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# Manufacturing and Performance of an Economical 1-D Shake Table

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**Abstract**

The researchers and engineers encountered many problems to precisely replicate earthquake waves. Earthquakes are one of the nature's worst catastrophes and are still unpredictable. Statistical research has shown that the earthquakes have increased in frequency in recent years and have become a major concern for the world especially for those countries which are located on the fault lines such as Japan, Bangladesh and Pakistan. So, it was imperative to device a mechanism to check earthquake response and apply some necessary mitigations for the safety of humanity. After many years of research an indispensable testing apparatus was designed named as Shake Table. This apparatus is extensively used in earthquake research centers globally because it is the best available apparatus to replicate the earthquakes imposed dynamic effects on structures. A uni-axial shaking table was designed, manufactured and installed in University of Engineering & Technology Taxila, Pakistan which is operated on 3 HP servo motor coupled with encoder, motion controller and supported on HSB mechanical linear drive. The system was assembled in a simple way with care to endure sufficient replication of given (recorded) motion by shake table system. This paper focuses on the designing, manufacturing and performance of an economical analytical model of 1-D shake table incorporating conjunction of structural dynamics and linear control theory.

*Keywords:* Designed and Manufactured; Dynamic Effects; Earthquake Waves; Linear Control Theory; Replicate; Shake Table.

## 1. Introduction

There are many specialties of civil engineering among which earthquake engineering is a new addition. The sole purpose of this addition was to design, test and construct earthquake resistant structures. After each strong seismic event, the knowledge on the earthquake response of structures is greatly increased by the observation and analysis of behavior of the different types of constructions. The new developments in construction industry are being rapidly incorporated in the relevant codes through the revisions that are almost carried out after some massive earthquake such as [1]:

1. Earthquake of 8.2 magnitude in Tangshan, Hebei that took lives of 655,000 people in 1976;
2. Kanto, Japan earthquake of magnitude 7.9 (Richter Scale) in 1923 took lives of 140,000 and left millions homeless;
3. In Ashgabat, USSR an earthquake occurred of magnitude 7.3 and claimed lives of 110,000 people.

Earthquake waves are the energy waves generated by an abrupt breaking of subsurface rock. These waves travel through earth and cause some serious damage to our infrastructures and structures. These waves are of two type's body waves and surface waves as shown in Figure 1. Body waves are released at the focus (hypocentre) and moves in all directions through Earth body. These waves move towards surface and after striking the Earth surface they generate new

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set of waves which are called surface waves. Surface waves travel along Earth surface and responsible of major destruction. These waves are recorded on accelerograph as shown in the Figure 2.

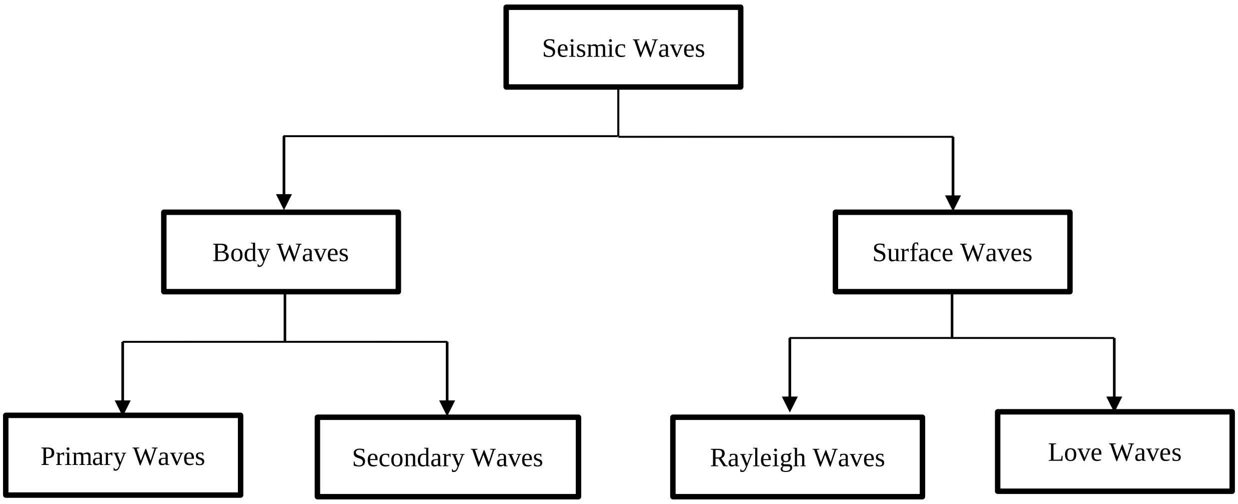



**Figure 1. Types of earthquake waves**

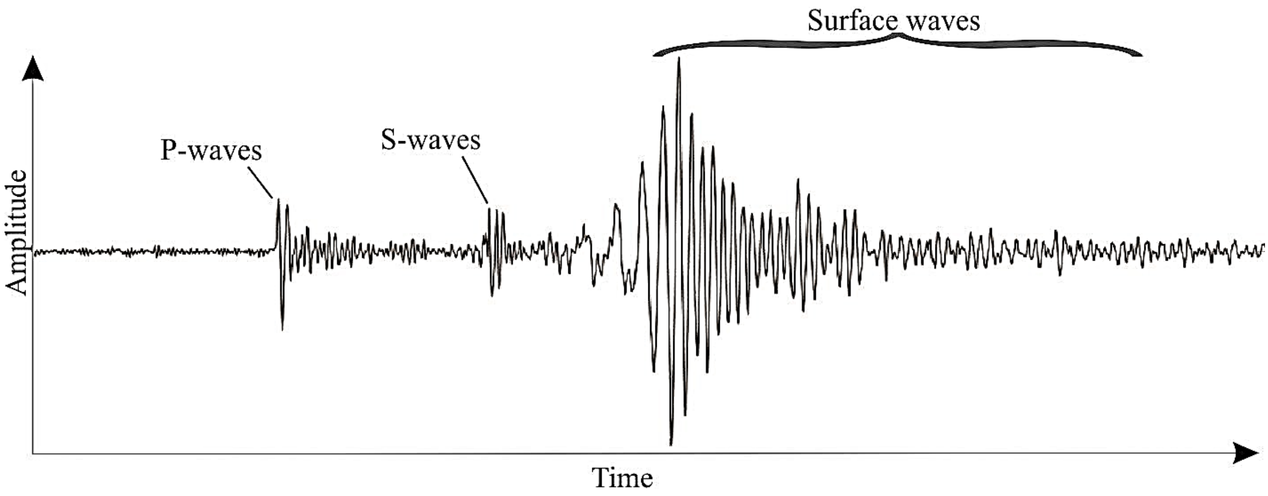



**Figure 2. A typical seismogram [2]**

Information on structural response resulting from real earthquake motion may not be reliable due to many uncontrolled parameters of both soil and structure. Even if extremely valuable information coming out of the observations of buildings that are subjected to a strong earthquake were not systematic and adequately documented and in its response received unknown parameters which are; input motion, original structural characteristics, pre-earthquake damage etc. The only method that can provide reliable results of the test of structures is on shaking table. Most important apparatus that is being used in earthquake engineering is shake table which was designed and manufactured with the sole purpose to study earthquake effects on structures. Shake table can be used to determine true cause of structure damage and reasons for any structure which survived any earthquake with negligible damage. No doubt that these days six-dimensional shake tables are being used for actual replication of earthquake simulations, but these systems are very complex and expensive due to regular maintenance and functioning cost [3]. Moreover, surface waves of earthquake that cause damage to our structure can be resolved in to one vertical and two horizontal directions, which means that horizontal shaking is dominant in causing damage (1H:2V) [3, 4]. Vertical component of surface waves (vector) can be neglected as they act in the direction of gravity loads (weight of structure). Therefore, 1-D shake table is simplest and easiest way of simulating earthquake motion which can be used for many investigations (exciting specimen in one direction) and also simplifies deduction of results.

## 2. Shake Table Testing

Shake table is one of the most effective seismic model testing that provide significantly effective understanding of liquefaction, foundation reaction, dynamic horizontal earth pressure and soil-structure interaction [5]. No doubt that mentioned forecasts are not easy to obtain [6, 7] but seismic experimentation facilities can allow us to determine the behavior of different types of materials and structures [8, 9] where determining such parameters theoretical are complex

[10]. Hence, shake table testing provide a wider investigation scope such as determination of dynamic behavior of soil and structures by using physical models, evaluation of tests which concludes to the development of new construction technologies or inventing new devices by which safety of structures can be enhanced [11]. 1-D shake table was used to study dynamic behavior of rigid blocks and steel frame (multi-plane) like structures incorporated with dampers by using shake table testing [11]. Several shake table tests were performed on sophisticatedly manufactured economical manual shake table to understand various geotechnical properties under earthquake loading [12]. Experimental analysis of shake table has been done by manufacturing one dimensional shake table aiming to protect structures from seismic effects in India [13]. Shake table has also been used to study seismic behavior on different soils such as clay [14], sandy ground [15], liquefiable soils [16] and structures such as earth walls (reinforced) [17], underground structures, and piles [16]. Another study was carried out in Malaysia in which seismic behavior of tropical soils (sandy silt and silty sand) was checked by applying different shaking frequencies in conjunction with different lateral displacements [18]. An investigation was carried out by using shake table to study dynamic effect of structure (base isolation) with SSI effect [19]. Moreover, in India a study was carried out to manufacture low cost 1-D shake table for earthquake research laboratory to study the effect of earthquake load on structures and soils [20].

## 3. Apparatus Setup

Shake table at UET Taxila, Pakistan is one dimensional, electrodynamically operated. It was designed and manufactured by using in- house knowledge, locally available materials (mostly) and fabrication capabilities. Shake table possesses mechanical linear drive, motion controller, servo motor, supporting system, sensors and glass container. Characteristics of shake table has been given in Table 1.

**Table 1. Characteristics of the shake-table at UET Taxila, Pakistan**

| | |
|---|---|
| **Specification of shake table** | |
| Shake table size | $3 \times 3\ in^*$ |
| Weight of shake table | 336.4 lb |
| Maximum velocity | 9.84 ft/s |
| Maximum payload | 2697.7 lb* |
| Maximum displacement | ±1.287 in |
| Maximum acceleration | 61.6 ft/s$^2$ |
| Frequency range | 50 Hz |
| **MLD specifications** | |
| Manufacturer | HSB (Beta 180-SSS) |
| Carriage size | 15 in |
| Maximum travel | 18.7 in |
| Repeat accuracy | 0.0012 in |
| Pitch | 0.4 in |
| Spindle diameter | 1.25 in |
| Max. Noise emission | 80 dB A |
| **Servomotor specifications** | |
| Manufacturer | Yaskawa (Model: SGMGH-10ACA21) |
| Thrust load | 110 lbf |
| Radial load | 265 lbf |
| **Servo pack specifications** | |
| Manufacturer | Yaskawa |
| Voltage | 200 v |
| Three channels with one cooling pan | |

* Can be extended

### 3.1. Mechanical Linear Drive (MLD)

MLD is the most important part of shake table responsible for earthquake simulation. It was custom made (make: HSB, Germany) with certain specifications to fulfil the requirements for competing worldwide shake table functioning attributes and was assembled with other locally available shake table components such as container, sensors, servomotor and servo pack etc. This is simply a linear actuator, which typically operates by converting of rotary motion into linear motion. The conversion is made possible by lead screw which operates in such a way that screw shaft proceeds in straight line by revolving actuator's nut. This drive is cheap, reliable, and automatic, DC/AC motor supported and be assembled with encoder. A detailed view of MLD's components has been shown in Figure 3.

### 3.2. Servomotor & Encoder (Servo Pack)

To make the shake table move fast and perfectly replicate the ground motion, mechanical linear drive was provided with servomotor and encoder. Servomotor linear actuator that enables accurate control of linear position and acceleration etc. Servomotor consists of a motor assembled with an encoder for position feedback and works on the principle of servomechanism (closed-loop) that controls motion and position by using position feedback. Servomotor is coupled with encoder to give speed and position feedback. Servomotor along with encoder has been shown in Figure 4.

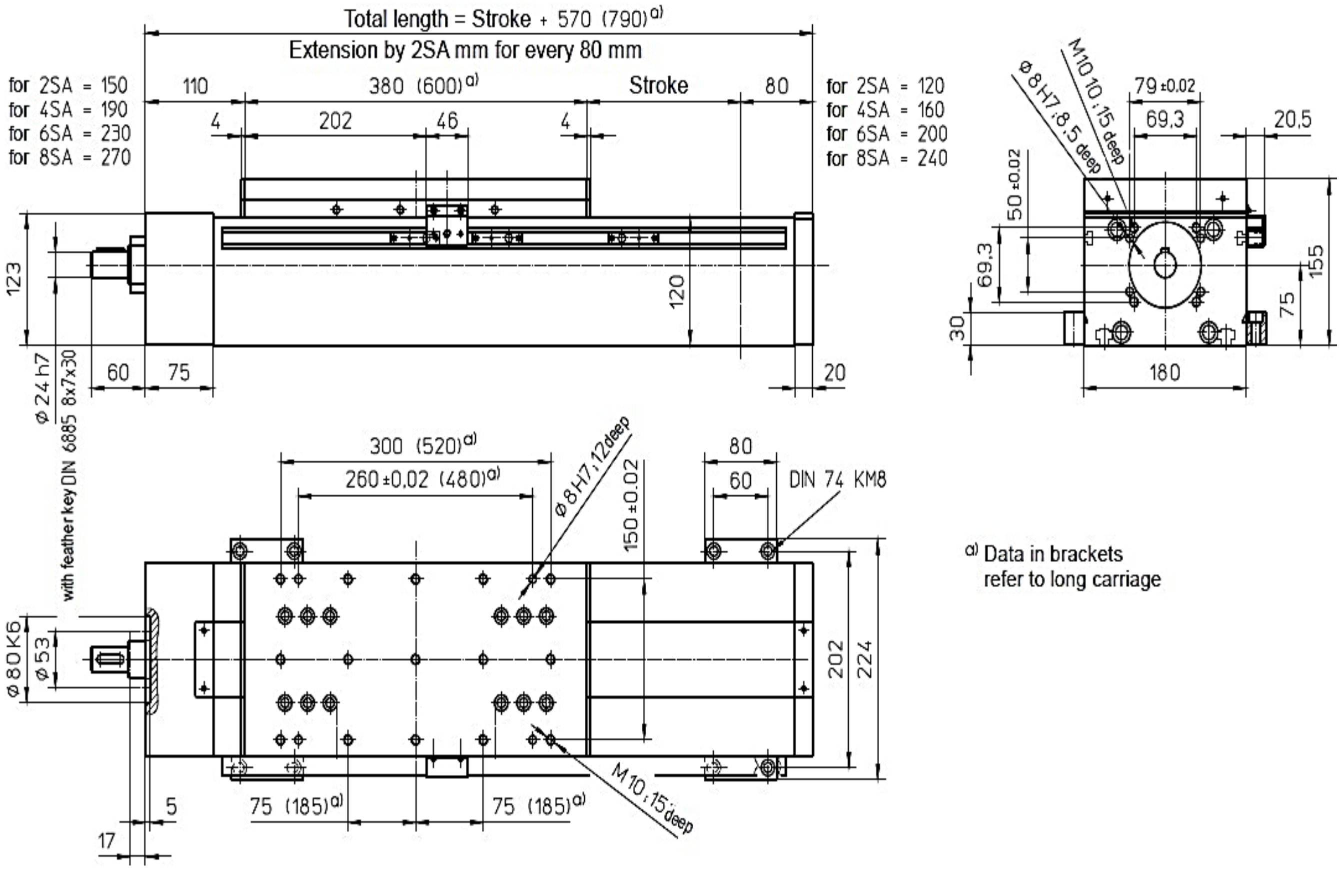



**Figure 3. Detailed specifications of MLD (HSB-Germany 2019)**

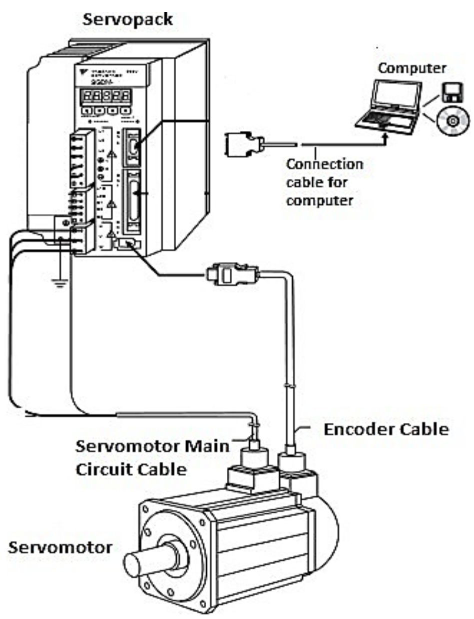



**Figure 4. Connection of servomotor and encoder [21]**

### 3.3. Motion Controller

Motion controller act as brain of shake table. It takes input wave/single from operator and compare it with feedback wave/signal from encoder. If an error persists between output/feedback position and input/desired position, motion controller makes corrections by bringing both waves in line with negligible error. Moreover, it creates motion profiles (series of position commands against time), which dictates the motor about position of load and required speed of doing it. Motion controller used in shake table has Digital Signal Processors (DSP's) for processing sufficient number of signals quickly and effectively. These DSP's perform mathematical and algorithmic operations better than microcontrollers.

### 3.4. Proximity Switches

Inductive proximity sensor has been used to detect extreme displacement of carriage way of mechanical drive can detect its extreme displacement. For determining whether input wave is within range or not, proximity sensors emit a beam of electromagnetic radiation and receive for a return signal. The objects being sensed are two metallic plates screwed to the sides of carriage way (of mechanical linear drive), screwed 2 mm above the proximity switches. Proximity switches used is shown in Figure 5.

**Figure 5. Inductive proximity sensor**

### 3.5. Accelerometers

For continuous record of motion being produced by the table or to record the values of acceleration being developed in the soil/structure, light weight, low power and complete three axis synchronized accelerometer have been provided which were connected to the data logger to store data in computer. These accelerometers record acceleration up to a value of ±3 g. Sensors measure the static acceleration and dynamic acceleration of 0.5-1600 Hz for the X and Y axes and of 0.5- 550 Hz for the Z axis.

## 4. Working Mechanism

Input acceleration time data is given to motion controller via computer which is converted to voltage time data by motion controller. Converted voltage time data is corrected via encoder of servo pack and transferred to mechanical linear drive for earthquake simulation. Simulation processed by MLD is recorded by accelerometers which are connected with data logger to be saved in computer. The whole system works on control theory (linear) in such a way that controller after receiving input file (set points (SP)) from the computer and compares it with the data points actually processed (process points (PV)). The difference between these two set of points is called SP-PV error signal. This error is again sent to motion controller to bring process data point equal to set data points. This process keeps on repeating until the error is negligible. The pictorial view, schematic diagram and flowchart for working mechanism of shake table is given in Figure 6(a) to 6(c).

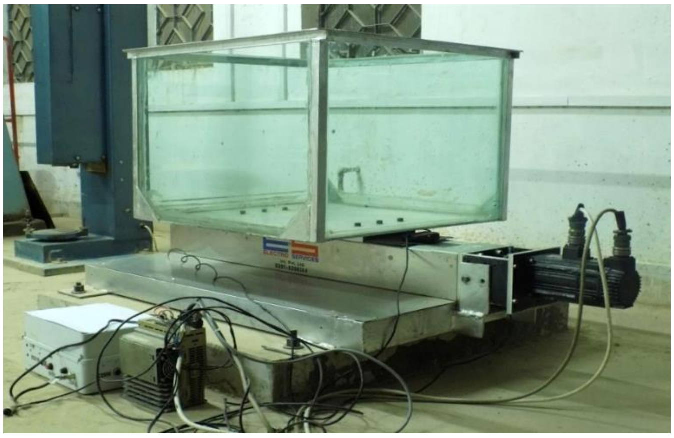


**Figure 6(a). Pictorial view of shake table at UET Taxila, Pakistan**

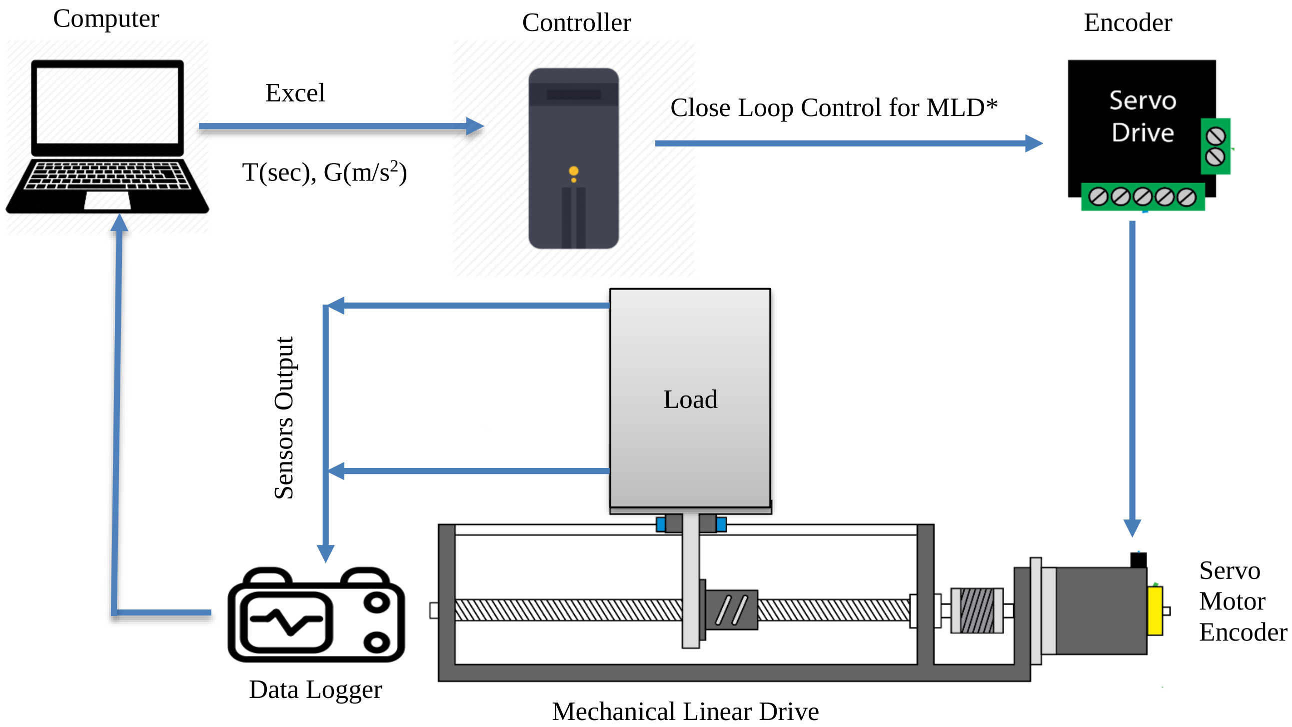



**Figure 6(b). Schematic diagram of shake table**

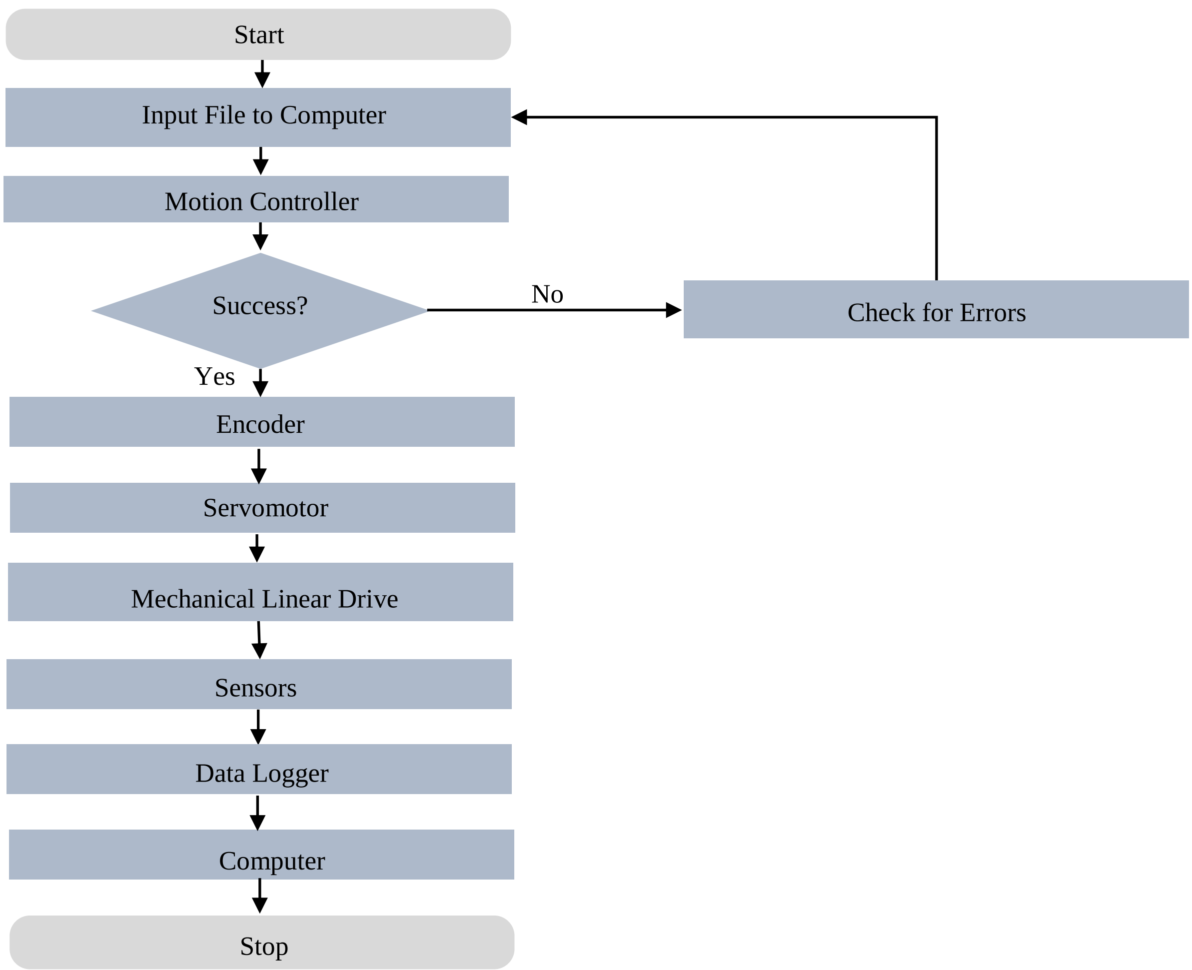
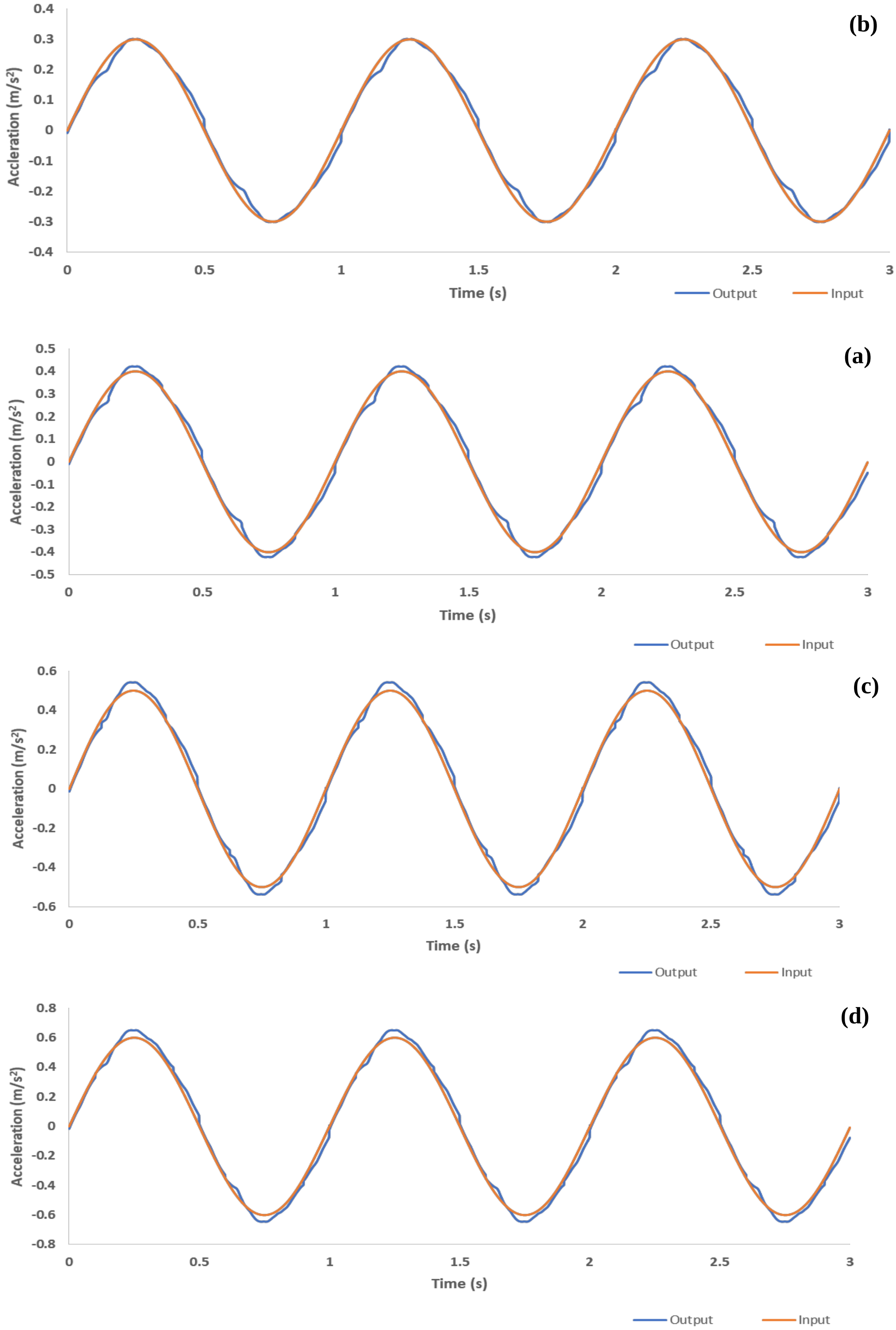



**Figure 6(c). Flowchart for working of shake table**

## 5. Results/Adequacy of Shake Table's Performance

Shake table output wave/single comprise variations of highly complex nature. Hence, a single input wave with same frequency and acceleration cannot define accuracy/quality of ground motion simulation produced by shake table. Accuracy or quality of simulation produced by shake table can be checked by giving different real earthquake and sine waves with different acceleration as an input and comparing it with the feedback/output. This comparison facilitates in investigating shake table performance insights in order to define certain shake table limitations including operating amplitude (acceleration) and frequency performance. Amplitude (acceleration) spectrum of five sine waves with different acceleration amplitudes and real earthquake (Chi-Chi and Landers) has been shown in Figure 7. Some variations can be seen near peaks is because shake table becomes static momentarily while changing its direction. Many runs with different acceleration amplitude show that there would be a best fit when amplitude is low but for large amplitude the difference is not that significant.



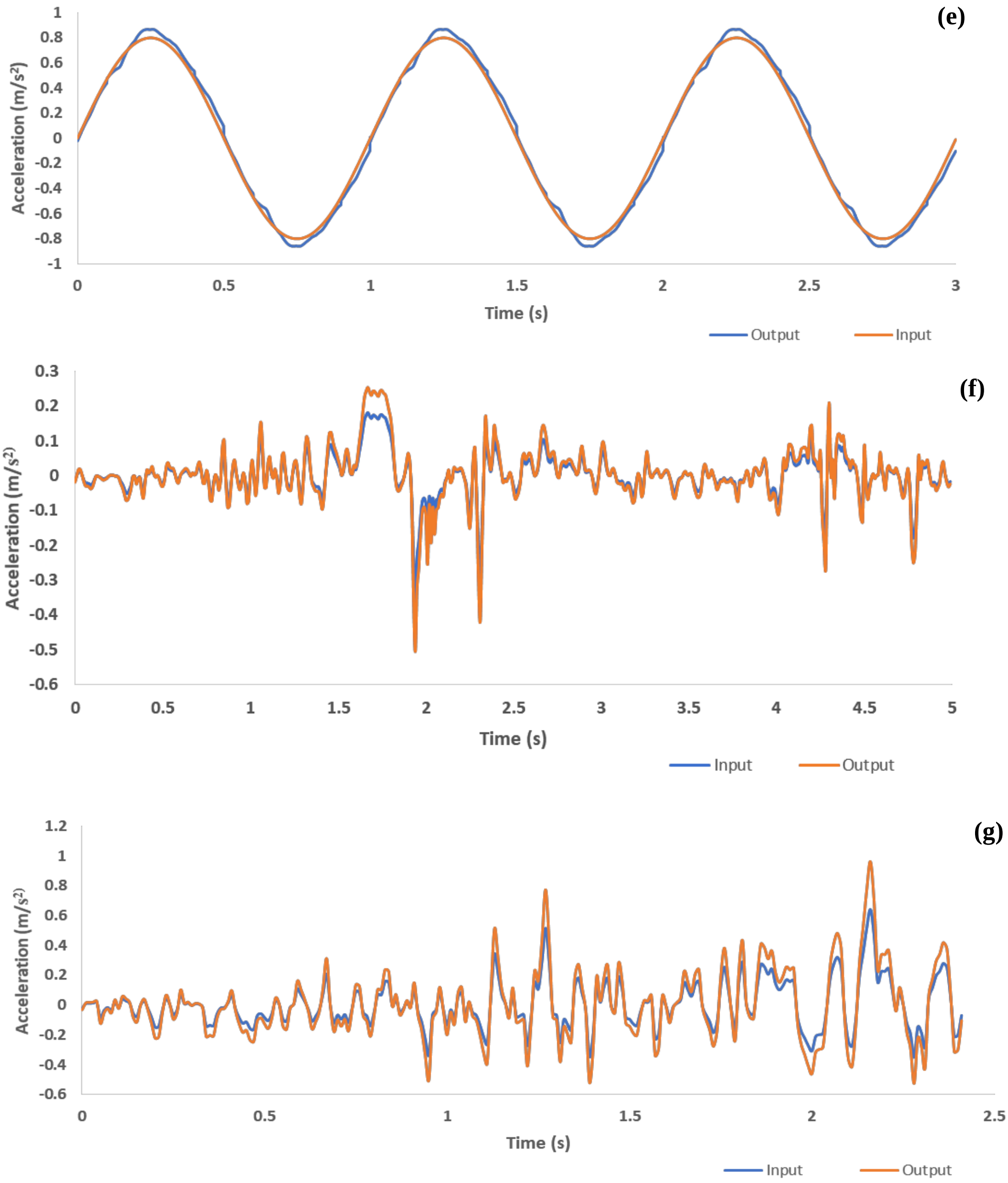



**Figure 7. Command and feedback of shake table with (a) 3 m/s$^2$, (b) 4 m/s$^2$, (c) 5 m/s$^2$, (d) 6 m/s$^2$ (e) 8 m/s$^2$, (f) Landers earthquake, (g) Chi-Chi earthquake**

During experimentation, there are some variations in output signal. The Dynamic filter has been used to filter these variations after simulation. This filter following demands four inputs from the user; Sampling frequency: Sampling rate is the values/second. For-example if there are 6000 readings in a sample and during is 1 minute then sampling frequency would be 100 Hz.

**Gain:** Acts an amplifier to increase/decrease amplitude of output wave/signal.

**High cutoff frequency:** Filters all the signals having frequency greater than the entered value.

**Low cutoff frequency:** Filters all the signals having frequency lower than entered value.

## 6. Discussion

1-D shake table are being used in earthquake research laboratories globally because of its ease to maintain and operate. For instance, EUCENTRE foundation and University of California (NEES project) preferred huge, efficient and powerful 1-D shake table instead of small six DOF table with relatively restricted performance capabilities [22]. Similarly shake table at UET, Taxila is versatile to be used for both academic and research purposes in order to perform scaled model analysis. This system is unique/different from other shake tables in the following ways:

### 6.1. Versatility

According to explored literature review this is the only shake table able that can be used for both geotechnical (soil related) and structural studies. It contains a glass container and mild steel plate (bolted on MLD) for studying behavior of different soils and structures respectively. For-example studying stability and response of soil and structure under dynamic loading.

### 6.2. Accuracy

No doubt that advanced shake table offer multi-directional earthquake simulations with accuracy, but they also offer some distortions significantly at peaks same as the shake table at UET, Taxila. By comparing results of manufactured system with single axis tables worldwide, it can be seen that this table behaves the same with some noise at edges/peaks with is due to inertia. Accuracy of this table can be judge by comparing input signal/wave with output signal/wave. The maximum difference between input and output waves is 0.06 $m/s^2$ (at peaks of Figure 7 (e)), which mean maximum error possible for this system is 6%.

### 6.3. Low price

The shake table at UET, Taxila is very cheap as compared to different 1-D shake tables worldwide. Reason for this available. Cost of mostly available single axis tables are available is usually above 30k USD but the one at UET, Taxila is only 3k USD including transportation charges. Cost breakdown of shake table is given in Table 2.

**Table 2. Cost breakdown of shake table**

| Sr. No. | Components | Quantity | Cost (USD) |
|---|---|---|---|
| 1 | Mechanical linear drive | 1 | 1000 |
| 2 | Accelerometer | 2 | 400 |
| 3 | Servomotor | 1 | 400 |
| 4 | Encoder | 1 | 300 |
| 5 | Glass container | 1 | 300 |
| 6 | Motion Controller | 1 | 300 |
| 7 | Data Logger | 1 | 300 |
| | **Total** | | 3000 |

## 7. Conclusion

Developing countries has a very low GDP and repeated destructions by earthquakes cause a heavy toll on their economy and restrict their economic growth. By installing such low-cost shake tables in their research center, such countries can study the response of earthquakes on buildings and can make their structures earthquake resistant. This table can be upgraded by incorporating some changes such as powerful motor, MLD and extending MS sheet size etc. Acceleration-time graphs shows us that shake table systems replicates signals with low acceleration perfectly but shows some noise at peak. A good match was observed when table was operated at acceleration of 0.3 and 0.4 $m/s^2$. The manufactured system has an efficiency of 80-90 percent (obtained by comparing given input by output).

## 8. Acknowledgements

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## 9. Funding

The total cost of this project as stated above was 3,000 USD out of which half amount was paid by UET, Taxila and half amount was paid by the authors.

## 10. Conflict of Interest

The authors declare no conflict of interest.

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