Development and performance of a laminar container for seismic centrifuge modeling

Zayed, M., Luo, L., Kim, K., McCartney, J.S., Elgamal, A.
Department of Structural Engineering – University of California San Diego, CA, USA

ABSTRACT
To simulate the dynamic response of geotechnical models and study soil-structure interaction problems with minimum boundary effects, a new light-weight laminar container has been designed and constructed at the University of California San Diego (UCSD). The container consists of individually-mounted aluminum laminates designed to slide independently on roller bearings mounted to an external frame. The laminates were designed to provide a low sliding friction response leading to a soft dynamic boundary condition necessary to accurately characterize liquefiable soil layers, while still providing a sufficiently stiff response to maintain at-rest lateral static earth pressures. Although not discussed in this paper, the container was also designed to provide basal drainage that could be used for specimen saturation and for testing unsaturated soils. A series of tests on dry sand layers were performed in this study to evaluate the static and dynamic response of the container for earthquake simulation, which confirm that the container has satisfactory performance for characterizing the seismic response of soft liquefiable soils.

1 INTRODUCTION

Geotechnical centrifuge testing of small-scale soil and soil-structure system models is a useful means of studying a wide range of complex boundary value problems in geotechnical engineering. Centrifuge modeling permits the simulation of phenomena encountered in large-scale civil engineering projects using small models under realistic stress states. Further, dynamic centrifuge testing of soil models can be an effective means for studying basic soil behavior in response to static and dynamic loading. Through proper application of scaling laws, measurements from centrifuge tests can be applied to full scale soil structures. In addition, the highly-controlled nature of centrifuge experiments permits calibration of numerical codes for seismic design. One challenge in dynamic centrifuge modeling is the identification of the proper container to provide adequate boundary restraints for both at-rest and dynamic loading, while still having low self-weight to minimize the payload on centrifuge shaking tables.

This paper introduces a new container used in simulating the dynamic response of liquefiable soil layers and studying soil-structure interaction problems with minimum boundary effects. Specifically, a new type of light-weight laminar container has been designed and constructed at UCSD. The container consists of 19 individually-mounted laminates fabricated from aluminum that slide independently on roller bearings mounted to an external frame. The individually-mounted laminates are expected to provide low sliding resistance and a soft dynamic response needed to accurately characterize liquefiable soil layers. This laminar container can be lined with a plastic membrane to test saturated soils.

A shake table mounted on the basket of the 50 g-ton centrifuge at UCSD was used to generate an earthquake-like motion at the base of the container while spinning at different g-levels. At a g-level of 50, the laminar container was used to simulate a prototype sand layer having a thickness of 13.3 m. Dynamic centrifuge tests on dry sand layers with the new laminar container were conducted. Accelerometers and displacement sensors were connected to the container and embedded in the sand layers to characterize the container performance and to evaluate the boundary effects. An analysis of the results from these sensors indicates that the container provides low boundary constraints during shaking of loose, liquefiable sand, while still having the rigidity to maintaining close to at-rest horizontal stresses during spin-up and plane-strain boundary conditions during shaking.

2 BACKGROUND

A variety of model container configurations are currently used for dynamic centrifuge testing. Stacked-ring devices, originally developed for simple shear testing of soil specimens, have been increasingly used to simulate free field boundary conditions in earthquake modeling of soil deposits. Specifically, circular and rectangular model containers horizontally excited at the base have been used for shaking table tests at 1 g (Yoshikawa and Arano 1989). Containers with different shapes were also involved in the centrifuge tests with higher g level (Lambe 1981; Whitman et al. 1981; Arulanandan and Anandarajah 1983; Hushmand et al. 1988; Law et al. 1991; Laak et al. 1994). The Flexible Shear Beam (FSB) container (Kutter 1996 and Divis et al. 1996), Equivalent Shear Beam (ESB) (Zeng and Schofield 1996 and Lee et al. 2013), and hinged-plate container (Fiegel et al. 1994) are also commonly used in centrifuge tests and have different dynamic properties while ensuring application of complementary shear stresses and hydraulic seals for testing water-saturated soils. A comparison between the performance of a new free-moving laminar box and an ESB container was described by Brennan et al. (2006), who observed that both containers are suitable for dynamic testing of dry sand. A transparent flexible shear beam container was also designed by Ghayoomi et al. (2013) to simulate the dynamic response of soil during horizontal earthquake shaking while visualizing the deformation of the soil layer and buried structures.

The most common containers used in centrifuge modeling are rectangular laminar containers. Laminar containers involve a stack of rigid rings that will deform in the direction of shaking with the modes of movement of the soil column, but will simulate plane strain conditions at rest. Whitman and Lambe (1986) listed six design goals necessary for an ideal container to reproduce boundary conditions on a soil specimen that perfectly simulate a column of soil. These six design goals are as follows:

1- Maintain a constant horizontal cross section during shaking.
2- Develop, on the vertical container-soil interface, dynamic shear stresses equal to those occurring on horizontal planes when the soil stratum is shaken.
3- Have zero mass.
4- Have zero stiffness to horizontal shearing.
5- Offer no resistance to settlement of the soil during placement, spin-up of the centrifuge, or as a result of shaking.
6- Retain water without leakage (except at top surface) and with insignificant membrane compliance.

An additional design goal is for the container to be sufficiently rigid to maintain at-rest horizontal stresses (i.e., that any horizontal deformations in the soil are elastic) during specimen preparation and centrifuge spin-up, and to be lightweight to minimize the payload on centrifuge shaking tables. Development of the laminar container, as described in the following sections, was guided by these design goals.

3 CONTAINER DESIGN AND DESCRIPTION

The philosophy of the laminar container design is that each rigid ring is supported by a cantilevered bearing connected to an external frame. This is different from previous laminar containers where there is a bearing layer between individual rigid rings. This approach of individually-mounted laminates has the advantage of avoiding a cumulative vertical load on the lower bearings which better facilitates shaking. The bearings are also configured in a way that sand grains cannot affect the laminate-bearing contact points, an issue that is encountered in conventional laminar containers that leads to long-term durability issues for the container. The bottom plate of the box is stationary and is mounted onto the shaker.

The outer dimensions of the container are 304.8 mm x 508 mm x 304.8 mm, while the inner dimensions are 241 mm x 381 mm x 266 mm, and the container consists of 19 aluminum laminates designed to slide independently on roller bearings mounted to an external frame. Each laminate measures 431.8 mm in length by 292.1 mm in width and has a thickness of 12.7 mm. The container can accommodate a maximum soil height of 266 mm. The mass of the entire container with all its components is 21.6 kg, and each laminate has a mass of 0.68 kg.

Components of the laminar container are shown in Figure 1. The laminar container is composed of corner supports, side supports, top frame, inner laminar frames, and base plate, in addition to bearing assemblies. The base plate was roughened to minimize slippage. Over the base plate and inside the outer frame, the interior consists of multiple laminar frames placed above one another, with the holes indented in the long-angled rails having a track that fits over 12 cantilevered bearings per layer. The gap between each layer can be defined by the user, and a gap of 1.0 mm was used in this study. Smaller gaps can be used but each layer should not touch the adjacent layers to avoid motion from being impeded. The side walls of the laminates in the direction of shaking can be roughened to provide complimentary shear forces, and the laminates are sufficiently restrained by the bearings that they will not pull upwards during shaking.

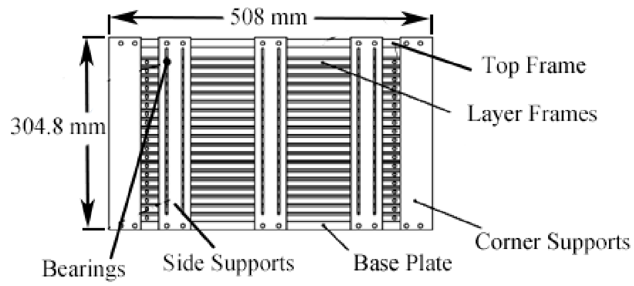


Figure 1. Dimensions and components of the laminar container

The laminar box was designed to be accommodated by the UCSD centrifuge facility. The centrifuge facility is equipped with a high-performance servo-hydraulic ES-9 shaking table obtained from Paul van Laak of Hong Kong UST, shown in Figure 2. This shake table mounted on the basket of the 50 g-ton centrifuge was used to generate an earthquake-like motion at the base of the container while spinning at different g-levels. For example, at a g-level of 50, the laminar container was used to simulate a prototype sand layer having a thickness of 13.3 m. Dynamic centrifuge tests using both dry sand models were conducted. Accelerometers were connected to the container and embedded in the sand layers to characterize the container performance and to evaluate the boundary effects. This test aims at simulating the lateral constraint of a soil profile at rest without rigid lateral boundary restraints.

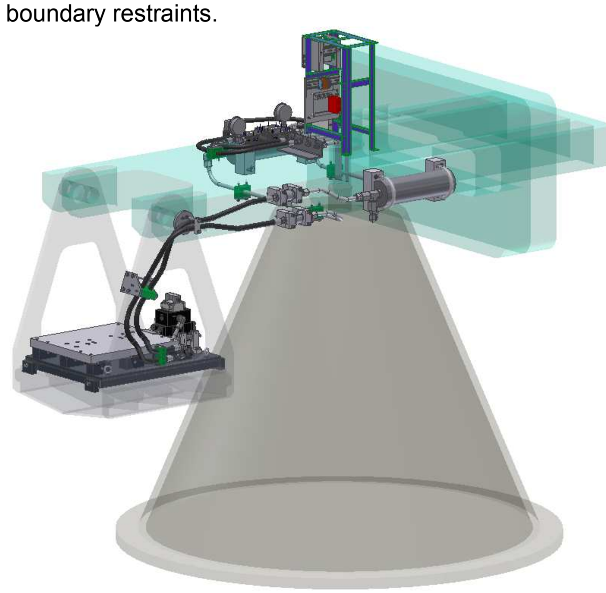


Figure 2. UCSD centrifuge shaker system

During geotechnical centrifuge testing, the shaking direction of the shake table and the direction of the laminates are parallel, which leads to horizontal shear waves that propagate perpendicular to the soil layer as shown in Figure 3.

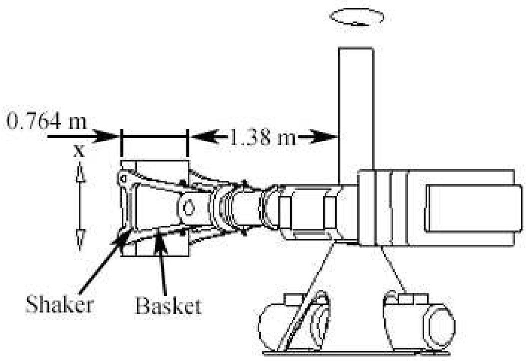


Figure 3. Direction of shaking on the ES-9 shaker

3 DRY SAND TEST

3.1 Experimental Setup and Description

To evaluate the performance of the laminar box, centrifuge experiments testing were performed on dry sand having properties listed in Table 1.

Table 1

Property	Value
D_{10}	0.16 mm
D_{50}	0.28 mm
D_{90}	0.6 mm
γ_{dmin}	16.12 kN/m^3
γ_{dmax}	13.97 kN/m^3
G_s	2.7

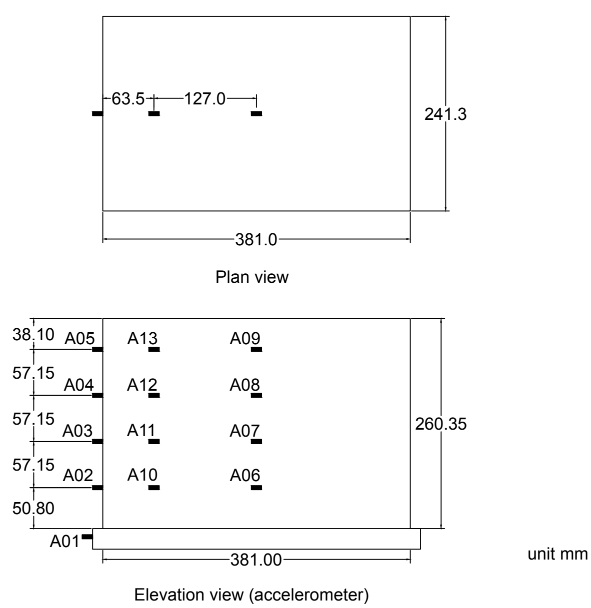


Figure 4. Location of accelerometers for centrifuge test

The distribution of accelerometers and LVDTs aims at illustrating the performance of this laminar containers. Both accelerometers and LVDTs were placed at different height along the container, two sets of accelerometers were embedded in the soil.The accelerometers are embedded in the soil and mounted along the laminar container at the locations shown in Figure 4. For each layer of soil, there are three accelerometers: one installed on the container, one embedded with the dry soil in the center position, and the last embedded between the edge of the box and the center position. This accelerometer distribution permits checking the effects of the laminar container boundary conditions on the movement of the soil layer.

Horizontal displacements of each container frame are measured using LVDTs which are mounted with an external rack. The settlement of soil can also be measured by attaching a LVDT to the top of the soil surface, although it should be noted that the reference frame for the vertical displacement is different than in conventional laminar containers. In conventional laminar containers, the vertical settlement is typically with respect to the top ring, while in this case the vertical settlement is with respect to the external frame of the container. The locations of LVDTs for horizontal and vertical displacements are shown in Figure 5.

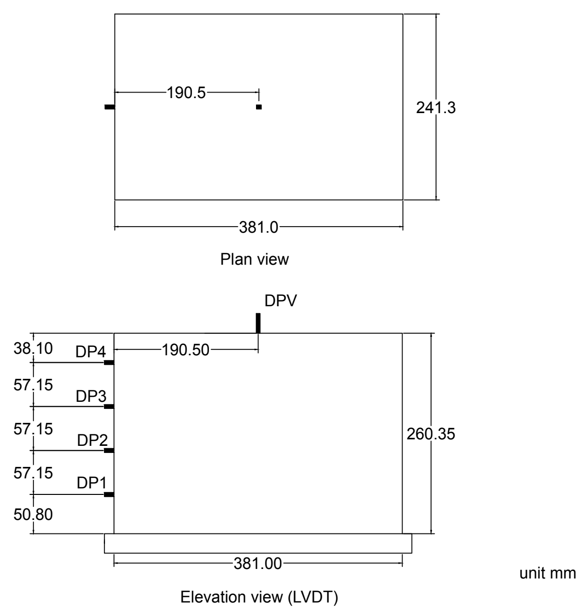


Figure 5. Location of LVDTs for centrifuge testing

3.2 Testing results

This model was spun up to 10 g and 30 g on the centrifuge and a given excitation was applied by the shaker to the base of the box. The natural frequency of the model was estimated by applying a pulse input and was evaluated as 100 Hz at model scale under 10 g level centrifuge test and 130 Hz at the model scale under 30 g level centrifuge test. Sinusoidal motions with an amplitude of 0.05 g and a frequency of 100 Hz with 40 cycles at the model scale were applied during the 10 g level test. An analysis of the results from these sensors was conducted to investigate the boundary effect of the container. The acceleration at the base in prototype scale during the centrifuge test at 10 g is shown in Figure 6.

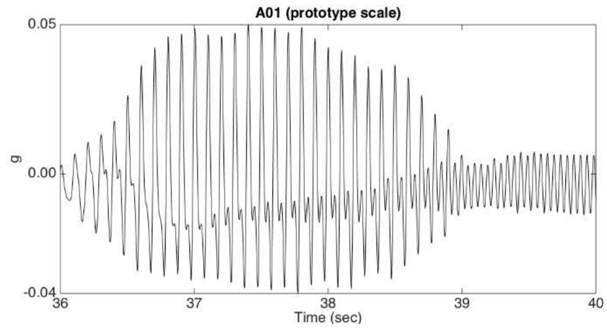


Figure 6. Input acceleration at the container base at 10g

The results from the accelerometers embedded in the soil and installed along the box edge during these shaking events are shown in Figures 7 and 8.

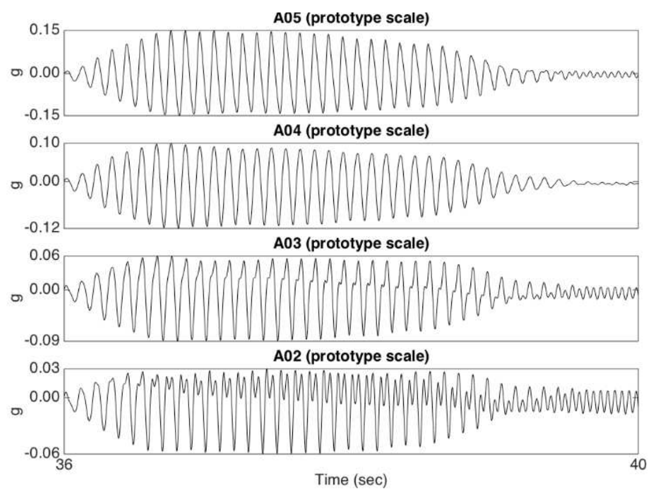


Figure 7. Results from accelerometers along the container laminates at 10 g

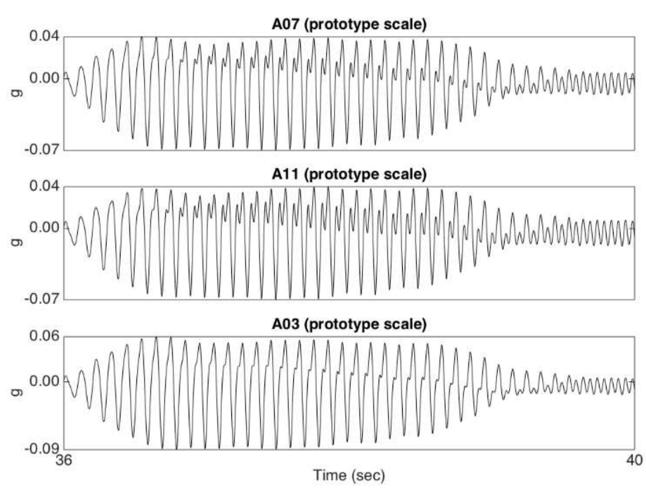


Figure 8. Results from accelerometers at same height (107.95 mm from the base) at 10 g

When the model was tested under a higher g-level of 30, a sinusoidal motion with a frequency of 130 Hz with 40 cycles in model scale was applied to the container, which is close to the natural frequency of the model (laminar container with soil inside). The previous analysis was done by applying pulse input to estimate the natural frequency of the model at certain g level. The base acceleration of the model, which is the same as the shaking table, is shown in Figure 9. The results from the accelerometers that were embedded in the soil and installed along the box edge during these shaking events are shown in Figures 10 and 11.

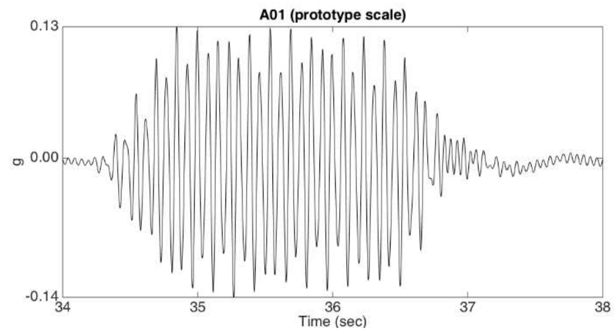


Figure 9. Input acceleration applied to the base at 30 g

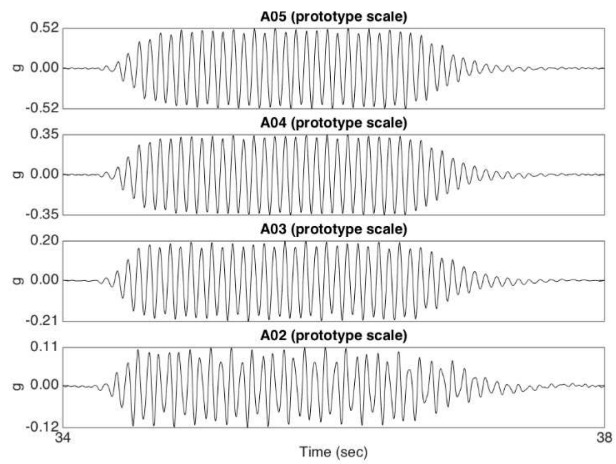


Figure 10. Results from accelerometers along the container laminates at 30 g

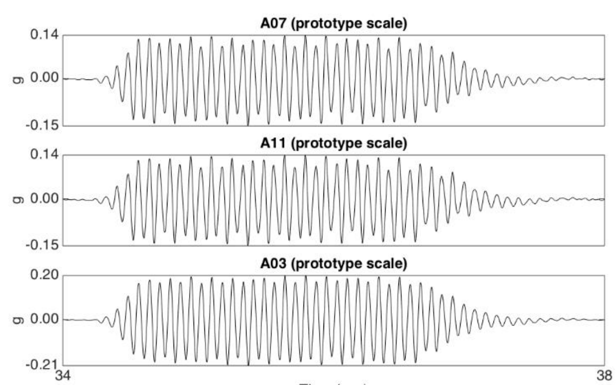


Figure 11. Results from accelerometers at the same height (107.95 mm from the base) at 30 g

Regarding the results shown in Figures 6 to 11, the accelerations measured across the container at different depths were relatively uniform. The similarity of accelerations with horizontal location along the same depth of the soil box indicates that the laminar container is providing soft boundary constraints and can simulate the soil dynamic response for soft dry soils. Comparing the results between different layers of soil, the accelerations for the upper layer of soil would be larger than the accelerations measured in the lower layer. When the frequency reaches around the natural frequency of the model, the amplification of the acceleration can be 5 times of the base acceleration.

The horizontal displacement is also an important means of characterizing the performance of the laminar container. Time series of the horizontal displacements of different laminates and the shaker at the base are shown in Figures 12 and 13. Evaluation of the time series indicate that there are different displacements with height, and that the laminates follow the horizontal deformations of the soil. The relative displacements between different frames shows a proper dynamic response of the laminar container during shaking.

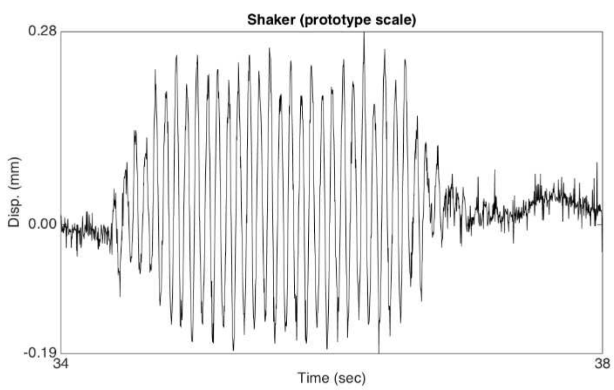


Figure 12. Horizontal displacement of the shaker

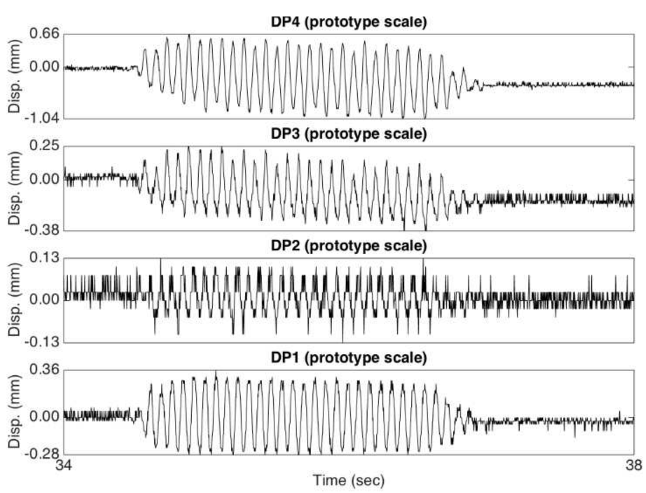
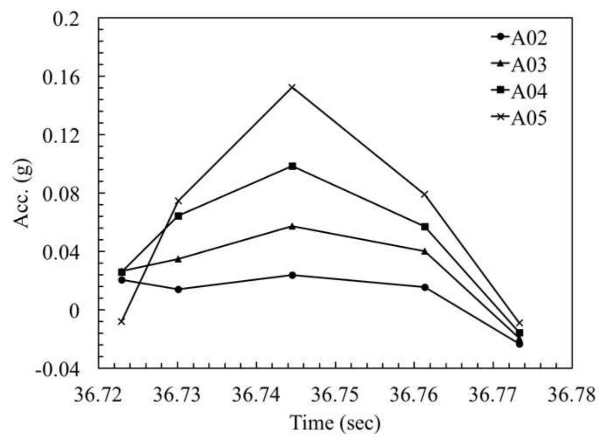
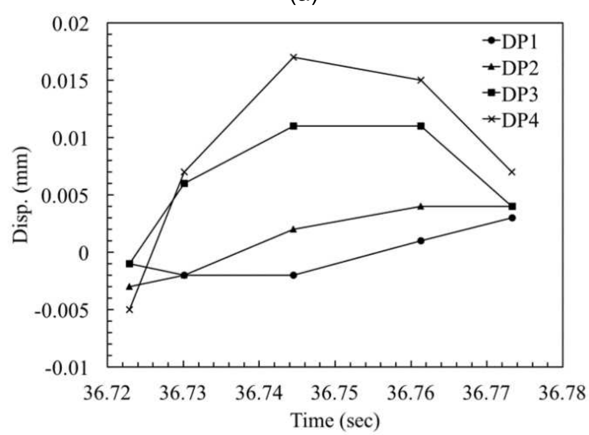


Figure 13. Horizontal displacement of each laminate

Figure 14 shows the accelerations and displacements at different heights for different times during a typical cycle. Although the magnitudes are different, the accelerations and displacements at certain heights are in phase indicating that the container and soil are moving together. The accelerometers and LVDTs which are close to the top surface give larger magnitudes.



(a)



(b)

Figure 14. Zoomed in time series at different heights during 10 g level test of: (a) Accelerations and (b) Horizontal displacements of soil and container boundary

The acceleration response at different heights in the soil model and at different times for the 10 g and 30 g tests are shown in Figure 15 and 16, respectively. The acceleration values are plotted along the container laminates, in the center of the soil layer, and close to the edge. From the results shown in Figures 15 and 16, the maximum difference between the acceleration responses at any depth of the soil layer, at the same time, does not exceed 10%, for both 10 g and 30 g tests. The shapes of displacement profiles shown in Figures 17 and 18 for the 10 g and 30 g tests, respectively, demonstrate the flexibility of this laminar container as it is moving together with the soil layer. The soft boundary effect of this laminar container gives sufficient flexibility to permit free deformation of the soil layer.

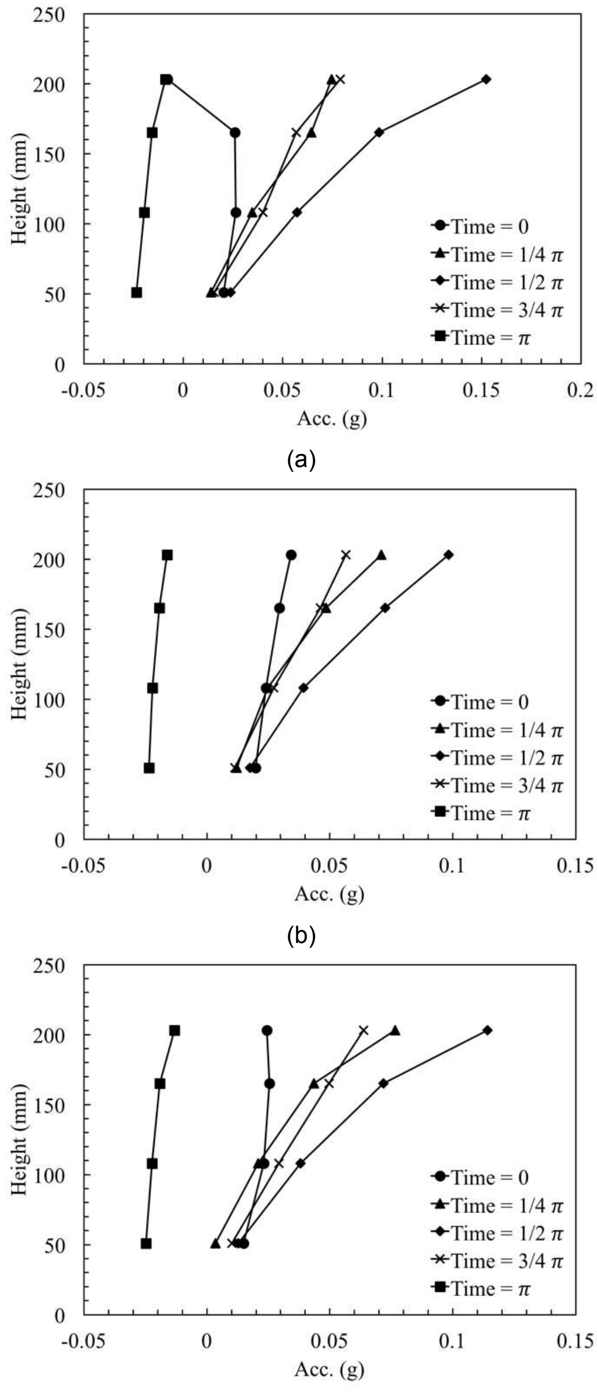


Figure 15. Accelerations at different depths in the soil layer in the 10 g test located: (a) along the container laminates, (b) in the center, (c) close to the edge

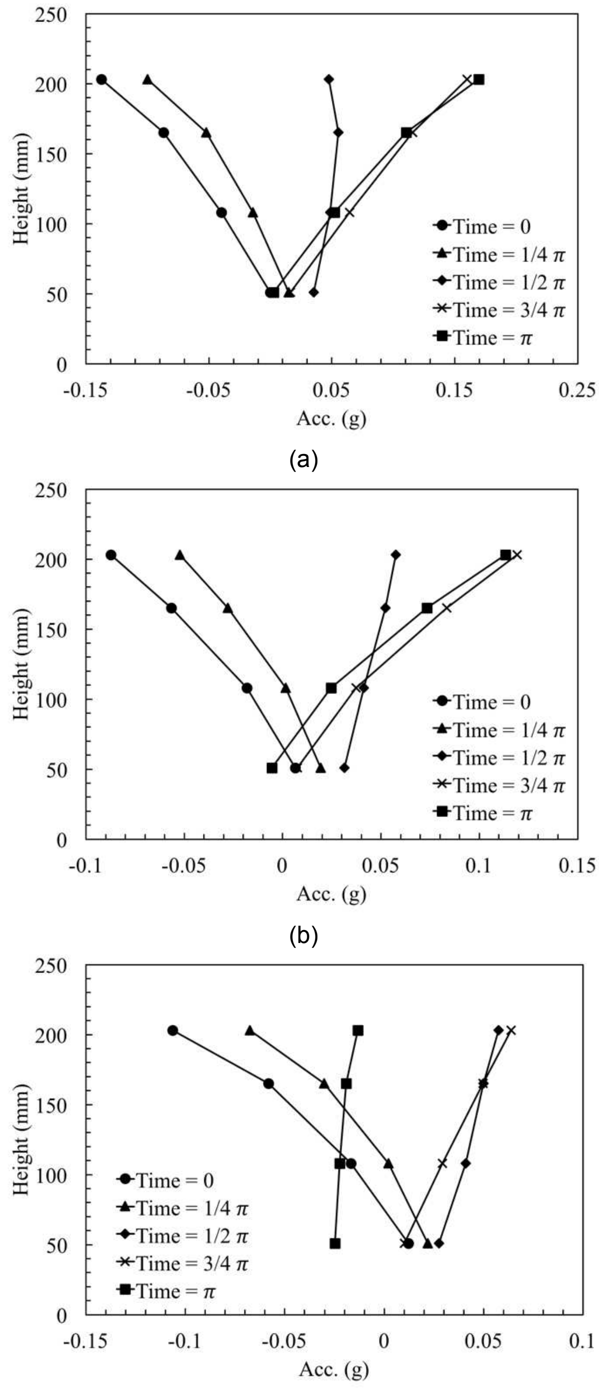


Figure 16. Accelerations at different depths in the soil layer in the 30 g test located: (a) along the container laminates, (b) in the center, (c) close to the edge

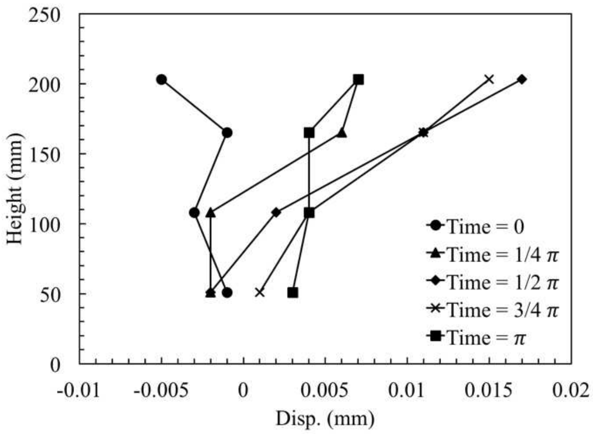


Figure 17. Displacements at different depths in the soil layer at 10 g test along the container.

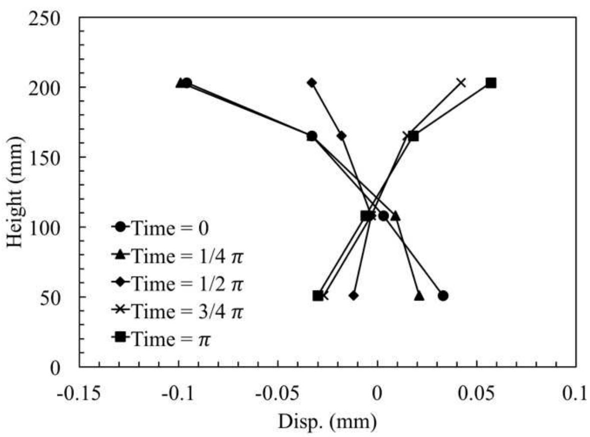


Figure 18. Displacements at different depths in the soil layer at 30 g test located along the container.

Regarding to the accelerations at the base of laminar box, the accelerations with respect to frequency are shown in Figure 19 for the 10 g test. The peak accelerations are around 90 Hz, so it can be assumed that the natural frequency of this laminar container with the soil is approximately 90 Hz.

4 CONCLUSIONS

A new type of light-weight laminar container has been designed for centrifuge testing with one-dimensional horizontal earthquake shaking input. The individually-mounted laminates provide a low sliding friction, leading to a sufficiently soft response needed to accurately characterize liquefiable soil layers. A shake table mounted on the basket of the 50 g-ton centrifuge was used to generate an earthquake-like excitation at the base of the container while spinning at different g-levels. Dynamic centrifuge tests using dry sand model was conducted. Accelerometers were attached to the container and embedded in the sand layer to characterize the container performance and to evaluate the boundary effects. Based on the analysis of the results from these sensors, the container provides low boundary constraints during shaking of loose sand, while still having the rigidity to maintaining close to at-rest horizontal stresses during spin-up and plane-strain boundary conditions during shaking.

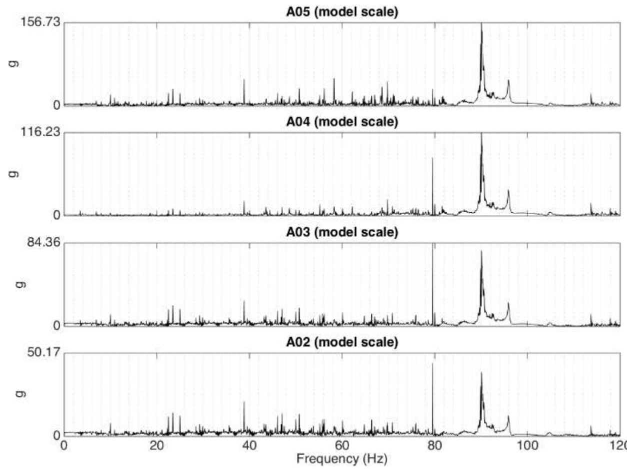


Figure 19. Accelerations at model scale with frequency domain from the 10 g test

5 ACKNOWLEDGEMENT

The authors are most grateful to graduate students at the UC San Diego, Department of Structural Engineering; Ahmed Ebeido, Jody Cheung and Mark Huang, for their contributions during the manufacture of the laminar container. Partial support was provided by the NSF Grant OISE 1445712.

REFERENCES:

Arulanandan K., and Anandarajah A. 1983. Dynamic Centrifuge Modelling. Recent Advances in Engineering Mechanics Practice. *Proc. 4th Engineering Mech. Division Specialty Conf. ASCE/END*, Purdue University, Illinois, Vol. I.

Brennan A. J., Madabhushi S. P. G. and Houghton N. E. 2006. Comparing laminar and equivalent shear beam (ESB) containers for dynamic centrifuge modeling. *Physical Modelling in Geotechnics, 6th ICPMG*. ISBN 0-415-41586-1.

Divis C. J., Kutter B. L., Idriss I. M., Goto Y. and Matsuda T. 1996. Uniformity of specimen and response of liquefiable sand model in large centrifuge shaker. *Proceedings of the sixth Japan–US workshop on earthquake resistant design of lifeline facilities and countermeasures against soil liquefaction*, 259–74.

Fiegel G. L., Hudson M., Idriss I. M., Kutter B. L. and Zeng X. 1994. Effect of model containers on dynamic soil response. *Proceedings of the international centrifuge conference*, 145–50.

Ghayoomi M., Dashti S. and McCartney J. S. 2013. Performance of a Transparent Flexible Shear Beam Container for Geotechnical Centrifuge Modeling of

Dynamic Problems. *Soil Dynamics and Earthquake Engineering*, 53: 230–239.

Hushmand, B., Scott, R. F., and Crouse, C. B. 1988. Centrifuge Liquefaction Tests in a Laminar Box. *Geotechnique,* 38(2): 253-262.

Lambe, P. C. 1981. Dynamic Centrifugal Modelling of a Horizontal Sand Stratum, *Sc.D. Thesis, Massachusetts Institute of Technology*.

Law, H., Ko, H-Y., Sture, S., and Pak, R. 1991. Development and Performance of a Laminar Container for Earthquake Liquefaction Studies. *Centrifuge 91, Ko & McLean Ed., Balkema*.

Lee, S.-H., Choo, Y.-W. and Kim, D.-S. 2013. Performance of an Equivalent Shear Beam (ESB) Model Container for Dynamic Geotechnical Centrifuge Tests. *Soil Dynamics and Earthquake Engineering,* 44(2013): 102-114.

Kutter, Bruce L. 1995. Recent advances in centrifuge modeling of seismic shaking. *Third International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics*, St. Louis, MO.

Van Laak, P., Taboada V. M., Dobry, R. and Elgamal, A.-W. 1994. Earthquake Centrifuge Modeling Using a Laminar Box. *Dynamic Geotechnical Testing II*, ASTM STP 1213, Philadelphia.

Whitman, R. V., Lambe, P. C., and Kutter, B. L. 1981. Initial Results from a Stacked-Ring Apparatus for Simulation of a Soil Profile. *Proc. Int. Conf. on Recent Advances in Geotechnical Engineering and Soil Dynamics*, Vol. 3, University of Missouri-Rolla, Rolla.

Whitman, R. V. and Lambe, P. C. 1986. Effect of Boundary Conditions Upon Centrifuge Experiments Using Ground Motion Simulation. *Geotechnical Testing Journal,* 9(2): 61-71.

Yoshikawa, M. and Arano, M. 1989. Dynamic Behavior of a Model Pile Foundation-Ground Systems in the Liquefaction Process. *Proc. of the Ninth World Conference on Earthquake Engineering*, 3: 599-604.

Zeng, X. and Schofield, A. N. 1996. Design and Performance of an Equivalent-Shear-Beam Container for Earthquake Centrifuge Modelling. *Geotechnique,* 46(1): 83-102.