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DESIGN AND EVALUATION CONCEPTS OF LAMINAR SHEAR BOX FOR 1G SHAKING TABLE TESTS

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SUMMARY

The boundary conditions for physical modeling in problems of earthquake geotechnical engineering have significant influence on the test results. In order to reduce the undesirable effects of boundaries on the model responses, the flexible containers are used.
The flexible containers are those in which the shear stiffness of the walls is proportional to the soil inside. There are different kinds of flexible boxes which are briefly reviewed in this paper and the general properties of different alternatives for the construction of a flexible box are studied for 1*g* shaking table tests.
Detail description of the design steps of a flexible laminar shear box for the shaking table of the Earthquake Research Center of Sharif University of Technology (SUT), is explained. The results of numerical simulations conducted for the determination of dynamic properties of soil model used in the designed box as well as static calibration tests of the container, are presented and the applicability of the designed container is evaluated.

INTRODUCTION

The physical model tests in geotechnical earthquake engineering have been developed as a method between element and in situ tests. This kind of tests is being used for the study of seismic behavior of level or inclined grounds in liquefiable soils or soft clays, soil-structure systems like shallow or deep foundations, retaining walls and embankments. Using the model test results in controlled conditions considering material type and boundary conditions, we can simply identify the failure mechanisms, optimize the design methods and determine the validity of the constitutive models and analytical methods.
The physical model tests in earthquake geotechnical engineering are conducted in 1g gravity field on shaking table, or the augmented gravity field in geotechnical centrifuge.
Considering the necessity of correspondence for stress levels in real situation and the model case, use of centrifuge in modeling of earthquake geotechnical problems lead to more applicable results, although there are still some deficiencies [1] and without minimizing the induced errors, the results of centrifuge tests are not reliable.

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Unlike the centrifuge tests, the geotechnical modeling in 1g gravity field on shaking table has some advantages, however; can not be used to produce the real stress levels. Since less space limitations are encountered for construction of large models, study of the system deformation modes in modern shaking table tests is possible. Furthermore, using of high capacity actuators makes it feasible to increase the stress level through the enlarging of the dimensions of the models.

In dynamic physical modeling tests the real half-space is modeled using a limited volume of soil in a container. Therefore, the influence of boundary condition of the models exists in both geotechnical centrifuge and 1g shaking table tests. The simplest and oldest way for geotechnical modeling is use of rigid or fixed-wall box. This sort of container is sufficient for gaining an insight for the simulated phenomenon. However in cases that the quantity of parameters and response are significant, using the rigid box is not suitable. That is mainly because of the stress waves reaching the rigid walls and reflecting back to the soil. Although the energy absorbent materials can be applied for solving this problem, in some cases as liquefaction modeling problems, which the model soil undertake significant deformations this method leads to inaccurate results. In such conditions, the flexible box is a good alternative. In flexible boxes, the stiffness of the walls is proportional to the stiffness of soil. For increasing the flexibility of the box walls, depending on soil type, model dimensions and the studied phenomena; one of the following methods could be used:

1- Setting each layer on the other, within the frame made of rigid light material which can easily move on each other. This kind of box is called laminar shear box [2, 3, 4, 5, 6, 7 & 8];

2- Setting the rigid frames on each other using rubber layers in between, with suitable shear stiffness. This type is known as equivalent shear beam condition [9, 10];

3-Applying rubber walls which are reinforced with light rigid rings [11, 12].

Using recently established shaking table in the Earthquake Research Center of Sharif University of Technology (SUT), new opportunities arise for conducting model tests on earthquake geotechnical problems in Iran, for the first time.

In this paper, after reviewing of the design concepts for flexible laminar boxes, the detail design and calibration procedures is explained for the laminar shear box of SUT.

REVIEW OF FORMER STUDIES

The history of using flexible boxes in model tests turns back to 1970s. In 1979 Kokusho performed shaking table test on level ground model made of fine sand in a 1*m* deep laminar shear box [3]. He illustrated the reduction of resonant factor with increasing in acceleration level which demonstrates the proper performance of boundary conditions of the box used .In 1981 Lamb & Whitman applied a similar idea in centrifuge liquefaction tests [5]. The box used consisted of several aluminum rings whose surface was polished by a Teflon layer. The main design considerations were as follow:

a) maintaining the fixed cross section during seismic loading;

b) Inducing dynamic shear stress on common surface of the soil and vertical walls which is equal to the shear stresses induced on common area of soil and the bottom of model;

c) having little mass;

d) minimum shear stiffness;

e) having no resistance to soil settlement;

f) water tightness of the model.

In 1993 DAR developed another type of flexible box for testing on shaking table of earthquake research center in Bristol University [10]. The design of this box is based upon the equality of dynamic stiffness of the container walls with soil column of the model in the required strain level. This device was constructed by putting aluminum frames on each other with rubber layers having specific shear modulus between them.

Another type of the box, analogous to the above-mentioned box was applied in centrifuge tests by Schofield & Zengl, which is called ESB (Equivalent Shear Beam) container [13]. In 1994 Fiegel et al.

developed a new flexible container known as HPC (Hinged Plate Container), having positive aspects of both laminar and ESB containers [1]. This type of container is composed of 4 aluminum frames which are connected to each other using hinge connections in the direction of the applied loads. These layers are assembled in a way that they can easily rotate as the soil is displaced. In the other direction the frame has the same mechanisms as the laminar box i.e. the layers can move easily on the ball bearings.
In 1994 Fiegel et al. [1] conducted the centrifuge tests under seismic loading using 4 types of laminar box including rigid laminar ESB and HPC being filled with dry sand [1]. They compared the performance of the 4 mentioned containers with each other .The different response of these 4 containers demonstrate that the laminar and HPC containers are more suitable in simulation in the vicinity of non-linear behavior of soil (i.e. the strain level more than 1%).

DESIGN OF A FLEXIBLE CONTAINER FOR SUT

General Specifications of SUT Shaking Table

The shaking table of SUT has 3 degrees of freedom. The testing platform is a square having 4×4 m^2 dimension and approximate weight of 12 *tons*, which has been made from steel plates. This shaking table has the capacity of tests up to 30 *tons*. The functional frequency of shaking table is 0 to 50 *Hz*. The input motion is provided through 3 hydraulic horizontal actuators, one in the *N-S* and the other two in the *W-E* direction; as shown in Figure1. Also, the properties of the actuators are given in Table1.

Figure 1: Shaking table of Sharif University of Technology (SUT)

Table 1: General specifications of SUT shaking table

	N-S Direction	*E-W* Direction
Max Acc. (No load)	5 *g*	4 *g*
Max Acc. (10 tone load)	2.9 *g*	1.6 *g*
Max Displacement	12.5 *cm*	20 *cm*
Max Velocity	50 *cm/s*	80 *cm/s*

The Objectives

The container should be designed in a way that the saturated granular soil will be permitted to deform freely as in natural ground when subjected to seismic loading. Reaching this goal and using the most versatilities of shaking table, it is strictly required that the container be a flexible one having the deformation capacity in two directions in the horizontal plane.

General Pattern of The Container

Considering the container with deformation capacity in two horizontal directions, the geometrical shape of the cross section could be square or circle.

The circle cross section is more suitable due to symmetry. However, constructing a container having square cross section is easier and since the measuring points are usually located in the center of the cross section, the probable stress concentration in the corners has little influence on the results. According to the capacity of the shaking table, the models weighing up to 30 *tons* can be tested on the shaking table, but it is preferable to commence with small scale models .Thus the square cross section with 1 *m* length is chosen.

For flexibility in the walls of the container a laminar system was applied, since in this system, the shear stiffness of the walls is limited to the friction between the layers and the influence of rubber membrane inside the box. So this kind, so called laminar shear box; at the time of liquefaction, has the least undesirable effect in the real behavior of the model, while the ESB system with constant shear stiffness and uniform along with the height of the container has complete difference with the real granular soil either in dynamic or static loading.

Components of The Container

The 3 dimensional layout of the container has been depicted in the Figure 2. The container consists of the following main components:

(a) Layers and ball bearings;
(b) Base plate and the saturation and drainage system in the floor;
(c) The upper and the side guides;
(d) Internal membrane used as a cut-off and keeping the moving bearings away from dust.

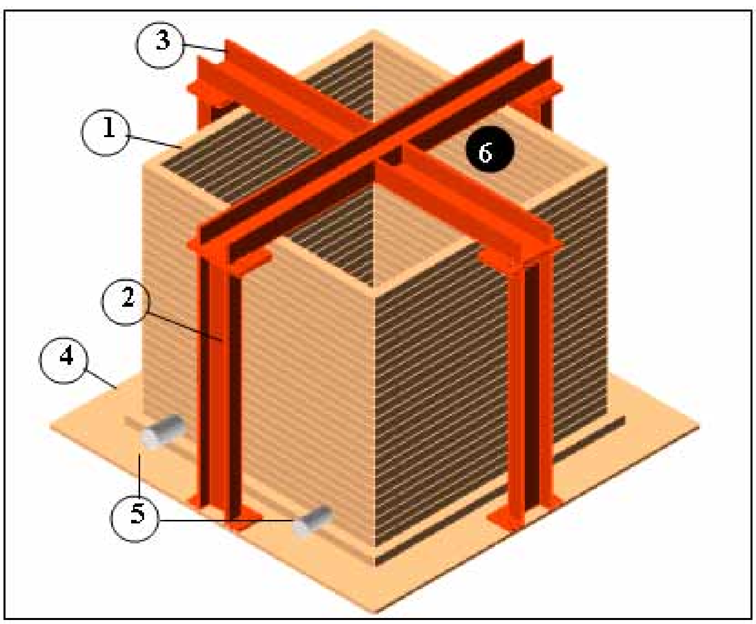

Figure 2: Isometric schematic view of the designed laminar container, 1) one of the frames; 2) side guide column; 3) upper horizontal guide cross; 4) base plate; 5) entrance and drainage pipes; 6) elastic membrane.

The layers and the mechanisms of the motion
Each layer is a square frame with 1×1×0.04 m^3 internal dimension which has been made from the hollow aluminum profiles with 40×40 mm^2 section and 2 *mm* thickness. The whole system is composed of 24 layers each being set directly on the other making the total height of 1 *m*. In order to minimize the friction between the layers, transfer ball bearings have been used so that the two dimensional motion in the horizontal plane is possible. This ball bearing consists of one main ball having the diameter of 16 *mm* which has been put in a hemispherical space full of fine balls .These balls are designed in a way that they can be simply and without additional devices installed on the surface of the layer and the base be alighted on the lower wall of the hollow aluminum profile. This makes the balls act as a column between the lower and upper hollow aluminum sections and prevents the surface from being deformed, by the point contact stress between the ball bearing and the surface of the aluminum profile. In order to make the distribution uniform, 12 rotating ball bearing are used in each layer and the gap between the 2 adjacent layers is 3 *mm*.

Bass plate and saturation and drainage systems
The lowest layer has been fixed on a steel base which this base in its turn, is fixed on a steel plate with 0.02 ×1.5 × 1.5 m^3 dimensions. In addition to preserving the upper layers, the base has some closed space for watering and dewatering via four valves. The water entrance area to the model is covered with porous stone. In this way, not only saturation and drainage of the samples is facilitated but also the bottom of the container gets rather tough, improving the contact of the soil with the bottom of the container and makes better shear stress transition to the model.
For hydraulic cut-off system and the protection of the ball bearings, the inside of the container is covered by a 2 *mm* thick rubber membrane.

The upper and side guides
In the four sides of the box and with a distance not more than 15 *cm* from the walls of the box, 4 steel columns have been installed, so as to prevent the frames from the oversize deformations while conducting the test.
Also, in order to prevent the layers from getting separated at the time of vibration, a horizontal steel cross has been installed above the columns tangent to the ball bearings of the uppermost layer.

DYNAMIC RESPONSE OF MODEL WITH NUMERICAL SIMULATION

In order to predict the dynamic behavior of the design box and also to have a better insight in phenomena related to this container a series of numerical modeling using finite elements have been conducted. To do this two and three dimensional models have been constructed using dry sand (Toyoura Sand) in flexible containers with different relative densities and different boundary conditions for the vertical boundaries of the models.
Also two dimensional models of the rigid container were also constructed in order to provide the basis for comparison. In all models, the maximum shear modulus, G_{max}; was determined regarding σ'_c through Equation 1 [14]:

$$G_{max} = 840(2.17-e)^2 (\sigma'_c)^{0.5}/(1+e) \quad kg/cm^2 \tag{1}$$

In which σ'_c is effective confining pressure and e is model void ratio. Two types of analysis were performed on the models: Modal analysis and the Equivalent Linear (EQL) method analysis. Using the modal analysis, it was demonstrated that the natural frequency of the first mode of vibration having different densities in the laminar shear box is in the range of 20-35 *Hz*, while this range as for the rigid box with the same material is 50-85 *Hz* [15].

Figure 3: Disassembled parts of the laminar shear box

Figure 4: General view of the laminar shear box fastened on the shaking table

In addition, it was demonstrated that the complimentary shear stress in the walls of the container has a great influence on the accuracy of the results of the model tests. In other words, there should be enough restrictions against the flexural moment induced by the soil inertia force inside the container or else the stress distribution induced by the weight in the model changes dynamically and the dominant deformation mode will not be of simple shear and the flexural mode predominates.

In the analysis of the response using equivalent linear method for decreasing the soil stiffness the model called Hardin-Drenvich was used and the reference strain required was calculated using Equation 2 [14].

Using the response analysis method, the graph of maximum acceleration in the surface versus the maximum input acceleration was drawn as in Figure 5, which shows that as the shear stiffness of the soil in the container decreases, the difference in the behavior of flexible and rigid containers is more evident and the requirement for a laminar container is increasing [15]. The dynamic loading for all analyses is a sinusoidal harmonic vibration with 5 *Hz* frequency.

$$\gamma_r = 0.000555\ (\sigma'_c)^{0.5} \tag{2}$$

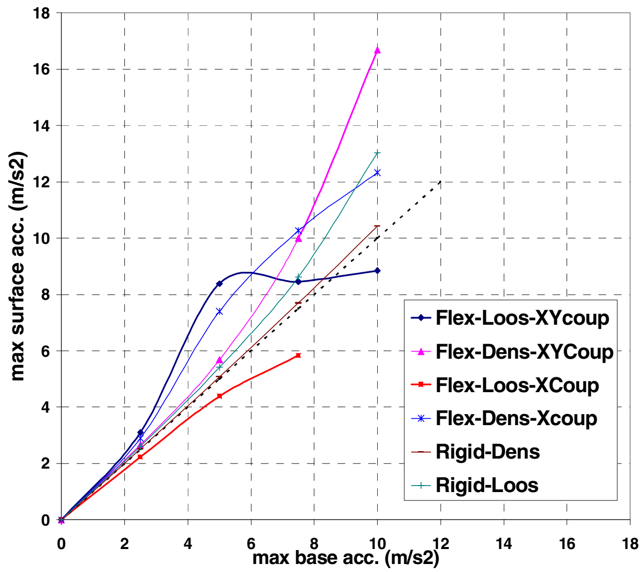

Figure 5: Variation of surface acceleration compared to base acceleration for flexible or rigid containers, filled with dry loose or dense sand, estimated EQL method

STATIC CALIBRATION TESTS FOR THE EMPTY BOX

The most important factors affecting the performance of the container are as follow:
(a)The influence of the inertia of the wall masses of the box
(b)The influence of the friction induced by the ball bearings and the surface of the layers
(c)The effect of the membrane
(d)The effect of the walls of the box when changing the stress field in the model

Inertia Effect of The Layers

The effect of the inertia is induced by the masses of the box walls and affects the measured acceleration in the model. If a is assumed as the measured acceleration in the soil inside the box this acceleration is less than the real value. If m_1 be the soil mass being in contact with one layer, m_2 the mass of corresponding frame and a_s the acceleration of the soil without the influence of the container:

$$a_s = ((m_1+m_2)/m_1)a \tag{3}$$

Then the $(m_1+m_2)/m_1$ is the coefficient that must be multiplied by the measured acceleration to eliminate the effect of inertia induced by the container walls [3]. m_1 depends upon the density of the tested soil and

m_2 for this container is 5 *kgf* for each layer. So the aforementioned coefficient for the loose models, having the unit weight of about 1300 kgf/m^3 is at most 1.1.

Influence of The Friction Induced By The Ball Bearings

The ball bearings used between the layers, significantly reduce the friction. In order to measure the existent friction force some static pull out tests were performed in both horizontal directions, as shown in Figure 6. Also, in Figure 7 the results of these static tests are shown.

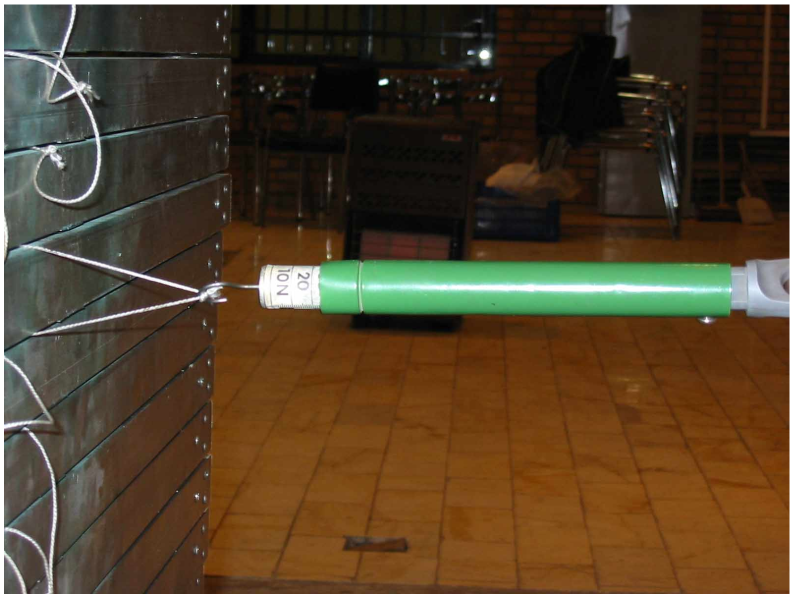

Figure 6: Static pull out tests for measuring of the friction force between layers

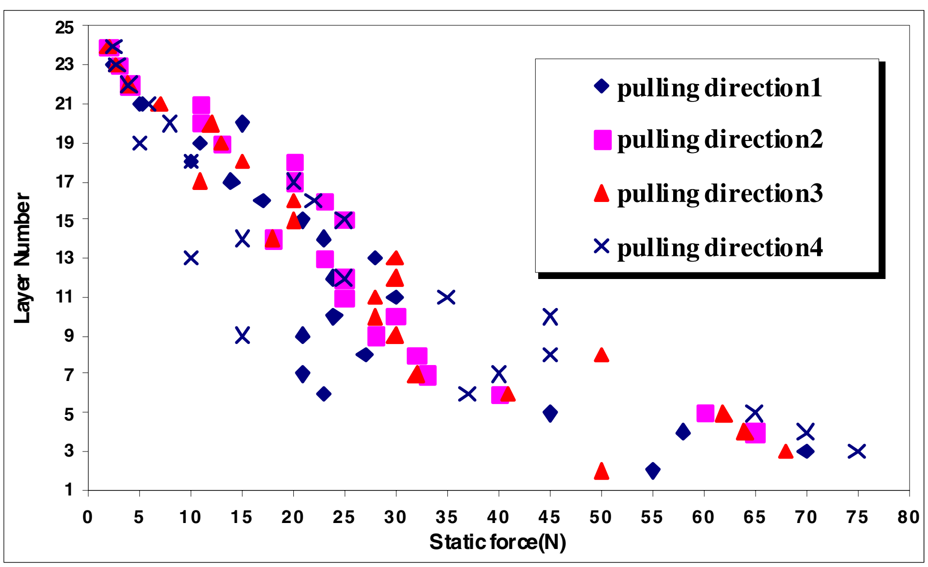

Figure 7: Results of static pull out tests for measuring of the friction force between layers

Considering the normal force acting on each layer, the mean coefficient is estimated to be about 0.022 [15]. Therefore, for a model of soil with the loose density, having the unit weight of about 1300 kgf/m^3, and the friction coefficient nearly 0.1 (assuming the friction angle to be about 6 degrees), the friction force in the lowest layer is 130 *kgf* while the static friction coefficient between the layers adjacent to the walls in the same elevation is 2.64 *kgf* which is about 2% of the friction force inside the soil model in this level.

CONCLUSIONS

Detail design procedure of a laminar shear container having the capability of two horizontal dimensional deformations for dynamic physical model tests in 1*g* gravity field on the shaking table of Sharif University of Technology was presented. Installing rolling transfer balls with specific details between the layers, cause the friction force to be reduced greatly and brought about the required resistance against deformations of the layers. The dynamic analysis for loose sandy models demonstrated that the natural frequency of the model soil in designed flexible container for small strains is in the range of 20-35 Hz. Using equivalent linear method it was shown that as the density of the model decreases, the need for the flexible container increases.

The static calibration tests of the container showed that the effect of mass of the frames and the friction between the layers, are negligible in the results of the dynamic model tests.

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