Shaking table tests in earthquake geotechnical engineering

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Research in earthquake geotechnical engineering has shown considerable development in the recent past. We focus here on developments of model testing in earthquake geotechnical engineering. Two aspects of model testing are given importance, namely manual shaking table and laminar box. Design, development, calibration and performance of these equipments are described. Model testing is the essential requirement of earthquake geotechnical engineering that helps in understanding the behaviour of geotechnical facilities and their performance during earthquake. Manual shaking table developed very economically can be used as an alternative to a more sophisticated shaking table. Laminar box is a sophisticated container which can enhance the accuracy in assessing the ground behaviour. Some of the important calibration techniques necessary are also discussed.

EARTHQUAKE geotechnical engineering in India has received tremendous boost after the Gujarat earthquake of 2001. Earthquakes are not uncommon, but the damage suffered during earthquakes is on the rise because of the population growth, overcrowding of civil engineering facilities in urban areas and improper understanding of ground behaviour among many. Recent earthquakes in Gujarat (2001), Chamoli (1999), Jabalpur (1997), Latur (1993) and Uttarakashi (1991) in India have increased the research activities in the country in the field of earthquake engineering. Developments in earthquake geotechnical engineering which include understanding ground behaviour during shaking, effects of earthquake on geotechnical facilities, site amplification studies, etc. have also shown tremendous progress. Studies in earthquake geotechnical engineering can be broadly classified into four groups, namely,

- Understanding the ground behaviour through element tests.
- Carrying out model tests to capture finer points such as rise in excess pore water pressure, ground amplification, etc.
- Development and use of analytical/numerical model to simulate ground behaviour.
- Application of the above concepts to field problems and to ensure their behaviour.

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Since the understanding of ground behaviour during shaking is still incomplete, the above four approaches are very essential. Unless all the four approaches are attempted on a problem, it becomes very difficult to understand the concept, mechanism of failure, permanent deformation and factors influencing the behaviour, etc. Unfortunately in India, though some analytical works are carried out in the field of earthquake geotechnical engineering, very little work is reported on element tests, model tests and analysis of field data. Lack of facilities for laboratory studies and non-availability of instrumentation in the field can be attributed as the main reasons.

1-G Shaking table tests

Model tests are essential when the prototype behaviour is complex and difficult to understand. In model testing, usually the boundary conditions of a prototype problem are reproduced in a small-scale model. Model tests are used to understand the effects of different parameters and the process leading to failure of prototype at a real time. The model tests can be divided into two categories, namely, those performed under gravitational field of earth (generally called shaking table tests) and those performed under higher gravitational field (centrifuge tests). Both shaking table and centrifuge model tests have certain advantages and limitations. Shaking table tests have the advantage of well controlled large amplitude, multi-axis input motions and easier experimental measurements and their use is justified if the purpose of the test is to validate the numerical model or to understand the basic failure mechanisms.

Shaking table research has provided valuable insight into liquefaction, post-earthquake settlement, foundation response and lateral earth pressure problems. For the models used in shaking tables, soil can be placed, compacted and instrumented relatively easily. Though higher gravitational stresses cannot be produced in a shaking table test, the contractive behaviour associated with high normal stresses at significant depths can be simulated by placing soil very loosely during model preparations. From undrained triaxial test results on Toyoura sand, Verdugo and Ishihara[1] showed that contractive behaviour at low confining pressures can be achieved by placing soil loosely. In shaking table tests of reduced scale models, the similarity rule in terms of stress and strain against the prototype cannot be satisfied because of the stress dependency of the stress–strain soil behaviour. Thus the model tests can be considered to be small prototype test.

A number of works have been carried out to understand the failure mechanisms and behaviour of earth structures using shaking table tests. Koga and Matsuo[2] carried out shaking table tests on reduced scale embankment models founded on saturated sandy ground. They investigated the cyclic stress strain behaviour of soil in the ground by using the acceleration and pore pressure records. Kokusho[3] has explained the use of 1 g shaking table tests in understanding the mechanism of flow failure in liquefied deposits. He reiterated that use of torsional simple shear tests, *in situ* soil investigation, case histories including shaking table tests were essential to understand and develop the lateral flow mechanism during liquefaction. Orense *et al.*[4] reported the use of 1 g shaking table tests in understanding the behaviour of underground structures during soil liquefaction. They have reviewed several shaking table test results from different authors on the behaviour of buried structures and possible mitigation measures against liquefaction failure using gravel drains.

In order to reproduce actual earthquake data, a six degree of freedom shaking table is essential. It is a very complex electro-hydraulic system which is very expensive and requires high maintenance and operational costs. However, when the response and failure mechanisms of earth structures like embankment, retaining wall, quay wall are of importance, single horizontal translational degree of freedom shaking tables are sufficient. The cost of actuators for shaking table exponentially increases as the payload increases. Considering these factors, a manual shaking table was designed and fabricated.

Manual shaking table

It consists of two wooden panels with spring steel plates between them. The height and number of plates were designed to achieve a relatively rigid platform requiring a very low effort to vibrate. Two wooden panels 600 mm wide and 1800 mm long were used such that one of them was a base and the other a platform to place the container as shown in Figure 1. In between them, four steel plates 300 mm long and 2 mm thick were provided to act as springs. The connections between plates and wooden panel were provided through steel bolts and angle sections. A handle was provided at the end to apply manual force. The shaking table was designed to apply harmonic sinusoidal shaking along longitudinal direction. From the past earthquake records it was found that the predominant frequency of most of the earthquakes that cause severe damage were in the range of 1 to 2 Hz and peak average amplitude of acceleration was around 0.5 g (ref. 5). Hence, the shaking table was designed to vibrate at around 2 Hz with 0.5 g level of acceleration. Also, this magnitude of shaking was necessary to liquefy the model ground when it was subjected to full payload of 7 kN. The average single amplitude displacement was found to be 25 mm. The best feature of this shaking table was that the maximum force required to generate this order of shaking was around 80 N as recorded by spring balance when the system carried full payload. The fact that a small magnitude of force was enough to shake sufficiently large mass indicates that the system vibrated on its own and continuous shaking was necessary to overcome the damping effects.

Figure 2 shows the shape of a input acceleration on the platform of shaking table both in time and frequency domains in a typical test. The zoomed input shows that the input was harmonic and sinusoidal and the predominant frequency was 1.8 Hz at a payload of around 5 kN.

Figure 3 demonstrates the range of input frequency and peak average amplitude of input acceleration in about 30 tests. It is seen that the average frequency content and the average input acceleration were 2 Hz and 0.58 g respectively.

To understand the effect of the mass on natural frequency of the system, tests were carried out by vibrating the shaking table with different masses. The height of the model ground was varied to achieve different masses. Accelerometer was placed on the platform to measure the input acceleration. From the time history of input acceleration, predominant frequency of shaking was evaluated. Assuming single degree of freedom system and hinged joints, the theoretical frequency of shaking was computed for various masses. Table 1 shows the comparison between the measured and theoretical frequencies of shaking. It can be observed that the two frequencies are comparable and that the frequency increased as the mass of the system decrea-

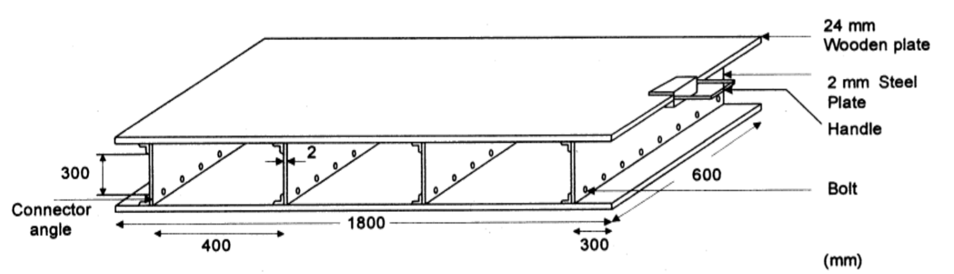

Figure 1. Schematic view of manual shaking table.

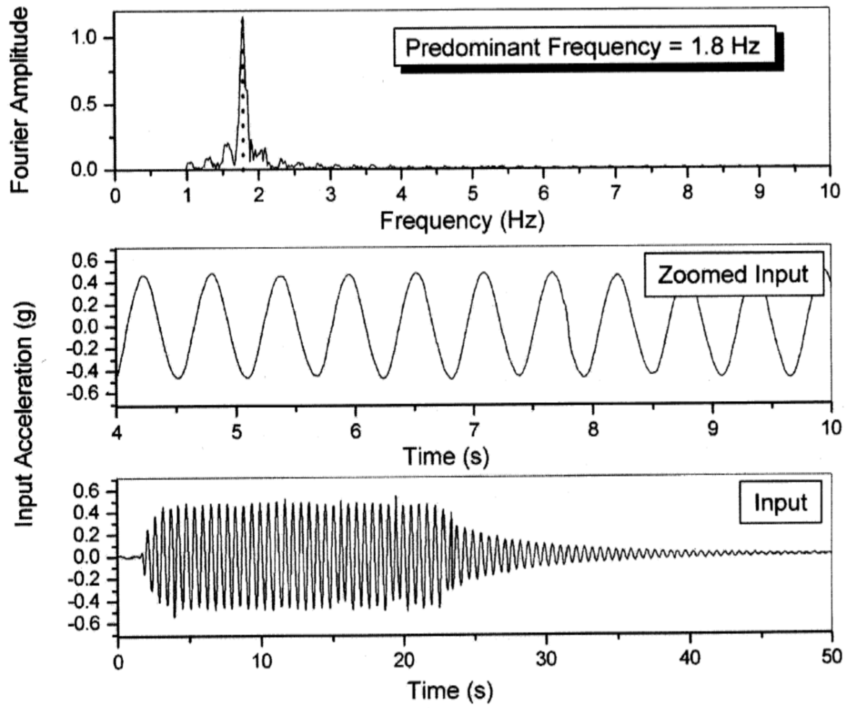

Figure 2. Typical input acceleration and its frequency content.

Table 1. Comparison between measured and theoretical frequencies of shaking table

Test no.	Pay load (N)	Measured frequency (Hz)	Theoretical frequency (Hz)
1	4790	1.75	1.66
2	4120	2.00	1.80
3	3060	2.50	2.08
4	2070	2.70	2.53

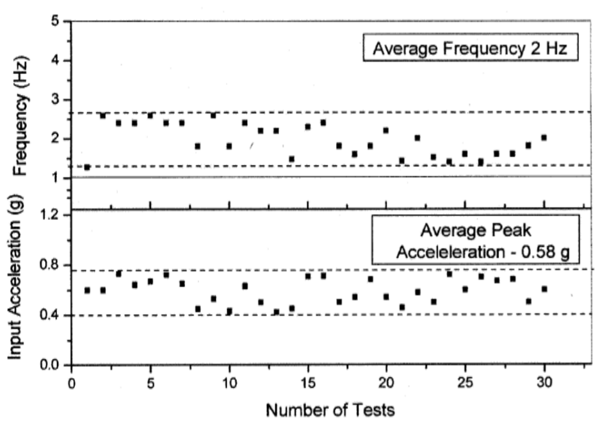

Figure 3. Predominant frequencies and peak amplitudes of input acceleration in various tests.

sed. The weight of the model ground in the tests varied from 2500 N to 5000 N and hence the frequency of shaking ranged from 2.6 Hz to 1.6 Hz as observed in Figure 3.

In order to verify the vibration components in three mutually perpendicular directions (namely, longitudinal, lateral and vertical motions) of the shaking table and to ensure that shaking was in longitudinal direction only, accelerometers were placed along longitudinal, lateral and vertical directions on the platform. Figure 4 represents the measured acceleration time histories in three different directions during shaking. It can be seen that the magnitude of acceleration components in the lateral and vertical directions were negligible compared to that in the longitudinal direction.

Model container

The geotechnical model cannot be directly mounted on shaking table because of the requirements of confinement. An ideal container should be large, flexible and transparent. However, it is impossible to provide all the essential features. The best solution will be arrived at when the soil model is directly placed on the shaking table. During the last decade many laminar boxes are being developed across the globe to suit field conditions better.

Laminar box

A laminar box is a large sized shear box consisting of several horizontal layers, built such that the friction between the layers is minimum. Hence the layers move relative to one another in accordance with the deformation of the soil inside[6]. This paper presents a laminar box designed at University of Tokyo, Japan and fabricated by Seiken Sha Company, Tokyo[7]. It was rectangular in cross section with inside dimensions of 500 mm by 1000 mm in size and 1000 mm deep. Figure 5 shows the overall view of the box. The box consisted of eleven rectangular hollow plates (hereafter called layers) machined from solid aluminum. Each layer had an external dimension of 1260 mm by 560 mm in size and 30 mm in thickness. 100 mm on either longitudinal side provided for special arrangement of side plates giving clear internal dimensions of 500 mm by 1000 mm. The top layer was 180 mm deep and weighed 661 N while the remaining layers were 82 mm deep and weighed 332 N. The gap between the successive layers was 2 mm. The bottom-most layer was rigidly connected to the solid aluminum base 850 mm by 1450 mm in cross section and 50 mm in thickness. The layers were designed such that their positions could be interchanged and that they could be reversed in direction (both sideways and upside down). On the long side of the layers, two long grooves were made on both faces for the intermediate layers and on one face each for the top and bottom layers for the provision of the bearings. Between the layers four sets of guide chains, two on each side were used. Each set of guide chain consisted of precision ball bearings 4 mm in diameter, 26 in number held within guide chain against lateral movements. Hence, guide chains provided lateral and vertical restraints and allowed free movement longitudinally. The grooves on the long side of layers were made in 'V' shape such that the contact area between the bearings and the layers was the minimum. The guide chains could also be used interchangeably. The short side of the layer was made such that it could rotate freely about the transverse axis so as to deform to the shape of the soil inside. This arrangement further reduced the boundary effect and provided a pure shear condition for the soil element eliminating the effect of rocking. The side plates were held in position by low stiffness springs so that even a small force was enough to rotate them.

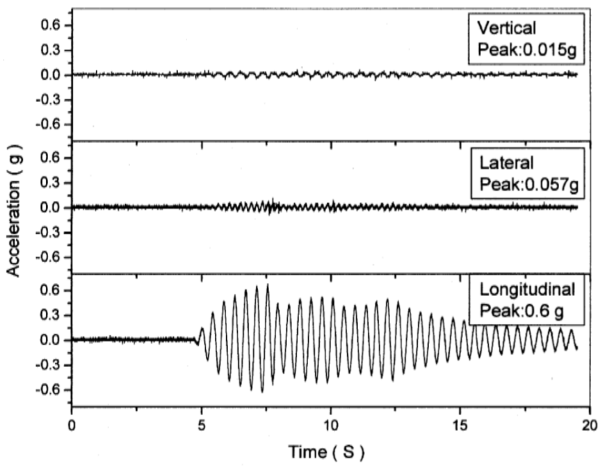

Figure 4. Measured acceleration time histories in the three direction.

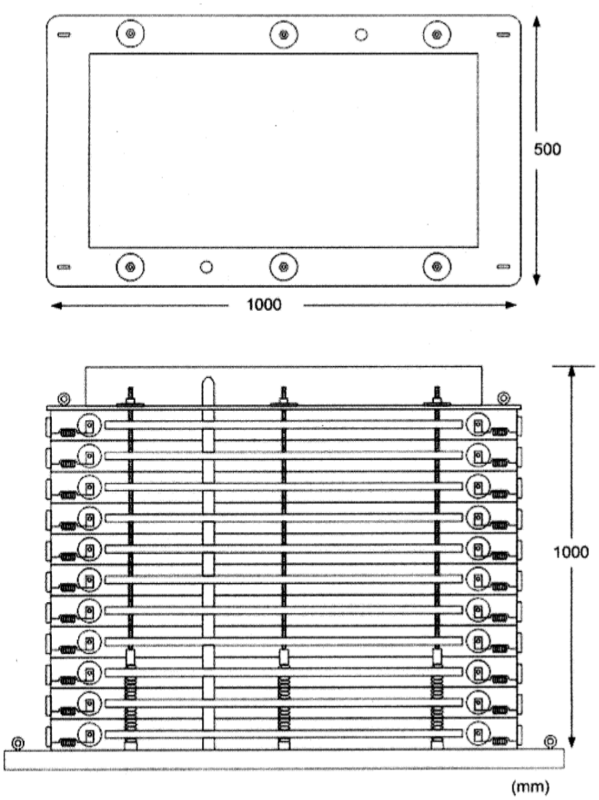

Figure 5. Details of laminar box.

The rectangular shape of the box has the advantage over the ring type container which is commonly used, that the bearings which move longitudinally reduce friction and that the possibility of lateral buckling is reduced. In the present laminar box, there was a provision to apply preloading so as to improve the contact between the bearings and the layers and to provide restraint against lateral deflection of long side or upward movement of layers. For preloading, six vertical bars, three on each of the long sides connected by stiff springs at the lower end were tied to top and bottom layers allowing the intermediate layers to move freely. Tension in the vertical bars could be adjusted depending on the requirements. There was a provision to distribute and measure the force on each bar precisely. The base of the box was fitted with 10 mm thick porous stone to distribute the water uniformly over the entire area in tests with saturated soils and to act as filter. There was a provision to allow water/air/vacuum from six points with control units at the base. Rubber membrane 2 mm thick was used inside to provide air tightness and not to allow soil to come in contact with walls or bearings directly. The base of the rubber membrane could be fitted at the bottom to the porous stone. Stopper bars and side keys were provided to arrest the movement of the layers and rotation of side walls when not in use.

An additional fixture was provided to place at the top for the purpose of increasing confining pressure by vacuuming. This fixture weighed 891 N and had a porous stone attached at its bottom for the purposes of distributing water/air uniformly and to act as filter. Provision to supply water/air/vacuum from the top of it consisted of nine points with a control unit at the center. The shape of this attachment was such that it could be fitted inside the top layer of the box and the protruding membrane could be stuck to the smooth round sides of the attachment so as to maintain air tightness. There was a provision to attach the transducers such as displacement transducer from outside. This frame could be fixed next to the box and the fixtures to fit transducers along its height could be positioned at any desired location both along vertical axis as well as along lateral axis. There was a provision to fix the base of the box rigidly to the shaking table by bolt arrangement.

Characteristics of the present laminar box

The present laminar box possessed the following characteristics.

- Layers and the membrane inside had minimum stiffness to horizontal shear.
- It retained water and air without leakage.
- It offered little resistance to vertical settlement of soil.
- Height of each layer was small which increased the flexibility for the deformation of soil inside.
- It was fairly large to better simulate field behaviour.
- It possessed capability to increase confining pressure.
- It maintained its horizontal cross section during shaking.
- It developed shear stress on the interface between soil and vertical wall equal to that on the horizontal plane.
- It did not allow for dilation of plates.
- It provided good contact between the bearings and groove.
- It allowed free movement of soil along the transverse cross section.
- It possessed provision for instrumentation.
- It was strong and stable against all the dynamic forces and moments.

However, relatively large mass (approximately 6000 N without the top lid) and high initial cost were a few shortcomings.

Calibration of laminar box

Main factors which may influence the performance of a laminar box can be classified as follows.

- Inertia effect
- Friction effect
- Membrane effect
- Wall effect

Initial tests were conducted on the laminar box with and without soil, with water and with thin and thick membranes and without membrane attached to it, to ascertain the effect of the above factors on the performance of the laminar box. The mass of the box itself contributes to the inertia effect. If a is the measured acceleration inside the soil, because of the inertia of the box itself, measured acceleration would be less than the actual. To account for this effect, simple correction factor can be used for recorded acceleration. Considering m_1 and m_2 to be the mass of soil within a layer and the layer of box respectively, then, total dynamic force is given as,

$$F_d = (m_1 + m_2)a.$$

However, it is desired that the entire force be transferred on to the soil. Therefore, if a_s be the desired acceleration in soil without the influence of box, then,

$$F_d = m_1 a_s.$$

Equating the above two equations, actual acceleration in soil is given by,

$$a_s = \frac{m_1 + m_2}{m_1} a.$$

Here, $(m_1 + m_2)/m_1$ is the multiplication factor used with the measured acceleration to nullify the effect of inertia of the mass of box. Hence, by putting $m_2 = 332$ N, weight of each layer, and weight of soil in a layer as m_1, inertia factor in different tests ranged from 1.4 to 1.5 depending on the density of soil.

The sophisticated bearing system reduced the friction between layers to minimum. However, some tests were conducted to confirm the same. Static friction between the layers was measured using a spring balance by applying pull force on each layer. The measured force on each layer, being a function of frictional resistance between the layers and the normal force from the top, was observed to increase with depth. Figure 6 shows the variation of static force on the box with depth. The maximum force was found to be 30 N, understandably on the bottom layer. Assuming soil to be placed over the entire depth and considering a low density of 13 kN/m^3 for soil and a low value of coefficient of static friction, $\mu = 0.5$, frictional resistance of the soil near the base would be around 3000 N. Hence, the static frictional effect of plates was around 1% or less. Figure 7 shows the variation of acceleration on different layers due to impulse type of force applied at the base of the box. Accelerometers were attached to different layers of the box externally. Tests were conducted at different magnitudes of impulse force by varying the force. In the figure, only the peak accelerations were recorded and it may be observed that the average acceleration recorded on any intermediate layer was less than 0.1 g. Acceleration in the top layer was only slightly higher due to the fact that it was heavier than the rest and that it was connected to the bottom layer by preloading bar. This result was achieved over a wide range of input accelerations ranging from 0.4 to 1.5 g. This implies that the force transfer between the layers was rather small. Even 0.1 g of peak acceleration recorded above could be due to the force transfer through the bearings. It was observed that an acceleration level of 0.5 g or more was better to cause slip between layers to efficiently utilize the box. In case very high frequency was to be achieved, slightly higher level of acceleration would be adequate.

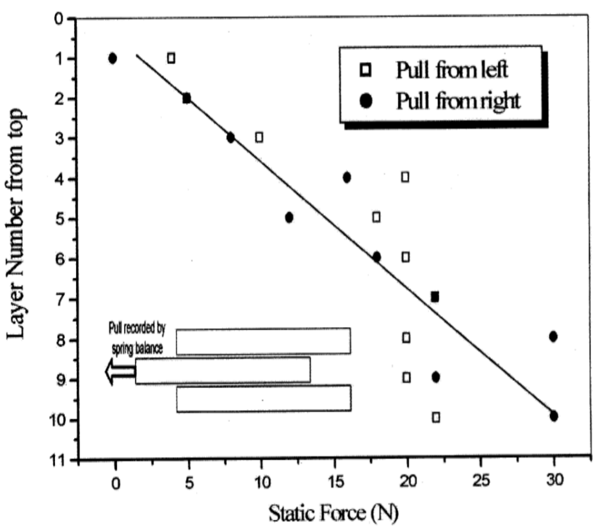

Figure 6. Static force required to move different layers of laminar box.

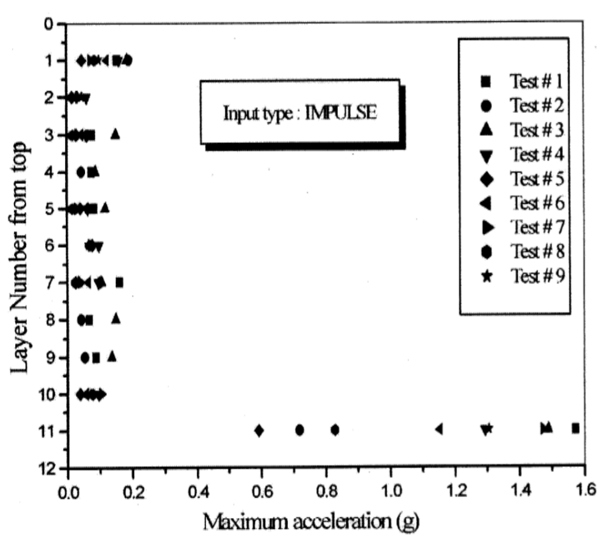

Figure 7. Maximum acceleration recorded on different layers of laminar box under impulse input at the base.

2 mm thick rubber membrane was used in the present study. Its stiffness was sufficiently small compared to that of soil. Hence it did not influence the performance of soil mass. In addition, its effect was localized near the edge. At the center of soil its effect was negligible. Tests were performed with either membrane removed or with membrane. But this did not cause any effect of membrane as it was not sticking to the surface of box. There was a need for confining pressure from inside to ensure proper contact between the membrane and the wall of the box. For this purpose, test was carried out with water inside at different frequencies and at different amplitudes of acceleration. It was observed that acceleration level in the intermediate layers had increased to around 0.1 to 0.15 g. To confirm the *P* wave effect of water, an accelerometer was suspended from the top at mid height into the box containing water from a reference surface free from shaking effect. When the box was shaken at different frequencies of 5, 10 and 20 Hz, the acceleration recorded was 0.06, 0.05 and 0.04 g respectively, suggesting that the increase in acceleration was due to the *P* waves transferred by water. Subtracting free acceleration from above, an acceleration level of less than 0.1 g was recorded in intermediate layers. In addition to ensure better that the membrane effect was negligible on deformation characteristics of ground, particularly damping, thin membrane 0.5 mm thick was also tried and the desired properties of soil were evaluated. It was observed that the thickness of membrane did not have any appreciable effect on the behaviour of soil[7].

For ensuring the boundary effect or wall effect, ground was made with dry Toyoura sand by raining and a relative density of 26% was achieved. Under impulse type of force, acceleration was measured at the same elevation and at different positions, one at the center and the other two close to the wall, 5 cm away. It was observed that the three acceleration records were similar, suggesting the wall effect was minimum.

Model tests with the present laminar box possessed the following features.

- Loading conditions were similar to the field loading.
- Effect of the boundary was negligible.
- Study of wave propagation through soil was possible.
- It was possible to test the ground models with large sized particles such as gravel.
- It was not possible to control either stress or strain during the test.
- Evaluation of all the parameters depended on the acceleration. Hence, precise measurement of acceleration was necessary.
- Evaluation of strength parameters was during shaking. Hence, valuable information was lost after the shaking was stopped.
- Achieving high confining pressure for saturated ground was difficult.

- Placing the transducers inside helped in measuring soil properties better. However, maintaining them straight (without tilt) was difficult. In tilted transducers corrections to measured recordings were applied.
- Achieving large strain level of the order of 100% was difficult. Hence, study of liquefaction problems such as flow failure was difficult.

Concluding remarks

Model testing under 1 G environment in earthquake geotechnical engineering has become an integral part of research. When financial constraints exist, it is difficult to procure sophisticated shaking table. In such situations, manual shaking table can be fabricated and used. Fabricated shaking table generated 0.5 g level acceleration at around 2 Hz with a payload of 7 kN. It produced uni-axial, harmonic, sinusoidal vibration. The vibration frequency of shaking table depended on payload. A very low effort of around 80 N was sufficient to initiate and keep vibrating the table.

Use of laminar box can improve efficiency of testing and can better simulate ground conditions. Laminar box can be used both under normal gravitational and centrifuge environments. Best features of the present laminar box included sophisticated bearings resulting in near friction less movement between layers and flexible side walls that provided pure shear condition. Calibration of laminar box included considerations of Inertia effect, Friction effect, Membrane effect and Wall effect. Tests to understand ground amplification, liquefaction and cyclic mobility phenomenon, excess pore water pressure generation and dissipation rates can be performed using such facilities.

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