Simulating Extraordinary Geophysical Events: Earthquake Shake Tables

Shake table paper to be presented at the Arab Conference on Astronomy and Geophysics 7th Assembly, 11-14 October 2021, Cairo, Egypt

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1. Introduction

Earthquakes are an extraordinary geophysical event caused by the elastic rebound of the earth's crust following a fault rupture. The energy released during this rupture radiates outwards for many kilometers and can produce damaging levels of vibration over many thousands of square kilometers. Therefore, civil structures and mechanical equipment must be designed to survive such events in order to minimize damage and loss of life. Much of the design effort can be done computationally, but it is also necessary to experimentally verify that these computations or new and unique designs are correct and effective. This requires testing of models or full-size structures and components on an earthquake shake table. Such tests are often done on mechanical and electrical components vital to the performance of critical facilities such as hospitals, fire and police stations, telecommunication centers, and conventional and nuclear power plants. These shake tables are often used in universities and in commercial laboratories offering such testing services. This paper is an introductory overview describing shake tables of various capabilities worldwide. Shake tables have been used for such studies for the past 100 years. For example, there is a Japanese patent application for a steam engine-driven shake table in 1923.

2. Small Educational Shake Tables

Small economical shake tables are used for educational purposes at universities to teach vibration theory, structural dynamics, and experimental techniques in the classroom and in the laboratory. These tables can also sometimes be used for scientific research. Similar to the larger tables discussed in following sections, this table is controlled by a PC-based digital controller capable of producing earthquake motion, random motion, impulse motion and sine sweep. The earthquake motions can be actual recorded earthquake time histories or artificially generated earthquake motions with specified frequency energy distributions. Figure 2.1 shows a small electric driven shake table with specifications given in Table 2.1. The table shown is typical, but larger and smaller tables of this type exist. Below is a link to a short video showing this table in operation. These small tables can be provided in 1, 2, or 3 DOF configurations.

Video Link: https://youtu.be/3MIoss2jT7A

Figure 2.1: 1-DOF Electric Actuator Driven Benchtop Shake Table for Educational Purposes

Table 2.1 Typical Small Educational Shake Table Specifications

Tabletop Size	70 cm x 70 cm
Nominal Maximum Test Item Mass	30 kg
Peak Acceleration	2 g
Peak Displacement	± 15 cm
Frequency Range of Operation	0-15 Hz
Number of Axes	1 Axis: 1 Horizontal (X)

3. Medium Size Uniaxial Horizontal Shake Table

Electric actuator shake tables are convenient and have low maintenance and noise compared to servo hydraulic driven shake tables. However, shake tables that can accommodate higher payloads, typically above 1 ton or more, usually employ servo hydraulic actuators.

The photo in Figure 3.1 shows a servo hydraulic actuator-driven uniaxial horizontal shake table with a 2 m x 2 m tabletop and a payload capacity up to 5 tons. This table is being used for structural and soil dynamic research in a university in Ningbo, China. The table shown is typical, and larger and smaller tables of this type exist. Tables with sizes up to 6 m x 6 m and up to 50 tons also exist. Below is a link to a short video showing this table in operation.

Video Link: https://youtu.be/XNAEsXLFVHA

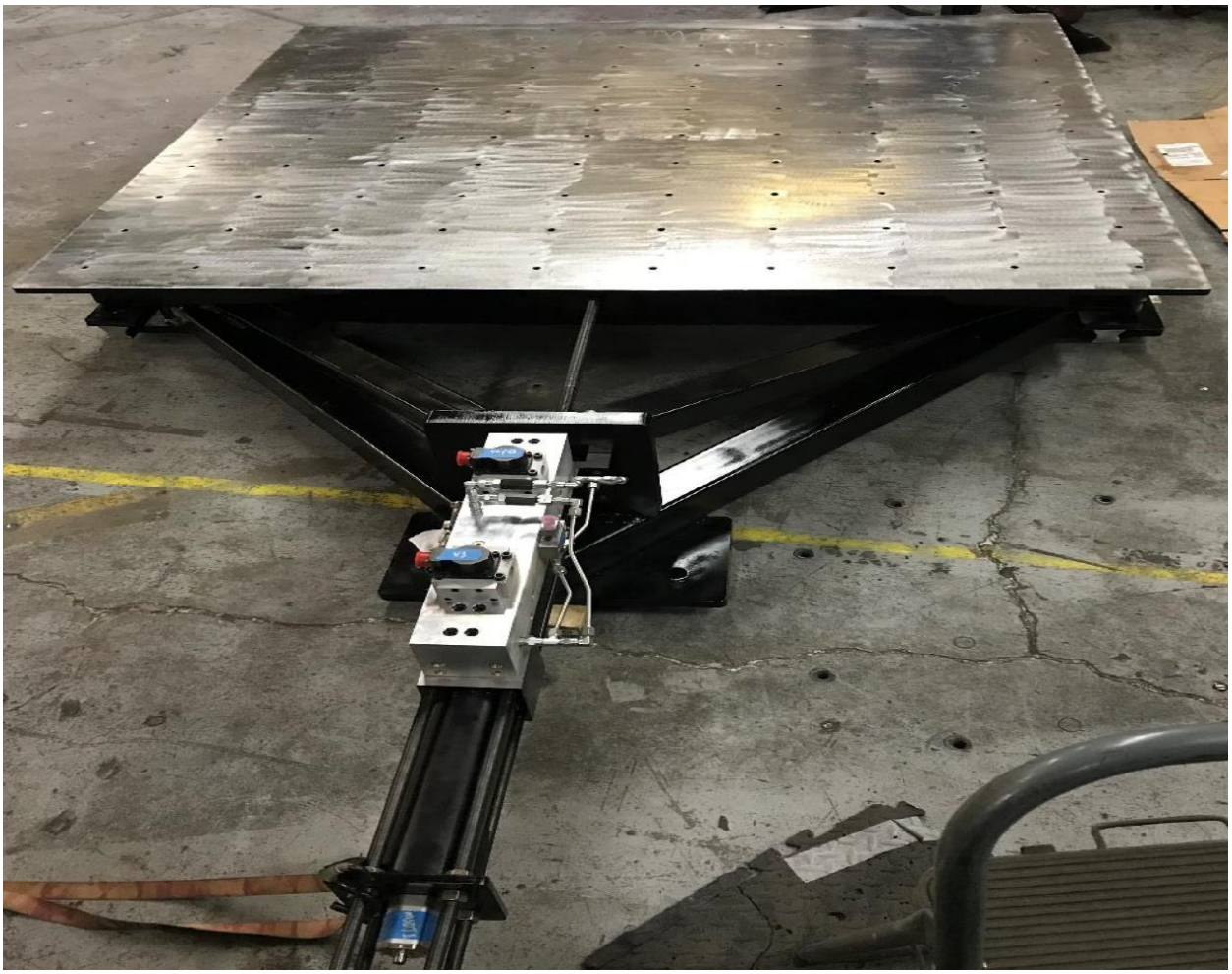

Figure 3: Photo of Ningbo Table in ANCO Laboratory

Table 3.1 Typical Horizontal Uniaxial Shake Table Specifications

Tabletop Size	2 m x 2 m
Nominal Maximum Test Item Mass	5 tons
Peak Acceleration	1.5 g
Peak Displacement	± 10 cm
Frequency Range of Operation	0-40 Hz
Number of Axes	1 Axis: 1 Horizontal

4. Biaxial Horizontal Shake Tables

Earthquakes, of course, cause independent simultaneous triaxial motion. Therefore, researchers often want a biaxial or triaxial shake table.

The photo in Figure 4.1 below shows an independent simultaneous biaxial shake table with 2 m x 2 m tabletop and 4-ton table capacity. This table is being used by the University of Nebraska-Lincoln, USA to study the stability of rock embankments and walls. The table shown is typical, and larger and smaller tables of this type exist. The table below gives typical table specifications.

Video Link: https://youtu.be/7_W55XcKCX8

Figure 4: Photo of UNL Biaxial Table

Table 4.1 Typical Horizontal (X, Y) Biaxial Shake Table Specifications

Tabletop Size	2 m x 2 m
Nominal Maximum Test Item Mass	4 tons
Peak Acceleration	2.5 g
Peak Displacement	± 15 cm
Frequency Range of Operation	0-40 Hz
Number of Axes	2 Axes: 2 Horizontal (X, Y)

5. Biaxial Horizontal/Vertical Shake Tables

Some researchers using a biaxial table prefer to have one horizontal and one vertical axis. Figure 5.1 below shows the drawing of such a horizontal/vertical biaxial table. Figure 5.2 shows a photograph of this typical horizontal/vertical shake table. This table is being used for university research in Chongqing, China and has a 1.5 m x 1.5 m tabletop and 2-ton payload capacity.

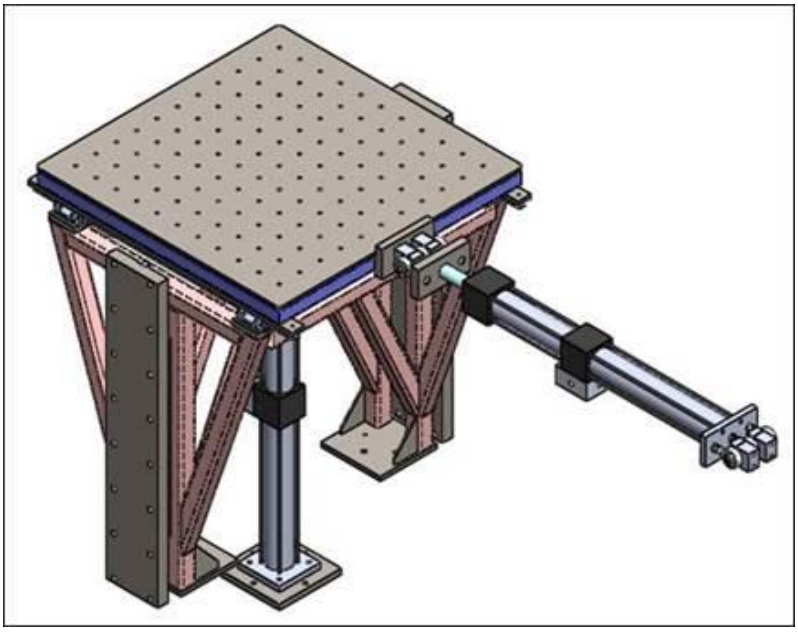

Figure 5.1: Drawing of Typical Horizontal/Vertical Biaxial Shake Table

Figure 5.2: Photo of Biaxial Table in Chongqing, China

Table 5.1 Typical Horizontal/Vertical (X, Z) Biaxial Shake Table Specifications

Tabletop Size	1.5 m x 1.5 m
Nominal Maximum Test Item Mass	2 tons
Peak Acceleration	2 g
Peak Displacement	± 15 cm
Frequency Range of Operation	0-40 Hz
Number of Axes	2 Axes: 1 Horizontal and 1 Vertical (X, Z)

6. Triaxial Shake Table with Electric Drive

The most realistic simulation of an earthquake requires simultaneous independent motion in all three axes, such as what is provided by a triaxial shake table. Figure 6.1 below shows a 1.6 m x 1.6 m triaxial table with electric drives. This table is located in Pennsylvania, USA, and is being used for seismic qualification of electrical equipment in US nuclear power plants. The link below shows this table in operation.

Video Link: https://youtu.be/G1mnvr5C7Z4

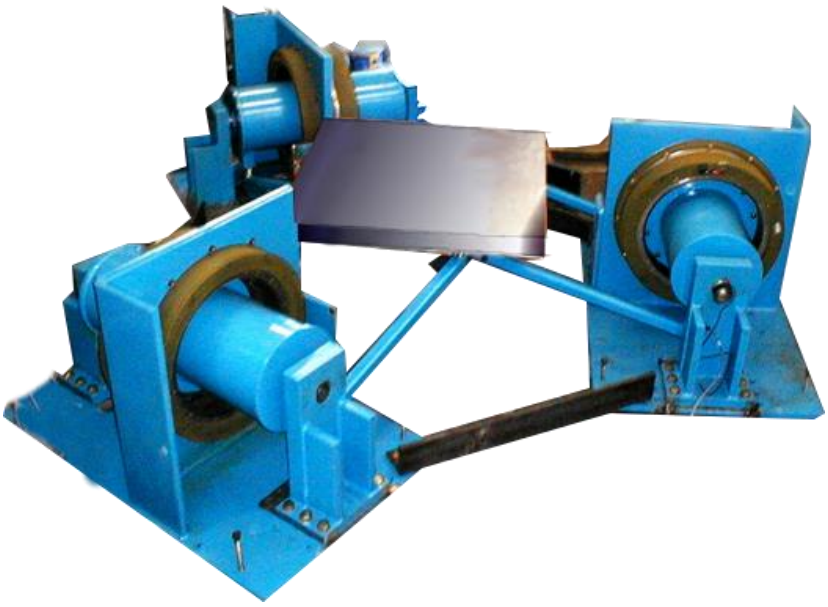

Figure 6.1: Photo of Electric Triaxial Table

Table 6.1 Typical Electric Triaxial Shake Table Specifications

Tabletop Size	1.6 x 1.6 m
Nominal Maximum Test Item Mass	0.5-1 ton
Peak Acceleration	Up to 6 g
Peak Displacement	± 20 cm
Frequency Range of Operation	0-70 Hz
Number of Axes	3 Axes: 2 Horizontal, 1 Vertical (X, Y, Z)

7. Triaxial Shake Tables with Servo Hydraulic Drive

The largest capacity triaxial tables are servo hydraulic. Figure 7.1 below shows a 3 m x 3 m triaxial table with 10-ton capacity. This table, located in Virginia, USA, is being used for seismic qualification of electrical and mechanical equipment in US nuclear power plants. The link below shows this table in operation. Note that, while this table is normally used in the 3 DOF mode (X, Y, Z), which is appropriate for earthquakes, it is equipped with six independent actuators, and therefore can also do 6 DOF motion, including pitch, roll, and yaw.

Video Link: https://youtu.be/upB7Pus567g

Figure 7.1: Photo of Servo Hydraulic Triaxial Table

Table 7.1 Typical Servo Hydraulic Triaxial Shake Table Specifications

Tabletop Size	3 m x 3 m
Nominal Maximum Test Item Mass	10 tons
Peak Acceleration	7 g
Peak Displacement	± 20 cm
Frequency Range of Operation	0-90 Hz
Number of Axes	3 Axes: 2 Horizontal, 1 Vertical (X, Y, Z), but can also do pitch, roll, and yaw.

8. Largest Shake Tables

The authors estimate that there are over 3000 earthquake shake tables worldwide. The largest shake table in the United States is at the University of California San Diego and its photograph is shown in Figure 8.1 below. This table is 8 m x 12 m in size, and can handle a maximum payload of 400 tons. It was initially constructed as a biaxial table (horizontal, vertical), but is currently being upgraded to a fully triaxial table, and this will be completed by January 2022. This table is unique in that it is located outdoors, and therefore allows for the testing of steel, concrete, and timber buildings up to approximately 10 stories.

A link for a virtual tour of this table is shown here:
https://youtu.be/2wuvDTE88lE

Figure 8.1: University of California San Diego Large Earthquake Shake Table

The largest shake table in the world is currently the E-Defense shake table in Japan. A photograph is shown in Figure 8.2 below. This triaxial (X, Y, Z) table is 20 m x 15 m in size, and can handle a maximum payload of 1200 tons. It has been used for testing full-sized structures and components and structures in nuclear power plants.

For videos and further information about this table, see the following link:
https://www.bosai.go.jp/hyogo/ehyogo/research/research.html

Figure 8.2: E-Defense Table in Japan

9. Geocentrifuge-Mounted Shake Tables

There are many specialty earthquake shake tables. For example, a shake table can be placed inside of a geocentrifuge. This allows earthquake testing of models of linear and nonlinear structures in soil and rock such as dams, offshore oil platforms, piles, and harbor structures. It is necessary to place the shake table inside a geocentrifuge in order to preserve the material properties in the scaled model. For example, if using velocity scaling with a scale model of 100, it is necessary to apply a static acceleration in the centrifuge of 100 g. This also requires the shake table to have very high acceleration and frequency capability. On the other hand, it only needs to have small displacement capability. The drawing in Figure 9.1 below shows a centrifuge basket with biaxial (horizontal, vertical) shake table inside that is placed in a 500 g-ton geocentrifuge in Tianjin, China. The link below shows this centrifuge in operation with shake table and test item inside:

Video Link: https://youtu.be/D4tkNkYI_rI

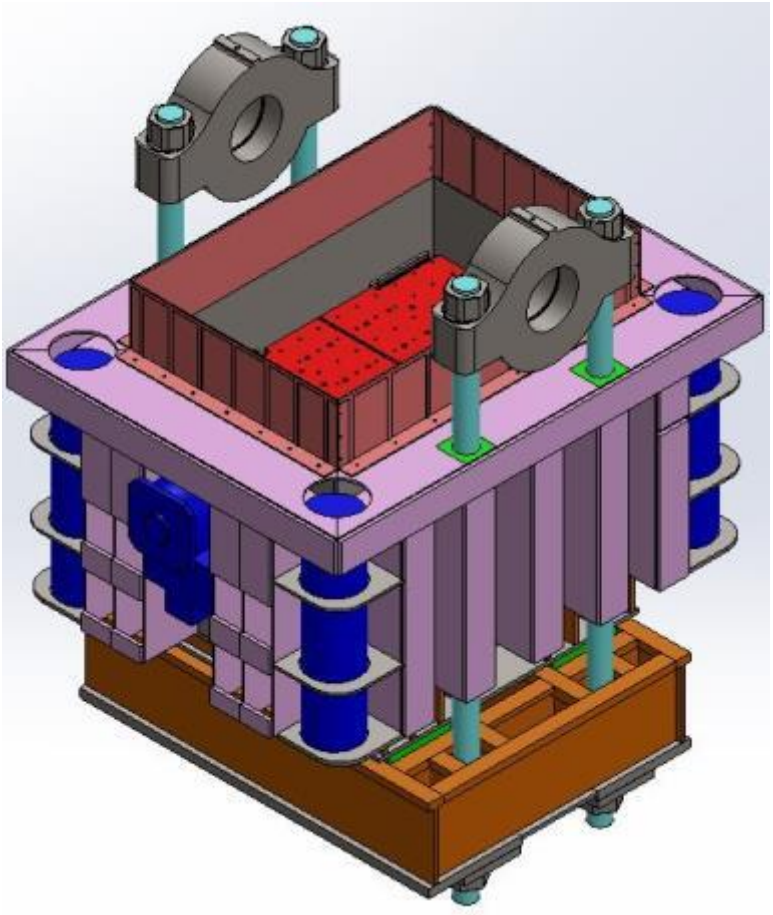

Figure 9.1 Drawing for Tianjin Basket and Table

Table 9.1 Specifications for 500 g-ton Geocentrifuge-Mounted Shake Table

Tabletop Size	1 x 1 m
Nominal Maximum Test Item Mass	1 ton
Peak Acceleration	40 g horizontal 20 g vertical
Peak Displacement	± 5 mm
Frequency Range of Operation	10-250 Hz
Number of Axes	2 Axes: 1 Horizontal, 1 Vertical (X, Z)

10. Public Education Shake Tables

Another specialty shake table is used for public education, and allows human passengers to ride on the table to experience an earthquake. These shake tables are used for public education on earthquake science and earthquake safety in museums or on mobile trucks, and are also used for training of emergency responders. They typically can handle between 1 and 40 passengers and are provided with many safety features to protect the passengers. Figure 10.1 is a photograph of a triaxial public education shake table with electric drives located at an emergency responder training center in Tashkent, Uzbekistan. Below is a link to a video of this table in operation:

Video Link: https://youtu.be/scp3hyDRY7s

Figure 10.1 Photograph of Tashkent Table

Note that the table is equipped with a simulated room to increase the realism of the passenger experience.

Table 10.1 Typical Public Education Shake Table Specifications

Tabletop Size	3 m x 4 m
Nominal Number of Allowed Passengers	20 passengers
Peak Acceleration	0.5 g
Peak Displacement	± 20 cm
Frequency Range of Operation	0-15 Hz
Number of Axes	3 Axes: 2 Horizontal, 1 Vertical (X, Y, Z)