1 Laminar box

In this research on the effect of SSI on the soil shear deformation, a laminar box was constructed. The soil container is composed of discrete layers that can move relative to each layer by a sliding mechanism. The advantage of using a laminar box is that the vertical propagation of horizontal shear waves from the bedrock to the surface of the soil can be simulated. The box should have minimal inertia while providing sufficient constraint of the sand. The composite shear stiffness of the laminar box should be significantly less than the soil deposit so that the response of the specimen is driven by the soil and not the laminar box itself (Pitalakis and Dietz, 2008). This was achieved by using aluminum section for each laminate layer. In this research the laminar box comprised of twelve layers of laminar with an area of 800mm by 800mm (Fig. 1(a)). When the effect of SSI is considered, the model was placed at the center of the sand surface. An accelerometer was placed on the sand surface, at 100 mm away from the footing of the structure to measure the ground acceleration during earthquake (Fig. 1(b)). In addition, to reveal the effect of SSI on soil response, the accelerometer was placed at the same location when the free-field condition was considered.

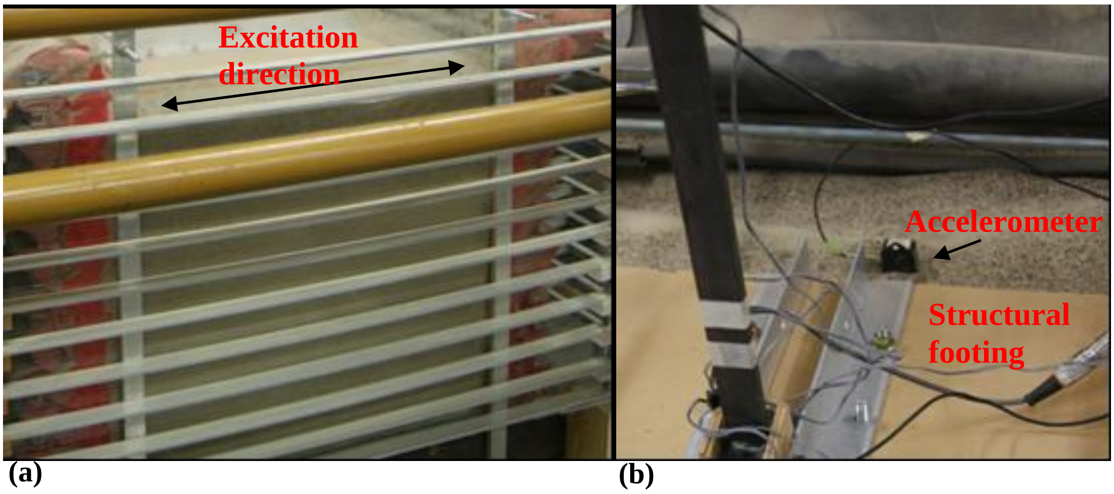

Figure 1: Laminar box with (a) free-field condition and (b) SSI

A common lacking feature of past laminar boxes was the lack of transparency of the box. Transparency of the box would allow visualization of the sub-surface layers of soil as it was being excited by the shake table. This aids the researcher in understanding the propagation of shear waves as well as soil response of every layer. For this purpose two transparent plexi-glasses were installed as the longitudinal faces of the box.

2.2 Structural prototype

The prototype was a four-storey office and had an inter-storey floor height of 3 m. The dimension of the floor plan was 7 m by 7 m. The columns of the building were 250UC73 for all levels. The primary beams were 310UB46 with continuous lateral restraint. Double-T floor slab units with depth of 350 mm were used on each floor with an additional 125 mm concrete topping. The seismic masses for each floor were calculated using the New Zealand Standard for Structural Design Actions (1170.5 2004) and were found to be 28.75 tonnes to give a total mass of the building 115 tonnes, excluding the foundation. The stiffness of each floor was 76000 kN/m. The structure was assumed to have a surface footing.

2.3 Model scaling

Building a large scale prototype for experimental testing would be excessively expensive and impractical in the laboratory. In this study, the limiting factor of using shake table is the hydraulic capacity to move the structure. To overcome this difficulty a scaled model is used to represent the prototype structure.

The physical property of the scale model should be selected so that its dynamic behaviour is the same as that of the full scaled building. Qin et al. (2013) has proposed a dimensionless variable to obtain the relationship between the dynamics of a prototype and its scale down model. Based on Buckingham π theorem (Buckingham 1914) and Hooke's law, Qin et al. has demonstrated that the dynamic response of a structure during earthquake can be represented by a reformulated Cauchy number (Equation 1).

$$\frac{ma}{ku} \tag{1}$$

, where m, a, k and u are the four physical quantities mass, acceleration, lateral stiffness and deflection, respectively.

The properties of the model (mass, lateral stiffness and dimension) and the acceleration of the excitation for the shake table test can be obtained based on the Cauchy number using the variable of prototype system. Table 1 summarize the mass, lateral stiffness and dimension of the prototype and the scale model.

Table 1. Properties of the prototype and the model.

	Storey Mass (kg)	**Lateral Stiffness (kN/m)**	**Storey Height (m)**	**PGA (g)**
Prototype	28750	76000	3	PGA
Model	6	63.33	0.2	PGA/3.75

2.4 **Single Degree-of-Freedom Model**

Generally, the influence of higher modes on structural response was considered to be negligible compared to the fundamental mode (Qin and Chouw 2010). An equivalent single degree-of-freedom (SDOF) model was used to represent the fundamental mode of the prototype structure. It has also been confirmed that a SDOF model was suitable for characterizing the overall behaviour of a multi-degree-of-freedom (MDOF) building (e.g. Decanini, Mollaioli et al. 2001).

Utilizing a SDOF system is a very crude approximation of a MDOF system. The behaviour of MDOF systems could be simply treated as a collection of several SDOF systems. The effective mass and height for the fundamental mode of the prototype can be obtained using the equilibrium of activated inertia forces and bending moment at the base (e.g. Chopra 2007). For the case considered the SDOF structure has an effective mass of M^* of 19.16 kg that was equal to 80% of the total prototype mass. The effective height h^* was calculated to be 0.59 m.

2.5 **Ground excitation**

The ground motion (Fig. 2) was simulated based on the Japanese design spectrum for hard soil condition (JSCE 2000). They were selected because of their clear defined frequency content (Chouw and Hao 2005).

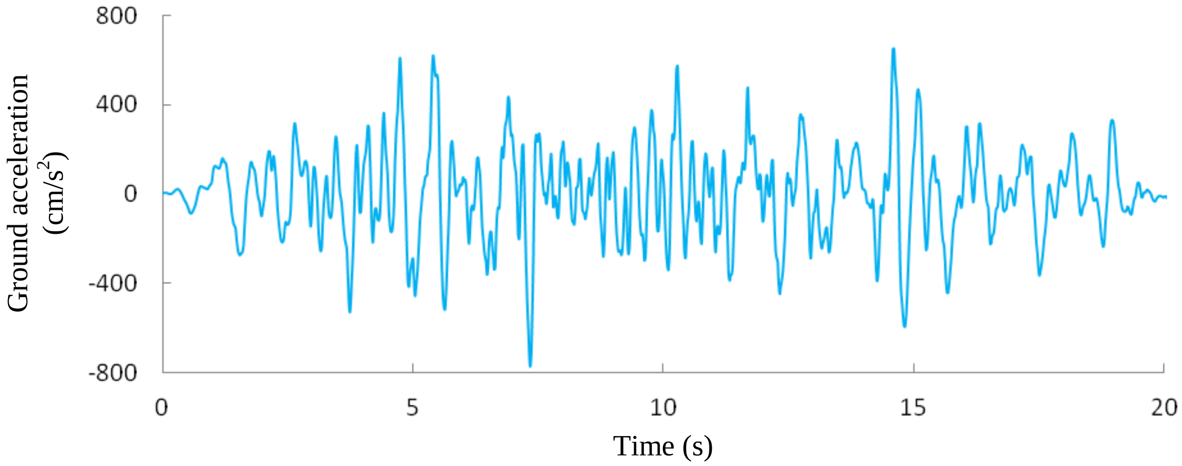

Figure 2: Applied ground acceleration

3 RESPONSE OF SOIL UNDER FREE-FIELD CONDITION

In the presented study, apart from the accelerometer placed on the surface of the soil, two accelerometers were embedded in the in the laminar box to measure the ground acceleration in the soil. The depths were 150 mm and 300 mm below the sand surface. Figure 3 shows the time history of ground acceleration at different depths. While the dotted line represents the accelerometer at 150 mm depth, the solid line illustrates the one at 300 mm depth. As expected the maximum ground acceleration at 150 mm depth is greater than that at 300 mm depth. In the considered case, the closer to the surface of soil, the greater the ground acceleration was observed.

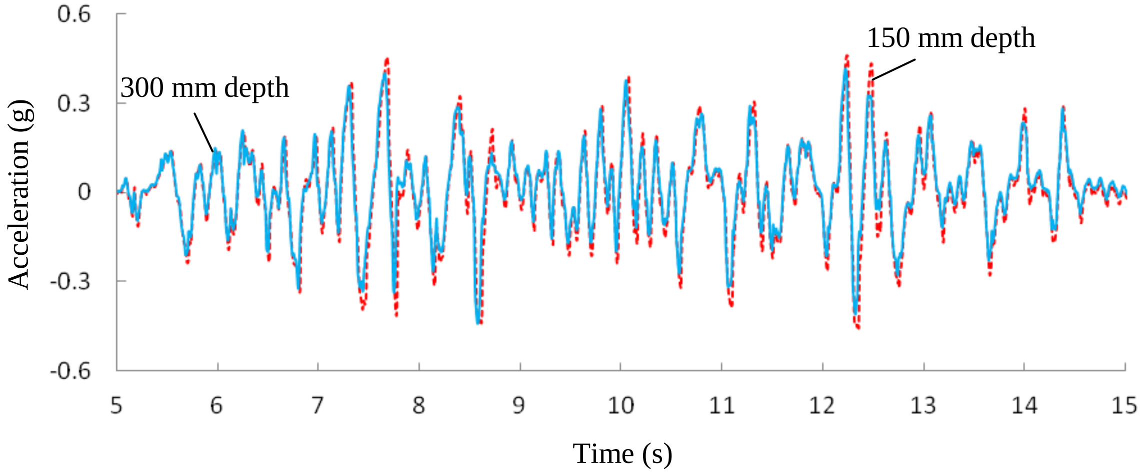

Figure 3: Acceleration in the soil with different depth

Figure 4 compares the ground acceleration on the surface (dotted line) and at 150 mm depth (solid line) of sand. Similar observation has been made. The ground acceleration at the surface is greater than that at 150 mm depth. Table 2 summarize the maximum ground acceleration in the soil with different depth. The peak accelerations on the surface, at 150 mm and 300 mm depths are 0.56 g, 0.46 g and 0.44 g, respectively. As expected in the free-field condition, the motion increases while propagating to the soil surface.

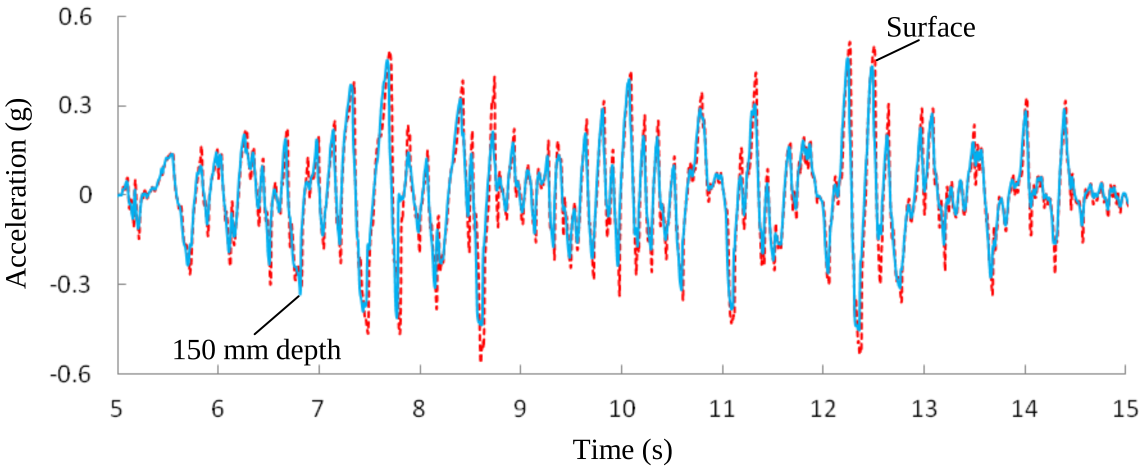

Figure 4: Acceleration at the surface and in the soil

4 RESPONSE OF SOIL WITH SSI

Figure 5 shows the acceleration at the soil surface. Two conditions were considered, one with SSI and one without (free-field). While the solid line represents the experiment with a surface footing structure (Fig. 1(b)), the dotted line illustrates the free-field response. Compare to the experiment with a structure, the maximum ground acceleration on the sand surface without SSI is greater. While the peak acceleration at the sand surface with structure was 0.55, the peak acceleration on the free-field sand surface was 0.56. It is evidenced that SSI can reduce the acceleration in the interface between the structure and soil. The excitation induced to the structure will be smaller than that obtained from free-field condition. Also in the case considered, with the effect of SSI the ground acceleration increases while the earthquake was propagating to the soil surface. The peak ground acceleration was increased from 0.41 g to 0.55 g from 300 mm depth to the surface of the soil (Table 2).

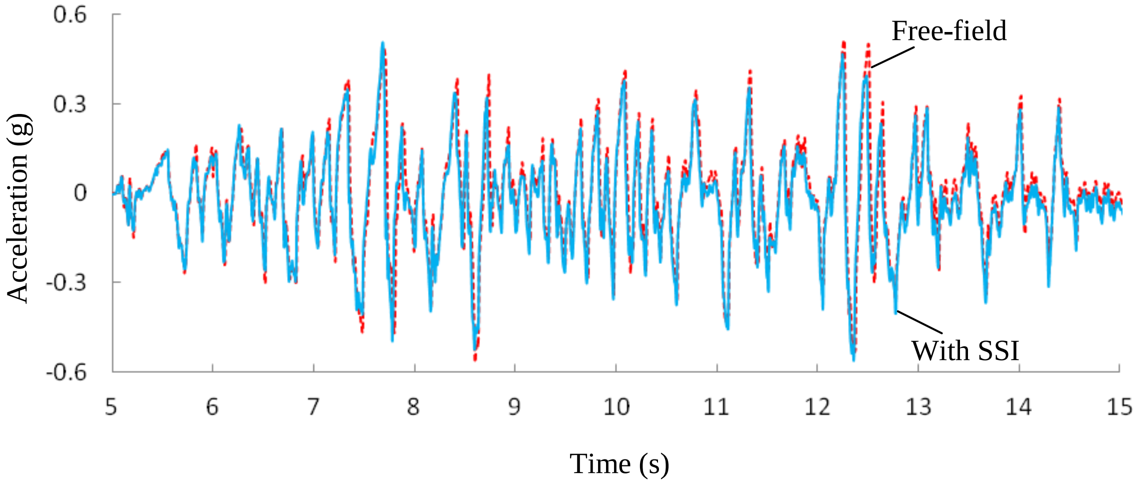

Figure 5: Influence of SSI on surface response

Table 2. Summary of maximum acceleration at different depth locations

Condition	Surface (g)	150 mm depth (g)	300 mm depth (g)
Free-field	0.56	0.46	0.44
With SSI	0.55	0.47	0.41

Using the measured acceleration at the top of the soil with different conditions i.e. with and without SSI, response spectra of the measurements were obtained. It was found that although the maximum acceleration at the surface of soil with different conditions was not significantly reduced (Table 2), the spectral accelerations were different.

Figure 6 illustrates the response spectra of ground motions with different conditions. The response spectra were calculated using 5% damping ratio. While the dotted line represents the spectrum of the ground motion with free-field condition, the solid line shows that with SSI. It can be seen that in the region of the fundamental frequency of the model (f = 2.91 Hz), the spectrum acceleration of the ground motion with free-field condition was significantly larger than that of excitation with SSI. While the maximum spectrum acceleration due to ground motion with free-field condition was 1.86 g, the maximum spectrum acceleration due to excitation with SSI was 1.83 g. These maximum spectrum accelerations were both found at the frequency of 5 Hz. In the region where the frequency is small than approximately 2 Hz and lrager that 5 Hz, the spectrum acceleration of soil with different condition was found to be similar. It is shown that the reduction of spectrum acceleration due to SSI is depends on the property of the structure. Nevertheless, The SSI will reduce the spectrum acceleration of the ground motion. The seismic response of the structure can be reduced.

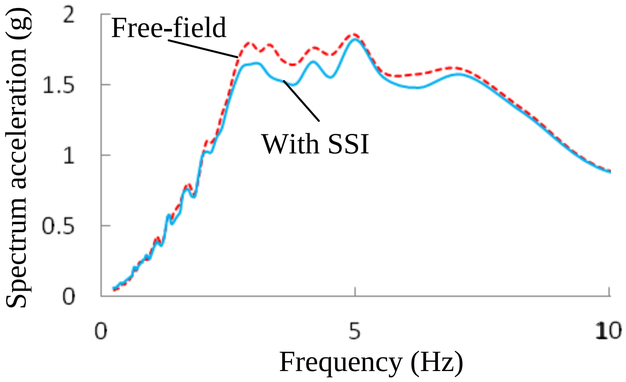

Figure 6: Spectrum of accelertation with different conditions

5 CONCLUSIONS

The study aimed to investigate the effect of SSI on the horizontal movement of soil. A laminar box was utilized to simulate the shear deformation of soil during shake table test. A SDOF model was used to represent a four-storey structure with a surface footing. Two different boundary conditions, i.e. with and without structure, with dry sand in the laminar box were considered. Accelerometers were instrumented at different location of the sand in the laminar box to measure the acceleration in the soil during earthquake.

This preliminary experimental study reveals that:

- In the considered case, the peak acceleration induced to the soil from earthquake increases when the earthquake wave propagates to the surface of soil.
- With the dynamic response of structure, SSI can reduce the excitation at the interface between the structure and soil. The soil response is smaller than the one of free-field site.

6 ACKNOWLEDGEMENT

The authors would like to thank the University of Auckland for the support under the Award FRDF 3700551 and the Ministry of Busines, Innovation and Employment.

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