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Research paper

Design, Manufacturing and Testing of Small Shaking Table

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Abstract

The seismic performance and the dynamic response of concrete gravity dams can be verified by several techniques. Both geotechnical centrifuge apparatus (under N-g values) and shaking table (under 1-g) are the commonly used techniques in the world. This paper deals with designing, manufacturing, and testing of small shaking table to investigate different geotechnical and engineering problems. The main body of the designed shaking table consists of steel frame (local iron) manufactured as a hollow box with steel plate, 6mm in thickness and one-direction movable platform (as a basket carrying the container of the model). Inside this main box, all the mechanical parts that work as one system to generate the motion of the seismic wave with an acceleration that needed to the test. The facilities of this shaking table, the movable base has a dimension of 0.8m x1.2m and the platform mass approximately 2 kN, the maximum allowable model weight of 10kN, the range of frequency from 0 to 20 Hz, the maximum acceleration amplitude of 1.2g and maximum displacement of 14mm. It can simulate only the single frequency motion (i.e. sinusoidal wave). The measured accelerations at different soil model level for the tested shaker under 0.6g sinusoidal waveform gave a reasonable prediction for the dynamic response and the amplification characteristics.

Keywords: *Acceleration; Dynamic Response; Pluviation; Sand; Shaking Table.*

1. Introduction

The researches in geotechnical and the water sources engineering fields witnessed distinguishable developments in the methods and techniques of studying the engineering problems concerning dynamic effects and seismic performance of structural elements problems. The simulating of real earthquakes on different hydraulic structures model (i.e. gravity dams, multi-story building, and infrastructures) using physical modeling is widely used last few years. The physical modeling is one of these techniques that can be used to investigate the behavior of such an important structure under earthquake loading. The physical modeling principles are widely used in many studies which were conducted on different small-scale models representing different prototypes scale around the worlds (Knappett et al., 2011; Donlon and Hall 1991; Ghobarah and Ghaemian 1998; Harris et al. 2000 and Tinawi et al. 2000) and amongst. Different parameters were measured and investigated under both real earthquakes (i.e. Bairrar and Vas, 2000; Tinawi et al., 2000 and Rosca, 2008 and amongst) and under single frequency, sinusoidal waveform (i.e. Ploulx and Paultre, 1997 and Al-Qaisi, 2016).
Large and medium-size shaking tables have been designed and widely used in few decades in the laboratories around the world to solve many problems under single gravity (i.e. 1-g) and provide an investigation of destructible effect (i.e. Gaven et al., 1998; Nagarajaiah and Gozdowski, 1998). Tens of studies were performed using the shaking table. Tinawi et al, 2000 carried out a series of shaking table test to make a correlation between the experimental results and numerical results when they studied a seismic response of gravity dams. Iai (1989) conducted a series of shaking table tests on a soil-structure-fluid model in a 1g gravitational field to make a similitude for shaking table.
In the State Key Laboratory of Disaster Reduction, Civil Engineering, Tongji University, China, multi-function shaking table has been built and installed to study many problems in civil engineering (Xiao et al. 2015). It has four movable tables (4mx6m each) in three degrees of freedom, Two main table has a payload limits up to 70 Ton each, whereas the other two tables with 30 Ton each (longitudinal, rotational and transversal). The national laboratory for civil engineering (LNEC) in Lisbon, Portugal has a 400 kN of 5.6m x4.6m 3D shaking table with maximum displacement reaches to 175mm for all the three axes. (Emílio et al., 1989).
The main objective of this paper is to present the design steps of the uniaxial single frequency shaking table with the one-face transparent container to improve the experimental activities in the geotechnical laboratories in engineering college of University of Wasit. This shaking table is used to investigate the dynamic behavior of concrete gravity dams with a scaled model by using the principles of the physical model to understand the effect of the dynamic responses of such structure. Many engineering problems concerning with earthquake geotechnical engineering can be analyzed and solved using this simple shaking table (i.e. the dynamic response of remediated slopes; laterally loaded single and group pile system; behavior of shallow and deep foundation during liquefaction due to dynamic loads and seismic performance of retaining walls) Small-scale models can be investigated correctly with taking into consideration the soil-structure interaction (SSI) due to earthquake excitations. The shaking table was fabricated in the workshop of the main laboratories of the Faculty of Civil Engineering Department, University of Wasit, Kut- Iraq.

2. Design of uniaxial shaking table

The main body of the designed shaking table consists of steel frame (local iron) manufactured as a hollow box with steel plate, 6mm in thickness and one-direction movable platform (as a basket carrying the container of the model). Inside this main box, all the mechanical parts that work as one system to generate the motion of the seismic wave with an acceleration that needed in the test. The facilities of this shaking table, the movable base has a dimension of 0.8m x1.2m and the platform mass approximately 2 kN, maximum allowable model weight of 10kN, range of frequency from 0 to 20 Hz, maximum acceleration amplitude of 1.2g and maximum displacement of 14mm.
The energy efficient servo actuator controlled with an electrical signal from labview subroutine (National Instruments) via computer to indicate the magnitude of the shaft movement is the main part of this shaker. Sinusoidal waveform or simple harmonic motion can be instructed to the servo motor via data physics and this makes the platform of the shaking table moves. The potentiometer resistance inside the servo changes as the motor rotates and this should be regulated by the amount of horizontal (axial) movement and the direction (clockwise or counterclockwise) which controlled by a control circuit.
To decrease the load on the servo-motor, a power transmission system or gearbox is used to convert the rotated servo motor to the shaking platform. Four screw base dampers have been fixed also at the shaker base to prevent any unfavorable vertical movement may be generated due to fast vibration of the platform during operation. Four main high resistance pulleys system are attached at the base that containing the weight of the model basket in one direction (horizontal). All the joints, connections of different parts, different bolts and nuts are used as well. Details of the shaking table and both the gearbox and the servomotor are shown in figure (1) whereas the shaking table is shown in figure (2).

Fig. 1: The main parts of the shaking table.

The upper part of the movable shaker base that can carry the container (filled with soil model) of the test manufactured from high strength steel base (10mm) to prevent any vertical or undesirable movement during the shaking with four main pulleys. The shaking system contained the main actuator (motor) with the specification tabulated in table (1).

Fig. 2: The main parts of the shaking table.

The motor is chosen with certain speed-torque characteristics to match speed-torque requirements of various loads (maximum load 10 kN). A motor must be able to develop enough torque to start, accelerate and operate a load at rated speed on the mechanical system necessary for the generation of the sinusoidal wave. Rubber strap to transfer of rotational motion generated from the motor to the iron rod of 60 cm long and 6 mm thick, moving along its longitudinal axis by a large pulley to turns the rotary motion is used also. An iron rod of 40 cm long and 8 mm thick, converts the drag and pull movement from the previous rode into a horizontal movement to generate a desired sinusoidal wave (fixed rate horizontal movement).

Table 1: Motor Specifications

Specification	Grade
TYPE	HIWIN 1000W
Tcs	27.5 Nm
Prtd	2.81 kW
Nrtd	3500 RPM
Vs	640 VDC
Rm	2.1 Ω
WEIGHT	14.5 KG

3. The used container

One face transparent container is manufactured for this shaking table. The dimensions of this container are (1.9m length, 0.6m wide and 0.85m height).The purpose of this one transparent side (made from thickness 10mm glass) is for monitoring the soil-dam behavior during the shaking as well as taking a short video and pictures using high speed camera. The other three sides were made from aluminum rings with a thickness of 4mm as well as a 10mm rubber layer.
The purpose of using this rubber layer is to reduce the wave reflection of both soil and water waves during the shaking of the container as the boundary effects are important in the physical modeling earthquake simulation. The main structural body of the container made from a local steel frame. This container will fill with cohesionless soil as a foundation for the small concrete dam, filled with water in the upstream and fixed with four main steel screws to prevent any undesirable sliding during the motion of the shaking table. This shaking table is allowed for movement in one direction as (single degree of freedom) and details of the upper part (the container) are shown in figure (3) whereas the main cyclic movable steel rode that responsible for making the movement is shown in figure (4).

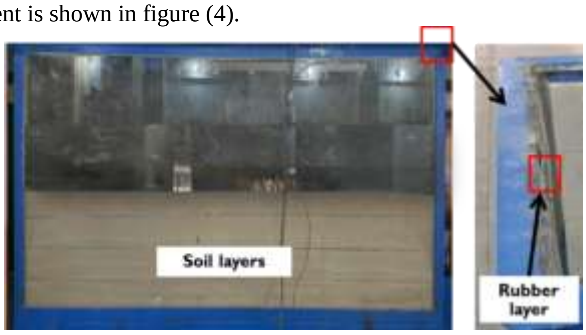

Fig. 3: The used container and the wave reflection rubber layer

Fig. 4: Movable steel rode and platform

4. Air pluviation technique

To use the same density characteristics, specifications and the behavior of cohesionless soils that will be used as a foundation for the dam model, some necessary steps should be taken in the laboratory. In order to achieve this purpose, the soil specimen must be reconstituted to its natural state. Sample preparation techniques can be influenced by fabric and stress-strain response of the soil particles. The three most common methods for preparation of sandy soil specimens are the tamping, vibration, and pluviation (Lo Presti et al. 1992; ASTM 2006). Among these methods, the air pluviation method is used extensively for preparation of large, uniform repeatable sand bed of desired densities for laboratory studies in order to achieve in-situ conditions and get suitable results which are highly reliable.

The air pluviation technique can be classified into three groups according to the type of opening under the sand storage or hopper. The first one is a single nozzle in which the soil is poured through the nozzle moving with a regular pattern (Fretti et al. 1995). The second is a curtain rainer, in which the sand is poured from the hopper through a narrow slot using a thin sand curtain (Butterfield and Andrawes 1970; Gemperline and Ko 1984; Garnier and Cottineau 1988 and Stuit 1995). The third type is a sieve of sand raining where the soil was poured using one or multiple sieves over an area equal to or slightly greater than the specimen container (Miura and Toki 1982; Cresswell et al. 1999; Abbireddy 2008).

The relative density (RD) obtained from air pluviation depending on several parameters such as (i) the deposition intensity (DI); (ii) the height of fall (HF); (iii) the porosity of the diffuser sieve; (v) particle characteristics; (vi) uniformity of raining sand; (vii) the opening width of the curtain in curtain technique(i.e. Rad and Tumay 1987; Fretti et al. 1995; Lagioia et al. 2006; Choi et al. 2010; Dave and Dasaka 2012 and Gade and Dasaka 2015). This technique has been widely used in geotechnical laboratories around the world (i.e. Aldefae et al. 2013 and Bertalote et al. 2014).

This technique is characterized by the following (i) easy of model preparation; (ii) easy during the installation of the instruments; (iii) can obtain uniform soil layers. The pluviator consist of a v-shape movable container and has pulley wheels and moving back and forth on frictionless bar's guide and the soil (sandy soil) falling down from an opening (slot) in the bottom of the container (hopper). As the relative density of the cohesion-less soil (silica sand here) is strongly influenced by the falling height, thus the pluviator contained a designed rope crane and attached to the main frame so that the container can be raised up and down to achieve the desired height. This mechanical pluviator can achieve a uniformly sandy layer with relative densities vary from 28% to 71% and this range represents threshold of both the loose dense state of the sand. The details of this v-shape container; the pluviator with the rope crane of mechanical movement are shown in figure (5) and figure (6).

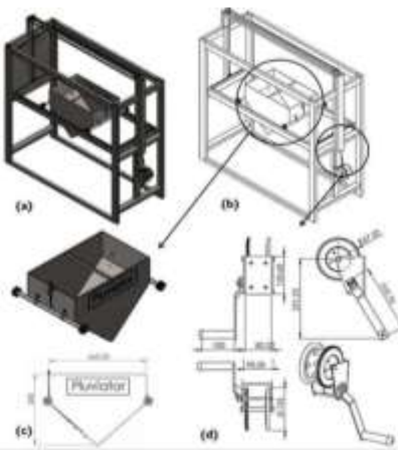

Fig. 5: (a) Pictorial view of mechanical pluviator; (b) Schematic view of pluviator; (c) V-shape container and (d) Mechanical chain and rope lever

Fig. 6: Air pluviator technique; (a) The raining frame pluviator and(b) Pluviator and container

5. Testing of the shaking table

The main purpose of designing this shaker is to investigate the dynamic performance of the concrete dam model constructed on sandy layers. At the primarily tests in this study, the shaker was tested by investigation the measured acceleration from the bottom of the model to the top (i.e. free field amplification should be noticed) to compare the amplification with the expected value. Five accelerometer sensors were distributed from the bottom to the top of the model (i.e. figure 7) as well as many others were fixed at the model of the dam whereas LVDTs (at different position at the face and at the top of the dam), Pore pressure transducers (beneath the dam at different soil depths) and water pressure sensors (to measure the hydrodynamic pressure at the upstream face of the dam) were used also and they are not included in the calibration test.

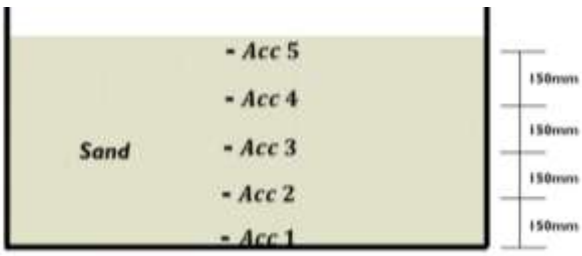

Fig. 7: Accelerometer distribution for the shaking table calibration

0.65g sinusoidal wave is used as an input motion at the base of the contained (represents the recorded at the underlying bedrock, i.e. figure 8 a). It was observed from the measured four accelerometers as shown in figure 11 that the values gave great representation for the expected amplification at the model surface (around 1.6 times the input motion). This value is consistent with the measured values of (Aldefae and Knappett, 2014 and Brennan and Madabhushi, 2009) showed that there are two distinct effects of this amplification: the side effect (because of the dynamic properties of the soil material, this strongly influenced by the material property); and a topographic effect (i.e. a geometric effect or effect of ground surface). This confirming that the boundary effects are well modeled with this container and the used rubber layers gave good performance to reflect the lateral cyclic waves during shaking.

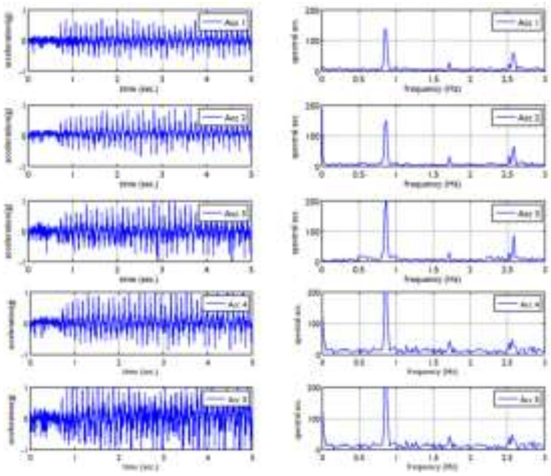

Fig. 8: Measured accelerometer during shaking table calibration

6. Dynamic response of gravity dam built on dry sand

The first shaking table test is performed using cohesionless soil (i.e. sand) in the dry state as a foundation beneath the concrete gravity dam model. The model was prepared at a medium dense state using the pluviation technique (air sand) using the mechanical pluviator as described in details in the previous section. Once the sand depth in the container reaches to the desired depth, the accelerometer was fixed horizontally in the direction of motion (uniaxial accelerometer) as the sand rains again above this level until reaching to the ground level. The thickness of the sandy layer was 55 cm. Later, the concrete dam model has been placed on the prepared sand level.

Too many instruments are used in this preliminarily test, five accelerometers distributed as shown in figure (9); two linear variable differential transducers (LVDTs), one to measure the settlement of the dam at pre-shaking, during and post shaking stage while the other to measure the cyclic horizontal displacement during the shaking and three water pressure sensors (which they were connected to the data logger to measure the cyclic water pressure at the upstream face of the dam where it are not included in this paper).

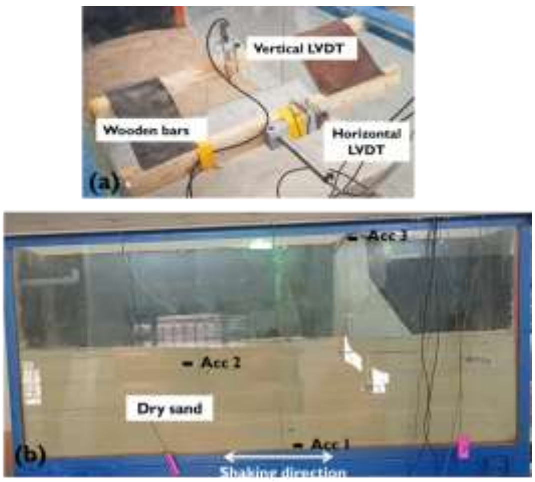

Fig. 9: Preliminarily test; (a) LVDTs positions and (b) Dam model-soil-container

The LVDTs were fixed to measure the settlement and the horizontal displacement of the dam during the shaking. Wooden bars are used are fixed at the long direction of the container where the LVDTs were connected to prevent any undesirable movement of the LVDTs particularly during the shaking (i.e. figure 9a). The first accelerometer is fixed at the base of the container to represent the input motion while the second is fixed few centimeters below the sandy layer at the upstream to investigate how the soil close the ground surface in free field far away from the dam (in empty case, an attenuation might occur comparing with the case where the dam fills with water) behave under dynamic loads. The other accelerometer is fixed at the crest of the dam to observe how the dam model behaves during the test and the amplification that may occur (obviously) at the crest.

The dynamic response of the dam-foundation model is assessed from the measured acceleration for both the soil (as a foundation for the gravity dam) and the dam itself. Figure (10) shows the measured accelerometer in this test. The AA.1 refers to the input motion (the accelerometer at the base of the container). Acc.2 was fixed far away from the dam at the upstream side (close to the ground surface) while Acc. 3 is tagged at the Dam model crest. It was clearly shown that Acc. 2 and 3 that the ground shaking (i.e. Acc. 1) is amplified due to site amplification (i.e. the amplification of the motion from the bedrock to the ground surface) as well as the crazy response of the concrete dam (i.e. Acc. 3). The free cyclic shaking of the concrete dam particularly at the crest and this is not surprising due to the fact that the tallest building (the height of the dam here) is more responsive to the low-frequency motion (the predominant frequency of the motion is around 1.7 Hz. This will be explained later in the failure mechanism of the gravity dam model in the next studies.

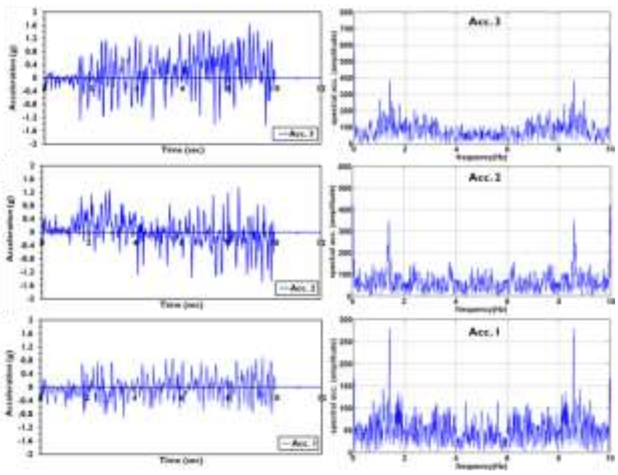

Fig. 10: The acceleration response of the dam-foundation system

7. Conclusions

In this paper, extensive efforts have been devoted to design, manufacturing and testing of simple small shaking table to improve and enhancing the experimental techniques at the laboratories of University of Wasit, faculty of engineering. The main conclusions are listed below:

1- The manufactured shaker can be used to investigate and study different geotechnical and water resources engineering dynamic problems under single frequency motion (i.e. sine wave form).
2- The dynamic response at different level in the soil model is very close to what have been measured by other researchers (i.e. the dynamic amplification). The calculated dynamic amplification factors from the measured acceleration were between 1-1.7 and these results validate the feasibility and the reliability of the tests and they were consistent with Aldefae and Knappet 2013; Brennan and Madabhush 2009 and this confirming that this

behavior are well simulated using both the soil container that used in this paper (i.e. the boundary effect) and the shaking table.

3- The designed and manufactured pluviator gave great soil uniformity and this was well observed from the measured acceleration from the base to the top of the model.

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