DESIGN AND PERFORMANCE OF A LARGE-SCALE SOIL LAMINAR SHEAR BOX IN SHAKING TABLE TEST

Huang Chunxia[1], Zhang Hongru[2], Chen Guoxing[1], Sui Zhilong[1]

[1] *College of Civil Engineering, Nanjing University of Technology, Nanjing. China*

[2] *School of Civil and Architectural Engineering, Beijing Jiaotong University, Beijing. China*

Email: chunxiah@126.com, hrzhang@163.com

ABSTRACT:

The liquefaction of saturate sand is an eye-catching problem in geotechnical earthquake engineering. Amongst the various remedial measures available, the use of stone columns is one of the most popular choices. This paper describes the design, fabrication and performance of a large-scale single axis laminar shear box to investigate the behavior of composite foundation of stone columns. A laminar shear box is a flexible container that can be placed on a shaking table to simulate vertical shear-wave propagation during earthquakes through a soil layer of finite thickness. Based on the seismic response of the semi-infinite free-field sand deposit, a large-scale laminar shear box, which can simulate prototype soil layer boundary conditions, is designed. The inner dimension of laminar shear box is 3m in length, 1.5m in width and 1.8m in height. The container consists of fifteen, rigid rectangular, laminar frames supported individually by bearings connected to an external frame so that the weight of the box is transferred off the table using an external frame. The bearings connected to external frame are used to facilitate smooth relative displacement between adjacent frames. The design details of the box are provided in addition to results of dynamic tests performed to commission the box. The results of this study show that the laminar box does not impose significant boundary effects and is able to maintain 1-D soil column behavior. Furthermore, the laminar box designed in this research can be adopted in other tests for seismic geotechnical problems.

KEYWORDS: Large-scale laminar shear box, Flexible boundary, Shaking table test, Seismic geotechnical problems

1. INTRODUCTION

Since the catastrophic failures due to saturate loose sand liquefaction in the Alaska and Niigata earthquake in 1964, much interest has focused on this phenomenon in seismically active areas of the world. There have been remarkable achievements in the research of soil liquefaction in the past 40 years. Stone column technique has been used since the 1970’s to improve soils prone to liquefaction [1]. Evidence of stone column performance during and after strong earthquake, although limited, has satisfied [2, 3]. Great advances in numerical analytical models to predict soil liquefaction behavior and stone column response to strong ground motion have been made in recent years. However, before these techniques are applied in real engineering problems, they must be properly validated. That is, it is indispensable to perform an experiment in order to investigate the behavior of composite foundation of stone columns for the resistance liquefaction.

The prime choice is performing an experiment on composite foundation of stone columns in situ taking reliability of test results into account. However, the experiment in situ cannot well carry out due to absence of the vibration source simulating seismic effect at present. Although the experiment utilizing explosive loading as vibration source has been done by several researchers, there is a great difference between blast wave (duration is several ms and frequency content is mostly constituted of high frequency) and seismic wave. Therefore, it is a feasible method to carry out laboratory model test. It is in principle, impossible for liquefaction process to satisfy similitude ratios in reduced models of prototype water-saturated sand in centrifugally accelerated field [5]. Accordingly, it is decided to carry out shaking table test of water-saturated sand and stone columns to make clear the composite foundation behavior to prevent liquefaction.

Modeling the performance of geotechnical structures in shaking table test requires the development of a model test box whose seismic response matches closely that of the semi-infinite free-field soil deposit. Any given shaking table will have payload and dimensional restrictions, which limit the size of model box that can be tested, and the test box imposes boundary conditions that do not exist in the prototype condition. One of the main concerns regarding earthquake model test is the boundary effects created by artificial boundaries of a model test box. A successful model box design should allow the model soil to deform under seismic loading in the same manner as the prototype condition.

A simple, rigid end walled box was used in shaking table test for seismic earthquake problems in the 1980's. However, the box will not allow the soil specimen to deform uniformly and inhibit the development of large shear strains, which are essential for meaningful, non-linear studies. To overcome this problem, several research groups have used variations of the 'laminar shear box' concept [4, 5], which allows the model foundation to deform under seismic loading in the same manner as the prototype condition. The laminar shear box is consisted of separate rigid rectangular, laminar frames stacked together. The friction between the frames is reduced by bearings so that the frames can move relative to each other, thus creating a flexible boundary and allowing the soil specimen to deform in a shear beam mode. Utilizing this kind of model box, Matsuda T, Goto Y [4], Mizuno H, Sugimoto M, etc.[5], Wu Xiaoping, Sun Limin, etc.[6] carried out the experiment on studying dynamic behavior of saturated sand, pile foundation and soil-pile-structure interaction respectively.

The laminar shear box is adopted in this research because the box allows the model soil to deform under seismic loading in the same manner as the prototype condition. The paper describes design details of a large-scale laminar shear box used in shaking table test to investigate composite foundation anti-liquefaction behavior and can be referenced in the research of earthquake-related problems.

2. DESIGN OF THE LARGE-SCALE LAMINAR SHEAR BOX

The primary design goals of laminar shear box include rendering correct response over the range of test conditions, including shear failure of the soil. For this laboratory test, laminar shear box structure should satisfy following requirements in detail.

i) The size of laminar shear box is large enough in order to simulate large-scale composite foundation of stone column, while the self-weight of the test box is as light as possible.

ii) Each rigid frame of laminar shear box has enough stiffness to produce little distortion under test, thus the distortion of frames itself can be ignored.

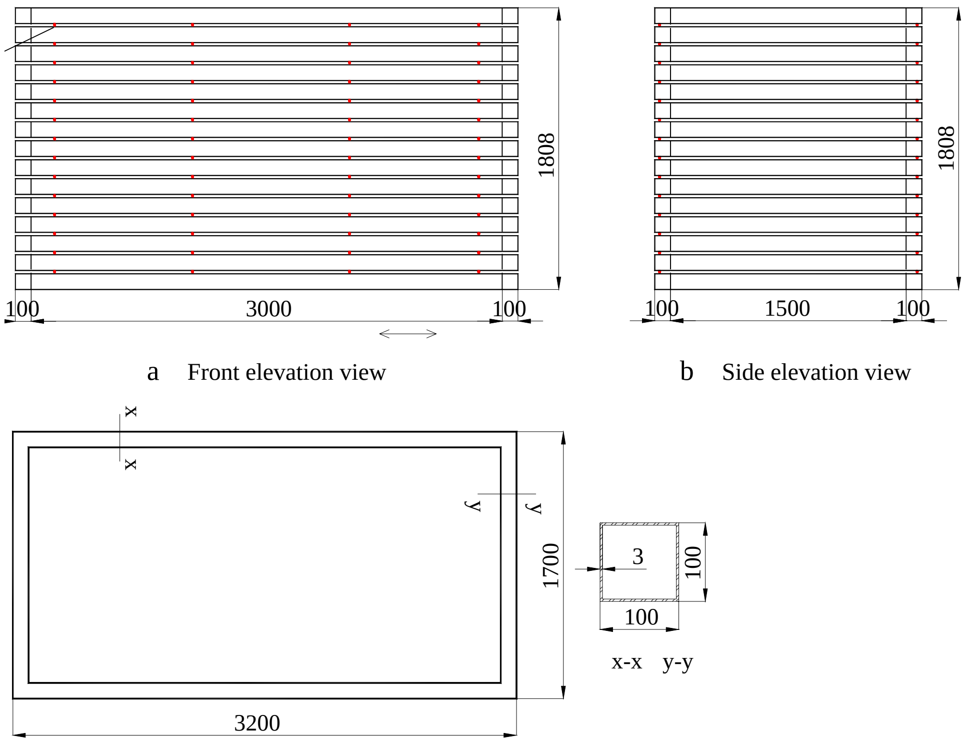
iii) It is needed to restrict lateral deformation of shear box while shaking because of only taking account of unidirectional deformation in this research.

iv) The whole box is firm enough to avoid breakdown while exciting.

v) It is necessary to reduce friction between the frames as much as possible. Thus, the deformation of the soil specimen is similar to semi-infinite free-field soil deposit.

vi) The fundamental frequency of laminar shear box keeps away from that of model soil to avoid resonate.

The flexible large-scale laminar shear box with approximate dimensions of 3m in length, 1.5m in width and 1.8m in height is illustrated in Figure 1. The container consists of fifteen, rigid rectangular, laminar frames (made from welded 100×100×3mm square steel pipe) supported individually by bearings connected to an external frame(see Figure 2) so that the weight of the box is transferred off the table using an external frame. This arrangement allows full utilization of the base shear capacity of small tables. The bearings connected to external frame are used to facilitate smooth relative displacement between adjacent frames. The steel frames provided lateral confinement of the soil, while the bearings allowed the laminar box to deform in a shear beam manner.



a Front elevation view

b Side elevation view

c Plane view

Figure 1 Design drawing of the laminar box (unit: mm)

Figure 2 Empty laminar shear box on the shaking table

A 3500 mm×1700 mm×15mm thick steel base plate is welded to the shaking table. The steel base plate has coarse sand epoxied to it to prevent sliding at the soil-base plate interface. The interior of the laminar shear box is then lined with thin flexible latex sheets, which prevent soil penetration into the gaps between laminate and provide watertight confinement in case saturated soils are tested.

3. The Dynamic Behavior of the Laminar Shear Box

3.1. Theoretical Analysis

It is necessary that fundamental frequency of laminar shear box is not near-to that of model soil in order to make sure accuracy of the test results. General-purpose finite element program ANSYS is adopted in modal analysis of the laminar shear box. The analysis model is a single span 15-story plane framework. Each of the side wall and steel sheet are both simplified as beam element, and the end wall is simplified as mass nodal. The calculated fundamental frequency is about 2Hz.

Assumed the shear wave velocity of loose saturate sand is 80～200m/s, the natural frequency of model soil is worked out by following formula [7]

$$f = \frac{1}{T} = \frac{v_s}{4H} \qquad (1)$$

Where f is natural frequency of soil, T is natural period, h is depth of the soil layer, *and* Vs is shear wave velocity. The depth of model soil is 1.8m and the natural frequency of model soil is 10-25Hz. Accordingly, the test box will not affect seismic response of model soil.

3.2. Tests Performed and Instrumentation Details

A series of shaking table tests were carried out to investigate the performance of the flexible box boundaries. Figure 3 shows a cross-section and plane view of the flexible box and the instrumentation layout. A total of six accelerometers were used to monitor the response of model soil. Four of the accelerometers were mounted on the soil surface. Accelerometers a4, a6, a5 were situated along the longitudinal axis of the soil layer ranging from the centre of the box to within 100mm of the boundary. a3 was situated on the transverse axis to 100mm of the boundary.

To investigate the effects of box boundaries, a small amplitude (0.12g) El Centro wave was applied to the table and flexible container to ensure linear soil behaviour. The readings of accelerometers a4, a3, a5 and a6 were compared to examine the influence of the box boundaries.

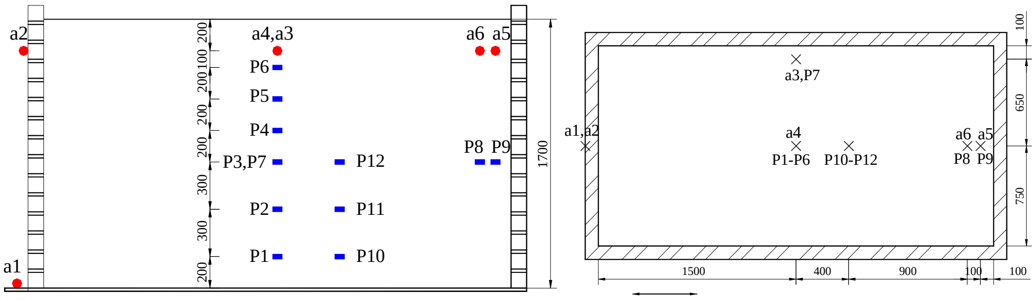


Figure 3 Arrangement of the instrumentation

3.3. Assessment of boundary effects

Figure 4 shows the comparison of acceleration time history of a3, a5 and a6 to a4 at input of El Centro (0.12g). The results show that the differences between the responses at a3, a5 and a6 to a4 were insignificant. The peak amplitude of a5, which was situated 100mm away from the box boundary, was little bigger than a4. These results demonstrate that the flexible boundaries of the laminar box functioned appropriately. The bigger peak acceleration of a5 can be attributed to factors, such as, the local rigid boundary effect within the lamina level, and possible compaction imperfections close to the walls of the box. However, the results suggest that the majority of the soil behaves according to the 1-D vertical shear wave propagation model [8].

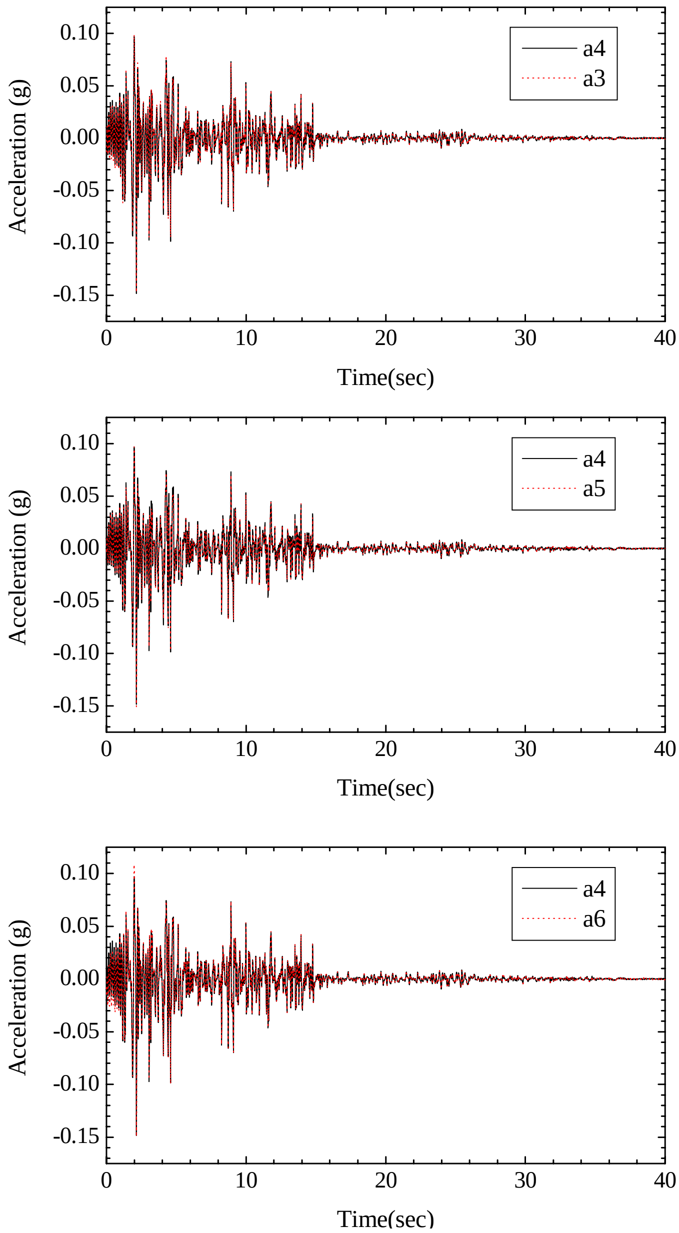


Figure 4 Comparison of acceleration time history of a3, a5 and a6 to a4 at input of El Centro (0.12g)

4 CONCLUSIONS

Laboratory model test is important in the research of seismic geotechnical problems because of the inadequacy of in situ data. Therefore, Physical modeling technique, such as the structure style and material behavior of model test box, is vital to simulate semi-infinite free-field soil deposit. This paper describes the design and performance of a laminar shear box, which overcomes the base shear limitations of a small 1-G shaking table. The performance of the laminar shear box is evaluated using a series of model tests. The test results show that the effect of boundary on measured accelerations is found to be negligible.

As we know, a wide variety of numerical models for modeling the dynamic behavior of geotechnical problems has been made during the past twenty years. Furthermore, sophisticated techniques are now available to handle the analysis of saturated materials and complex soil structures [9]. However, there are few experimental or prototype data against which these models can be compared. As mentioned above, before these techniques are applied in real engineering problems, they must be properly validated. This inevitably means some form of comparison with physical test data. The large-scale laminar box developed in this research can offer an interesting insight into the seismic behavior of large soil specimens.

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