Experimental and numerical study of soil response in a laminar box

W.M. Cheung, X. Qin, N. Chouw, T. Larkin & R. Orense

The Department of Civil and Environmental Engineering, University of Auckland, Auckland, New Zealand.

2013 NZSEE Conference

ABSTRACT: For studying dynamic soil behaviour, laminar box tests provide advantages over a conventional rigid box. The ability to allow shear deformation of soil while providing sufficient surrounding confinement is a more realistic representation of the free-field boundary conditions and thus soil-structure interaction. Despite the use of a laminar box in earthquake research, there are insufficient studies specifically aimed at determining the response of soil in the box. Also only a small number of numerical models have been developed to simulate the response of soil during earthquake motion. Even fewer numerical models have been verified by observations in the experiments. These result in limited consideration of the dynamic behaviour of soil in seismic design based on experimental data obtained using a laminar box. In the study reported herein, a laminar box was developed to examine the response of dry sand subjected to a ground motion recorded from the Christchurch earthquake sequence. A two-degree-of-freedom numerical model was developed and verified using the experimental findings. The results have shown that the model is appropriate for simulating the response of dry sand measured in the experiment.

1 INTRODUCTION

Since the two major earthquakes struck Christchurch in September 2010 and February 2011, extensive investigations have been undertaken to evaluate the damage. The investigations revealed that significant soil deformations occurred throughout the CBD and induced numerous damage to structures. The damaged structures were not limited to residential housing but also to infrastructures founded on shallow foundations and pile foundations, including bridges. These observations confirmed the significance of soil deformation in inflicting structural damage. In addition, Qin et al. (2013) has confirmed that soil deformation can affect the performance of secondary structure.

Youd et al. (2002) proposed several empirical equations to estimate lateral spreading based on SPT data. The equations were developed based on lateral displacements deduced from previous earthquake events. However, these equations can under or overestimate the actual soil movement by up to 50 to 200%. The low level of reliability in the prediction could lead to over-conservative seismic design or under estimation of design requirements. Although this method is widely accepted to estimate lateral spreading, the lack of reliability suggests that relying solely on this approach is inappropriate, and suggests that other studies including laboratory or field experiments are necessary.

Small scale laboratory tests are relatively accurate for predicting deformation of a homogeneous soil specimen. However, a small scale soil element is less preferable in earthquake research compared to a large scale soil specimen. Admittedly, a large scale homogeneous soil specimen used in a laminar box test provides a better representation of the effective confining stresses and boundary conditions in free-field soil. A laminar box is a flexible soil container that can be excited using base excitations to replicate earthquake actions on the soil specimen (Fig. 1). The ability to allow approximate constant shear deformation while providing sufficient confinement is a more realistic representation of the free-field boundary conditions.

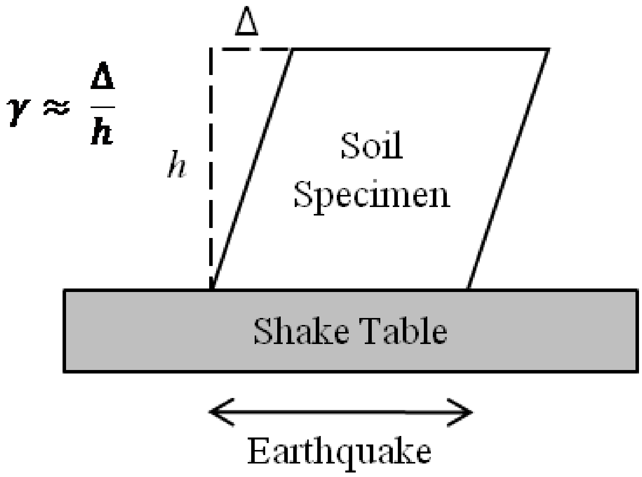

Figure 1: Shear deformation of soil in a laminar box subjected to earthquake motion, where γ is the shear strain

Matsuda and Goto (1988) developed a laminar box to assess the dynamic properties of soil during an earthquake. The concept of simulating soil response using a lumped mass model was proposed. Other researchers had developed laminar boxes with unique features. Patilakis et al. (2008) used rubber sections to separate laminar frames in order to provide flexibility of the box in the lateral direction; Ueng et al. (2010) developed a bi-directional laminar box and the soil specimen was subjected to bi-directional excitations; Hosseinzadeh (2010) developed a cylindrical laminar box. Currently, there are a limited number of numerical models to simulate the response of soil in a laminar box subjected to earthquakes, and a comparison with experimental results is rare.

The objectives of the studies presented herein are as follows:

- To construct a box that allows shear deformation in the soil specimen.
- To excite the soil specimen by a shake table and measure the response of the soil at different depths.
- To compare the experimental response of the soil in a laminar box against the results obtained from a numerical model simulation.

2 METHODOLOGY

2.1 Laminar box

Figure 2 shows the laminar box constructed for this study. It consists of 12 layers of rectangular rigid aluminium frames. Aluminium was used because it is relatively light while it has sufficient stiffness to provide the confinement. Each laminar was stacked on top of each other separated by ball bearings to allow relative movement with minimum friction. A volume of soil 800 mm long by 800 mm wide by 700 mm high can be tested. The inner surface of the laminar box was sealed by a rubber membrane. Because of the weight limitation on the shake table, only a 380 mm depth of dry sand was considered in the study. The soil specimen in the laminar box was formed by raining the sand from a fixed height of 1 m above the base of the box. The maximum shear strain allowed in the specimen was approximately 17%.

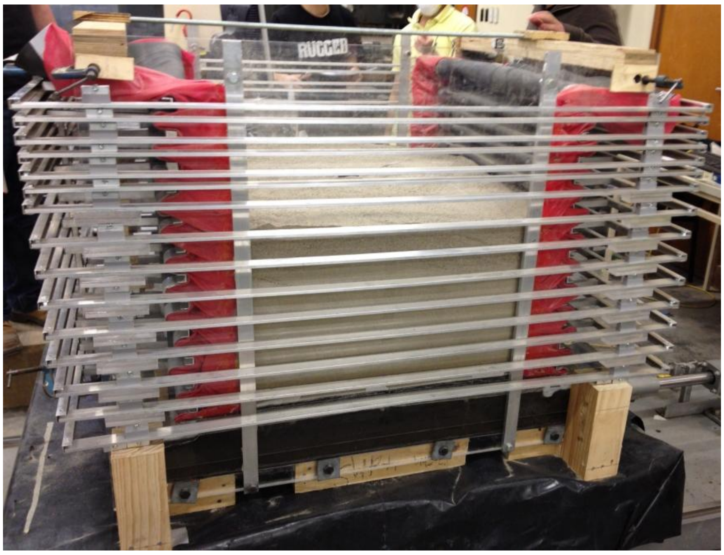

Figure 2: Laminar box on a shake table

2.2 Sand properties

Rad and Tumay (1987) had performed an experiment to investigate the effects of the raining height to the relative density of sand specimens. It was suggested that sand falling through any distance greater than the distance needed to develop the terminal velocity produces sand specimens of very similar relative density, and the raining height should be at least 30 cm. Since the raining height for this experiment substantially exceeded 30 cm, the relative density was considered to be constant for the entire sand specimen. The relative density for the considered sand specimen was 46.7%, and it was determined by physically measuring the density of the sand after raining. The sand properties and the grain size distribution curve are presented in Table 1 and Figure 3, respectively.

Table 1. Summary of sand properties

Parameter	Symbol	Value	Unit
Density	ρ	1503	kg/m^3
Unit weight	γ	14.7	kN/m^3
Specific gravity	G_s	2.67	
Void ratio	e	0.78	
Minimum void ratio	e_{min}	0.6	
Maximum void ratio	e_{max}	0.93	
Relative density	D_r	46.7	%

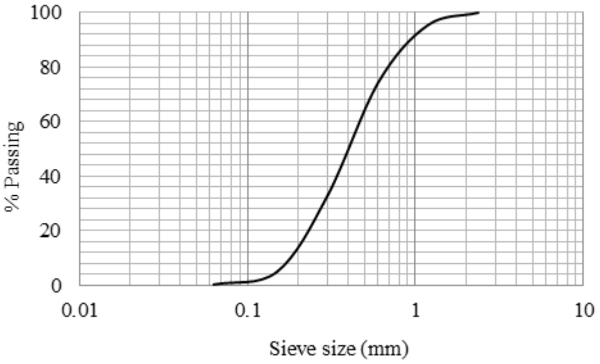

Figure 3: Grain size distribution curve

2.3 **Instrumentation**

Two smart particles were embedded within the sand at two different depths: on the sand surface and at 160 mm depth below the surface. A smart particle is a three dimensional wireless accelerometer (Wang et al. 2012). Thin strings were used to secure the lower smart particle into the same location prior to sand raining, while the smart particle on the surface was placed carefully after the sand surface was levelled. Another accelerometer was attached to the shake table to measure the actual excitations being applied. Three draw wire transducers were used to measure the lateral displacements of the sand layer at the same elevation as the accelerometers, as well as the lateral displacement of the shake table.

2.4 **Excitation**

Five strong ground motions recorded at the HPSC station in the 2011 Christchurch earthquake sequence were used in the series of experiment (GeoNet 2012). In this study, only one of the five ground motions will be considered. The actual acceleration time history applied in the later numerical analysis was recorded from the accelerometer attached to the shake table. The time history of this excitation is presented in Figure 4a, and the corresponding response spectrum for 5% damping is presented in Figure 4b.

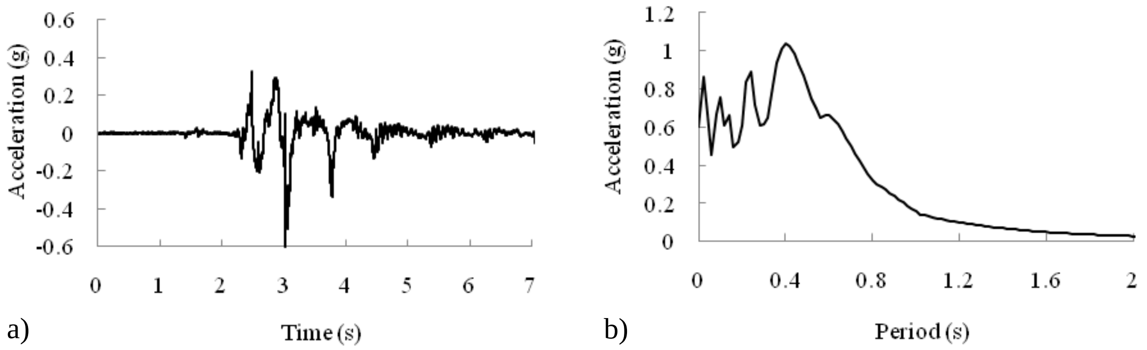

Figure 4: Applied shake table excitation, a) time history, b) response spectrum

2.5 **Numerical model**

A two degree-of-freedom (2DOF) model was developed to simulate the response of dry sand in a laminar box when subjected to earthquakes. The model, which followed the formulation proposed by Matsuda and Goto (1988), involves a lumped mass configuration (Fig. 5). Each lumped mass represents the soil layer enclosing the corresponding smart particle. The masses were interconnected by a shear spring in order to simulate the lateral stiffness of the surrounding soil. The soil stiffness vector {K} of the soil layers was calculated from equation 1 below:

$$\{K\} = [D]^{-1} [M] \{Y''\} \qquad (1)$$

where M_i is the lumped mass of the soil layer with i = 1 and 2. For M_1, this was taken as the soil mass associated with the smart particle at a depth of 160 mm, while M_2 was taken as the soil mass associated with the smart particle at the surface. Y'' is the absolute acceleration of the soil layer which was obtained from the smart particle measurements. [D] is the relative soil layer displacement, and it also was obtained from the experimental measurements. The average K values deduced are summarised in Figure 5.

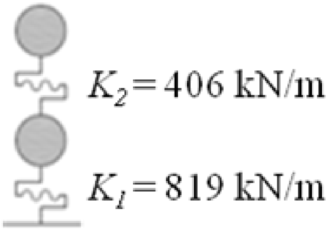

Figure 5: 2DOF model

The damping ratio (ξ) of the soil was calculated using the H-D model proposed by Hardin and Drnevich (1972). The level of damping was based on the reference shear strain of the soil, and it was taken as 0.65 times the maximum shear strain recorded from the experiment during the passage of the earthquake (Seed & Idriss 1971). The adopted ξ for the model was 26%.

3 RESULTS AND DISCUSSION

Figure 6 shows the acceleration time history comparisons between the experimental result and that of the numerical model simulation. The dashed line represents the experimental data, while the solid line represents the soil acceleration simulated by the 2DOF model. The time window between 2 and 4 s is displayed to enable a better visualisation in the comparison of the results. For the sand at 160 mm depth (Fig. 6a), the 2DOF model was able to accurately simulate the experimental soil response. In contrast for the sand at the surface, examining Figure 6b reveals that the level of accuracy simulated by the model significantly decreased compared to the previous time history comparison. In several occasions the acceleration simulated was significantly higher than what was observed from the experiment. This was demonstrated at the time intervals between 2.6 and 2.8 s, and between 3.0 and 3.4 s.

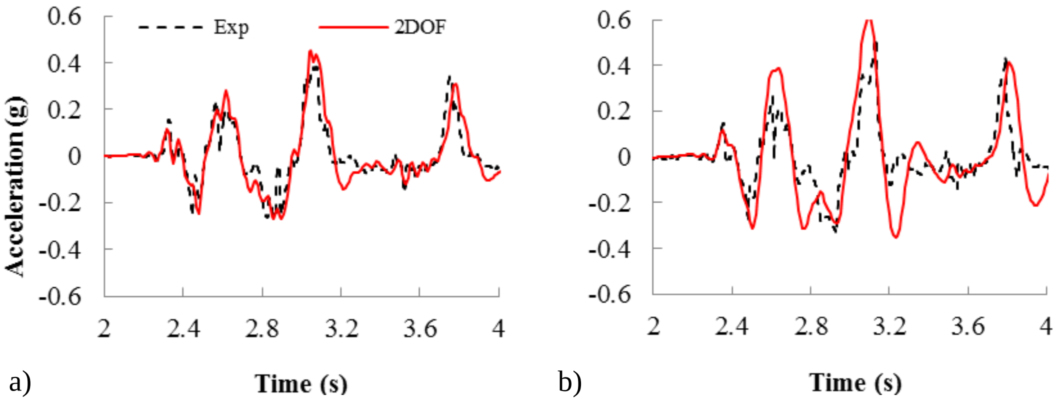

Figure 6: Acceleration time history comparison for sand at: a) 160 mm depth, b) surface

For the sand at 160 mm depth, the difference in peak acceleration between the experimental measurement and the numerical model simulation was approximately 0.06 g, while for the sand at the surface, such difference was approximately 0.09 g. In summary, for this excitation case, the numerical model was able to model the acceleration measured in experimental testing accurately. Furthermore, the equations adopted for calculating the lateral stiffness of the sand rely on the shear beam mode of deformation. The good agreement between the numerical simulation and experimental values implies that the soil in the laminar box is functioning predominately in this manner.

As mentioned above in relation to the observation in Figure 6b, the accuracy of the numerical model reduced for the sand surface compared to the sand at 160 mm depth. A possible reason for this is that the sand at the surface has close to zero effective stress, this leads to almost zero confinement pressure and ultimately very low lateral stiffness of the soil. In a very low confining stress the empirical equations used for calculating damping and shear modulus become unreliable. This results in relatively high difference between the experimental findings and the numerical model simulation.

Figure 7 shows the absolute displacement time history due to the applied excitation, where the dashed line represents the shake table displacement, the solid line represents the sand at 160 mm depth and the dotted line represents the sand surface. In the time window between 3.0 and 3.1 s, the figure clearly illustrates the lateral deformation occurred in the sand. The residual lateral deformation recorded at the end of shaking was approximately 4.5 mm for the sand at 160 mm depth. This highlights the advantage of using a laminar box to simulate soil movement. By allowing shear deformation, a high level of plastic deformation was achieved in the soil and this feature could be used to analyse the change in sand properties during an earthquake, namely, the shear modulus and the lateral stiffness of the sand specimen.

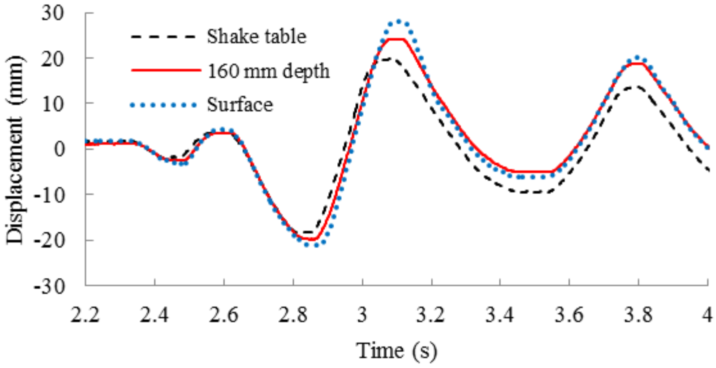

Figure 7: Absolute displacement time history due to earthquake excitation

During an earthquake, the shear strain of the soil changes constantly with time and position. This will alter the shear modulus (*G*) and the lateral stiffness (*K*) of the soil continuously during the entire earthquake excitation. As this behaviour was not accounted for in the numerical model, an improvement to the proposed model is currently being investigated by incorporating the nonlinear shear strain dependent *G* and *K*. Furthermore, the vertical displacement in the sand during shaking will also affect the *G* and *K* of the soil. This effect shall be incorporated by investigating the vertical movement of the smart particles.

4 CONCLUSIONS

In this study, a laminar box was used to assess the response of dry sand subjected to different earthquakes. The ground motion considered was selected from the Christchurch earthquake sequence. Accelerations activated in the soil at different soil depths were measured using smart particles. The experimental results revealed that:

- The laminar box allowed a high level of shear deformation between the soil at different depths. Therefore, it enables a more realistic determination of the response of soil subjected to earthquake motion.

Based on the experimental findings, a lumped mass model was developed to simulate the response of dry sand. The performance of the model was compared against the experimental findings. For the considered excitation case, the comparisons revealed that:

- For sand at 160 mm depth, the numerical model was capable of modelling the acceleration obtained from the experiment with high accuracy.
- When simulating the response of the sand on the surface, the accuracy of the model reduced compared to the sand at 160 mm depth due to the low confinement stress at the sand surface.
- The good agreement between the numerical simulations and experimental values suggests that the soil in the laminar box deform in a shear beam manner.
- The lumped mass model can be used for simulating the response of dry sand in a laminar box subjected to earthquake motion.

5 REFERENCES

GeoNet. 2012. Strong-Motion Data. Retrieved from http://info.geonet.org.nz/display/appdata/Strong-Motion+Data

Hardin, B.O. & Drnevich, V.P. 1972. Shear modulus and damping in soils, *Journal of Soil Mechanics and Foundation Division*, Vol 98(7) 667-692.

Hosseinzadeh, N. 2010. Shake table study of Soil-Foundation-Structure Interaction (SFSI) effects in rocking and horizontal motions of the building structures, *Proceedings of the 9th U.S. National and 10th Canadian Conference on Earthquake Engineering, Toronto, Canada. July 25-29, 2010*.

Matsuda, T. & Goto, Y. 1988. Studies on experimental technique of shaking table test for geotechnical problems, *Proceedings of Ninth World Conference on Earthquake Engineering*, Vol 8 837-842.

Patilakis, D., Dietz, M., Wood, D.M., Clouteau, D. & Modaressi, A. 2008. Numerical simulation of dynamic soil-structure interaction in shaking table testing, *Soil Dynamics and Earthquake Engineering*, Vol 28(6) 453-467.

Qin, X., Chen, Y., & Chouw, N. 2013. Effect of Uplift and Soil Nonlinearity on Plastic Hinge Development and Induced Vibrations in Structures, *Advances in Structural Engineering*, Vol 16(1), 135-148.

Rad, N.S. & Tumay, M.T. 1987. Factors affecting sand specimen preparation by raining, *Geotechnical Testing Journal*, Vol 10(1) 31-37.

Seed, H.B. & Idriss, I.M. 1971. Simplified procedure for evaluating soil liquefaction potential. *Journal of the Soil Mechanics and Foundations Division*, Vol 97(9) 1249-1273.

Ueng, T.S., Wu, C.W., Cheng, H.W. & Chen, C.H. 2010. Settlement of saturated clean sand deposits in shaking table tests, *Soil Dynamics and Earthquake Engineering*, Vol 30(1-2) 50-60.

Wang, K.I-K., Salcic, Z., Wilson, M.R. & Brook, K.M. 2012. Miniaturized wireless sensor node for earthquake monitoring applications, *7th IEEE International Symposium on Industrial Embedded Systems (SIES'12), Karlsruhe, Germany. June 20-22, 2012.*

Youd, T.L., Hansen, C.M. & Bartlett, S.F. 2002. Revised multilinear regression equations for predition of lateral spread displacement, *Journal of Geotechnical & Geoenvironmental Engineering*, Vol 128(12) 1007-1017.