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Seismic Modeling with an Earthquake Shake Table

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Seismic Modeling with an
Earthquake Shake Table

Jordan E. Barnes

A THESIS

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Abstract

An earthquake shake table was constructed with three orthogonal directions of motion to simulate seismic waves. The peak amplitude and directions of motion are adjustable by the user. The table’s acceleration was measured at different amplitude settings for all three directions of motion, and that data was fit to the Peak Ground Acceleration (PGA) scale. This allows the table motion to be calibrated to the proper magnitude of an earthquake. An earthquake equivalent to 5.0 intensity on the PGA scale was achieved.
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1 Introduction

Earthquakes are powerful forces of nature that are caused by movement of tectonic plates. The Earth’s crust is composed of seven major tectonic plates, as well as smaller secondary and tertiary plates. These plates are in constant motion. Tectonic plates are either sliding past, or moving towards or away from one another. These plates store potential energy. When the potential energy becomes too great, it is converted into kinetic energy from the movement of the plates and causes an earthquake. Since these plates are in constant motion, many earthquakes occur around their boundaries. The boundaries are visible in Figure 1.

Figure 1. Seismic activity along plate tectonic boundaries. The boundaries of the tectonic plates can be clearly seen. The color of the dots indicates the depth of where the earthquake occurred. Image from ref [1].

Earthquakes vary in magnitude and duration [1]. When an earthquake erupts, waves of energy are released into the ground and can affect structures and the landscape for miles around. These waves of energy are known as seismic waves.
In the field of seismology and structural engineering, scientists are always working to create safer and more stable infrastructure. One consideration is to be able to survive earthquakes. To better understand seismic activity and how they affect structures, earthquake shake tables were invented to model seismic waves and simulate an earthquake. Earthquake shake tables have been on the leading edge of seismic design and technology. The earliest use of a shake table dates back over a century [2]. Modern earthquake shake tables are typically expensive. Can a reliable and accurate apparatus be created with a reasonable budget of just a few hundred dollars? This project is posed to do just that.

Shake tables are used to test structural models and components, usually to the point of failure. These tables give the operator a wide range of seismic waves and scenarios to test against the structure’s integrity. The more advanced earthquake shake tables can even recreate recorded earthquakes [2].

Earthquake shake tables are utilized by Universities, seismic researchers, and structural engineers. The largest earthquake shake table test in the world took place in Japan in July 2009 and is pictured in Figure 2(A) [3]. Figure 2(B) shows an earthquake shake table that is at University of California, Berkley and was used in a seismic competition among a variety of universities that included Oregon State University, University of Florida, and University of California, Davis [4]. These apparatuses are invaluable for seismic and structural research because of their unique abilities.
Figure 2. Other earthquake shake tables. (A) Life size model of the six story wood framed building that was the largest seismic test in the world [1]. (B) An earthquake shake table at University of California, Berkley [4].
2 Theory

2.1 Beginning of Earthquakes

Earthquakes begin when plate tectonics shift abruptly and release a large amount of energy. This event will usually cause a shift in the Earth’s crust. The Earth’s crust reacts similarly to water when it comes to earthquakes. For example, when a rock is dropped into water, it creates ripples. When the Earth releases a large amount of energy (the rock dropping into the water) ripples are created as well. These ripples or waves are known as seismic waves.

2.2 Seismic Waves

Seismic waves are characterized by whether the wave is on the Earth’s surface or below and by the direction of propagation the particles undergo relative to the direction of a wave. There are four different types of seismic waves in total. These waves have been split into two categories. The categories of waves are known as body waves and surface waves. Body waves move through the body of the Earth, while surface waves propagate along the surface of the Earth.

There are two different types of body waves: primary and secondary waves. Primary waves are longitudinal, like sound waves. These waves are created by alternating rarefaction and compression. This can be imagined as pushing a slinky and watching the compressed region travel from one end to the other. This occurs because the direction of particle displacement is in the direction of wave travel. This apparatus will not model this wave form. Secondary waves are a shear motion so the particle displacement is perpendicular to the wave propagation [5]. This is exactly how a wave moves through a rope. Secondary waves can be modeled by motion perpendicular to
propagation, here considered as the Y direction. Refer to Figure 3 for a simplistic view of the different wave motions.

Surface waves move much differently than body waves. Surface waves are analogous to ocean waves; the waves can only be felt on the surface and not when one is under the surface by a few feet. There are two main types of surface waves: Love waves and Rayleigh waves. Love waves are comparable to secondary waves, but are propagated horizontally instead of vertically. These waves can be modeled by one direction of motion in the X or Z direction. The Rayleigh wave is the most complex seismic wave. It includes longitudinal and transverse waves, which create a circular motion of the displaced particles, with particles near the surface moving in larger circles than those deeper below the surface. This wave will require two directions of motion in the Y and Z or X and Y directions as shown in Figure 3.

Figure 3. Seismic Wave Motions. A. Compression motion of a Primary wave. B. Shearing motion of a Secondary wave. C. Motion of a Love wave. D. Oceanic motion of a Rayleigh wave.
2.3 Introduction to Peak Ground Acceleration Scale

There are many scales for measuring seismic activity. The most familiar scale is the Richter scale. The Richter scale measures the magnitude of the energy released by the earthquake. However, the amount of energy released by the earthquake does not necessarily relate to the strength of seismic waves, which cause the damage to structures. The damage is closely related to the actual ground movement caused by an earthquake. This is of more interest than the amount of energy an earthquake releases.

The Peak Ground Acceleration (PGA) scale is a much better indicator of how much damage seismic waves can cause. This scale is created by measuring the acceleration of the ground during an earthquake [6]. While the Richter scale yields a single number for any given earthquake, the PGA scale depends more on the local geology and distance from the epicenter, so a given earthquake will result in varying PGA values at different locations.

Table 1 shows how the different intensity of g’s created by the ground acceleration is perceived by people [7]. Since $g$ is the acceleration of gravity on Earth, \(9.8 \, m/s^2\), $g$ is approximately one tenth of the measured acceleration (in $m/s^2$). For example, if the measured acceleration is 0.01 $m/s^2$ then the acceleration is 0.001 $g$. This is shown in Table 1. The PGA scale is used by engineers to design safety ratings for building components, write building codes, and assess damage. The PGA scale will be applied to the data collected during this experiment.
On March 11, 2011, Tohoku, Japan experienced an intense earthquake. It was the biggest earthquake that had ever been recorded in the Japan area. This earthquake occurred on the subduction plate boundary between the Pacific and North American plates. The duration of the earthquake was about 5 minutes at a magnitude of 9.0 on the PGA scale. The largest value of the PGA scale recorded was 2.7 g [8].

### 2.4 Earthquake Shake Table

Measuring acceleration at different amplitudes will be the basis of the experiment. The most practical way to create acceleration of a surface is converting rotational motion to linear motion. This can be done by using a motor, which gives constant rotational motion, and placing an arm that is offset from the motor’s axle with the other end connected to a plate, which will give the plate linear motion. This setup can be seen in Figure 4. A motor fitting and plate will have to be machined so the arm may be attached. The linear travel range for this experiment was 1.2” because that is the maximum allowed by the linear guide track. This meant that the largest radius could only be 0.6”.

---

**Table 1. Various measurements of g-forces. Table from ref. [7].**

<table>
<thead>
<tr>
<th>g</th>
<th>Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.001 g</td>
<td>Perceptible by people</td>
</tr>
<tr>
<td>0.02 g</td>
<td>People lose their balance</td>
</tr>
<tr>
<td>0.50 g</td>
<td>Well-designed buildings can survive if the duration is short.</td>
</tr>
<tr>
<td>&gt;1.24 g</td>
<td>Intensity is a 10 on the PGA scale.</td>
</tr>
</tbody>
</table>
Figure 4. Converting rotational motion into linear motion. The linear motion travel distance will be twice the radius the arm is placed at on the plate.

The pin can be moved to various radii can be placed on the plate to simulate different amplitudes of earthquakes. A motion sensor will collect the data and measure the acceleration at different amplitudes. This aspect will be talked about more thoroughly in the experiments section.

We predict that we will be able to simulate seismic waves of different amplitudes and in three directions of motion. The amplitudes and frequency are determined by the radius at which the pin is located and the rotations per minute (RPM) of the motor. The motion of the shake table will be equivalent to a simple harmonic oscillator, as pictured in Figure 4, will create a sinusoidal motion. A simple harmonic oscillator is where the restoring force is proportional to the displacement. The equation for a simple harmonic oscillator is

\[ y(t) = A \cos(\omega t + \phi) \]  

(1)

where \( A \) is the amplitude of the wave, \( \omega \) is the angular frequency, \( t \) is time, and \( \phi \) is the phase shift. Taking the second derivative of equation (1), the equation for measuring the amplitude of acceleration, becomes

\[ a(t) = -\omega^2 A \cos(\omega t + \phi) \]

(2)
\[ |\text{Accel}| = |\omega^2 A|. \tag{2} \]

Since \( \omega \) is the angular frequency of the motor in this case, it will not change. \( A \) is the only variable that changes. Therefore there should be a linear relationship between acceleration and amplitude.
3 Experimental Setup

This apparatus models the motion that creates seismic waves. The apparatus incorporates three directions of motion, which are able to move simultaneously. Secondary seismic waves, or shear waves, were modeled with an up and down motion. The Love waves were modeled by perpendicular motion, similar to the Primary waves. However, the most complex wave to model is the Rayleigh wave. These are an oceanic wave motion; to complete this circular motion at least two directions of motion are needed to move at the same time. Many earthquake shake tables only incorporate one or two directions of motion. This apparatus gives the user a more truthful assessment of possible seismic wave activity the structure could undergo.

3.1 Component Selection

The basic design of the apparatus is based on converting rotational motion into linear motion and then measuring position for the different amplitudes of the three directions. The issues were how to guide and power the motion in each direction, by what means to create the different amplitudes for all directions, how to connect them together in an appropriate, working order, and how to collect data from the apparatus.

Linear guides were chosen for the X and Z directions. Linear guides consist of a track and a block. The block moves along the track and is very rigid and strong. The linear guides used can be seen in Figure 5. The Y direction needed a different design because the linear guides would not work vertically. Motors are the best choice to power the directions because they provide a constant rotational motion. A fitting was applied to the axle of the motor so an arm can be offset from the motor’s axle. The fitting and offset arm will convert rotational motion to linear motion. Monitoring the movement of the apparatus will be done by a motion sensor connected to a computer.
Materials were carefully selected for this apparatus. The motor mount and amplitude plate were machined from a solid aluminum shaft and are pictured in Figure 7. Aluminum was also chosen for the angle iron for the Y direction and can be seen in Figure 3(A). The motion plates were cut from aluminum sheets. Aluminum is an easy material to machine due to its soft properties, which is why it was chosen for these specific parts.

Brass was also used in multiple places in the apparatus. Unlike aluminum, brass will not create metallic dust due to the frictions and stress the piece will undergo during operation. The motor arms were machined out of a brass shaft. This is because brass is a harder material and better suited for this piece. The spring cylinders are made out of brass as well.

3.2 Lateral Directions

The linear guides were bought from LM76, which specializes in linear motion guides. The particular model is called Speed Demon SG. The track is an extruded aluminum body with two steel shafts that are the contact points for the wheels on the block and can be seen in Figure 5(B) [9].
Figure 5. Components of linear track and block. (A) 1. The track. 2. Steel shaft the block wheels roll against. 3. Top view of the block. 4. Bottom view of block with the wheels. (B) Cross sectional view of the linear guide, showing the wheels rolling against the steel shaft.
The block is made out of aluminum and is pictured in Figure 5(A). The wheels can be preloaded. Preloading is setting the force the wheels exert against the tracks. By having a preload setting, this gives the user the ability to control the force the wheels roll against the tracks with. Each block’s preload settings can be partially seen in Figure 6(B). One guide and block were used for each of the X and Z directions and were set equally.

### 3.3 Vertical Direction

The Y direction design was more complex than the X and Z directions. This design is comprised of roller bearings at each corner, sliding along angle iron guides, which is pictured in Figure 6(A). A single roller bearing is placed on a machine bolt that had the bolt head cut off and the end pounded out to make a mushroom shape so the roller bearing is not able to slide off. Two nuts were threaded on the other end, which secured the bearing against the mushroom end. This design is visible in Figure 6(A). To attach the modified machine bolt to the motion plate, a modified wire splicer was used. The hollow brass segments under the Y direction plate allowed for springs to be placed inside them, which softened the overall motion. This allowed the motor to lift the plate more uniformly on every rotation. The springs can be seen in Figure 6(B).
Figure 6. Vertical direction design and side view of shake table. (A) How the ball bearing is attached to the machine bolt and how the Y motion linear guides operate. (B) A side view of the entire table. The Y direction springs and motor plate are clearly visible as well as the motor arm. The back of the Z direction motor can be seen also.
3.4 Directional Power

A motor that has a substantial amount of torque and moderate rotations per minute (RPM) will be appropriate to power the directions of motion. This characteristic will provide an ample amount of shaking and be able to move the shake table’s weight. The motor chosen for this project has 15 lb. in. of torque and 60 RPM. The mount has a small step so it can rest on the larger part of the axle, allowing the nut to be tightened against the motor mount using a socket wrench, holding it securely in place. Both the motor mount and plate are pictured in Figure 7.

This plate covered the nut that is holding the mount on to the axle and was fastened to the mount by two screws on opposite sides of the plate. Holes were drilled and tapped into the plate at different radii in order to model different amplitudes of that specific direction of motion. Due to a lack of space on the motor mount plate itself, there was only room
for six amplitude holes. These holes are shown in Figure 7. This is acceptable since anything above this amplitude will cause moderate damage to most structures.

Designing and attaching the motor arm to the motion plates was the next hurdle. Since there were multiple axes of motion, there is a possibility that the motor arms could fight each other during certain movements. This would have happened if the X and Z directions were moving at the same time. This problem was solved by attaching the motors to the motion plate directly underneath the plate it was powering and can be seen in Figure 8.

To acquire the proper length of the arms, the linear blocks needed to be placed in the middle of the linear guides, with the largest amplitude hole at 12 o’clock with respect to the motor’s axle. Once the appropriate measurements were taken, a pair of 90 degree
supports were screwed into place. These supports are pictured in Figure 8. A machine bolt was then placed through the arm and two 90 degree supports, then fastened firmly as pictured in Figure 8. This design was used for all directions of motion. This allowed the motors to power the motion plates on the linear guides and roller bearings. This design has proven to be sufficient for the purpose of this experiment.

3.5 Collecting Data

Data was taken from one direction of motion at a time. The PASCO Motion Sensor II, shown in Figure 9, was used for this experiment. This sensor was chosen because of its versatility. It can measure position, velocity, and acceleration simultaneously. The sensor can also be plugged into a PASCO Interface on a computer, which allows DataStudio to be used. DataStudio is a PASCO computer program that collects the data.

The PASCO Motion Sensor II uses a series of 16 ultrasonic pulses to measure the position, velocity, and acceleration of a target. The electrostatic transducer in the motion sensor transmits a surge of 16 ultrasonic pulses. The pulses bounce off the target and the echo of the pulse is recorded by the transducer. The time between the rising edge of the pulse and the rising edge of the echo is measured using the speed of the sound wave and this allows the sensor to measure the position of the target. The velocity is calculated by the change in position of the target. Acceleration is measured similarly, but uses multiple velocity measurements to calculate the acceleration. For this experiment, only position was measured because the direct acceleration graphs were too scattered and no clear data could be taken from them. Instead, acceleration was measured manually at each amplitude setting for each direction [11].
The PASCO Motion Sensor II was used to record data for this experiment [11].

The sensor was easy to position to take data. Figure 10 shows how data was taken in the X and Z directions. The sensor was positioned the same length away from the motion-detecting plate for both directions. For the Y direction, the sensor was simply placed over the top of the shake table. Since the Y direction had a more violent motion, the sensor was placed about six inches farther away than the X and Z directions to ensure the safety of the sensor.
Figure 10. Schematic of data collection. A. Motion sensor connected to a computer. B. Motion detecting plate. C. Motion plate. D. Linear guide. E. Motor arm attached to motion plate and motor mount plate. F. Motor mount plate connected to motor axle. G. Motor enclosure.
4 Results

4.1 X and Z Directions

Data were taken on a stable experiment table with the motion sensor positioned in parallel to the appropriate direction being measured. A schematic of this setup can be seen in Figure 10. The X direction was measured first, then the Z and Y directions. Using the program DataStudio, the sensor was set to record data at 250 Hz. This was the highest frequency that could be selected while staying within the measuring distance confines of the sensor. Selecting a higher frequency would require the sensor to be closer to the apparatus than was possible. Each run lasted for 10 seconds. This time period is longer than the average durations of earthquakes. During this time, the software was set to record position even though it could also record velocity and acceleration. It was discovered that recording position then depositing a fit line on to the data to derive acceleration provided the clearest data. The acceleration could be calculated by taking the second derivative of the position. Amplitudes were recorded from largest to smallest. Typical data are shown in Figure 11.

Figure 11 shows the motion of the table in the X direction. This data makes sense because the motor rotated at 60 RPM, which means a full cycle every second. As the graph shows, there is a full cycle every second. This was calculated by taking the total time divided by the total cycles, which came out to ten. The graphs for other amplitudes in the X direction were similar, but with smaller or larger maximum amplitudes, which is to be expected in this design due to the fact the motion creates a sinusoidal motion.
The maximum amplitudes were taken from each amplitude setting. Then the acceleration was measured and graphed against the radii of the amplitude settings. This can be viewed in Figure 12.

![Graph](image)

Figure 11. The recorded position for a typical experimental run. Data from the sensor are the black squares. A fit line (in red) has been placed over the data to best represent the data taken. This data is from the X direction.

The small differences in the data points of the graphs are due to the small differences in the radii from each amplitude plate in the respective directions. The acceleration data of each direction of motion increases linearly with the radius, which is expected from equation (2). This is because only the distance the motion plate travels is changing while the rotational speed frequency of the motor is not being changed.
Figure 12. X direction amplitude data. The fit line (solid line) and measured (squares) data showing the dependence of maximum measured acceleration on amplitude setting for (A) the X and (B) the Z directions of motion.
4.2 Y Direction

The Y direction data, shown in Figure 13, are noisier than data for the X and Z directions, as can be seen in Figure 11. The Y direction data were still recorded with 250 Hz frequency, but the motion sensor was a little farther away from the apparatus than the previous directions. This is because of the more violent motion the Y direction goes through during operation, making the data less clearly sinusoidal.

Two major factors degraded the Y direction motion, resulting from a combination of the motor specification and the table design.

![Position graph for the fifth amplitude setting in the Y direction](image)

Figure 13. Position graph for the fifth amplitude setting in the Y direction. The table tended to bounce, and also did not remain entirely level, during the Y direction motion, but the overall sinusoidal shape is still distinguishable.

First, the motor barely had enough torque to complete the rotations; it was pushing the motor’s limits. As the arm would push up against the table, the motor would actually tip backwards slightly on the mount. This reduced the amplitude from the expected value. Finally, the Y direction was a much more violent motion than the previous ones. This is
due to the distribution of weight across the table. Since most of the weight is at one end of the table due to the stacked design, the lighter end would bounce a little on the way down, which was picked up by the sensor.

Figure 14 illustrates the acceleration, which data increase linearly with the radius for the Y direction. However, the data points are more scattered than the previous directions.

Since the motion was more violent than the other directions, the sensor saw extra motion from the small bounce the springs caused. This made the data points distributed less evenly than the previously recorded directions. Also, the maximum measured acceleration is considerably less than the X and Z directions. The Y maximum acceleration is slightly above $0.25 \text{ m/s}^2$. The X direction maximum acceleration is $0.35 \text{ m/s}^2$ and the Z directions maximum is $0.42 \text{ m/s}^2$. 
My predictions were correct in that the experiment allowed for the measurement of the acceleration of the different directions of motion. Acceleration can be converted to g-forces. The X direction had a maximum g-force of 0.035 g. The Z direction had the greatest maximum g-force at 0.042 g and the Y direction had the least at 0.025 g. The acceleration is controllable and has a respectable range of values the operator can use to run tests. This table should be looked at as testing different seismic waves against a structure since it is controlled manually rather than digitally. This aspect makes it hard to simulate a specific earthquake.
5 Conclusion

The position data taken from the apparatus was mapped on to the PGA scale. The Z direction achieved 0.42 $m/s^2$ and is a 5.0 intensity on the PGA scale. The X direction achieved a similar results of 0.35 $m/s^2$. This value sits in the range of a 4.0 intensity earthquake. The Y direction achieved the smallest amplitude of 0.25 $m/s^2$. This is because the Y direction motor is located at the bottom of the shake table and the motor struggled with the overall weight of the table. However, this value is in the range of intensity of 4.0 on the PGA scale.

There are a few design issues that could be improved. First, the linear guides should be lengthened; secondly, the Y direction motor needs more torque; thirdly, variable speed motors would be desirable; fourthly, circuitry and electronics could be included.

For this apparatus, the linear travel distance is 1.2” for the X and Z directions. If the linear guide length was increased, this would allow a larger amplitude plate (in diameter) to be used. This would lead to wider ranges of amplitude settings for each direction and the upper end of the PGA scale could be explored. Doubling the length would be sufficient and would create a linear travel distance of 2.4”. This distance would simulate an earthquake of 10 intensity on the PGA scale. The Y direction would need a motor with more torque so it could handle the weight of the entire table better than the current one. If this happened, the length of the angle iron guides would need to be increased to accommodate the extra travel length. Also, varying the motor’s speed would be an option to achieve a higher acceleration in a small distance. New motors may need to be purchased to make higher accelerations possible.
New experiments could be tested with the earthquake shake table. An experiment could be setup to test how well this apparatus models previously recorded earthquakes. If power inverters and new motors were purchased, the shake table could be setup to model real earthquakes if circuitry and electronics were included in the design. Students in introductory courses could use this apparatus to see how velocity and acceleration are calculated from position in a more entertaining way than is currently being used.

This apparatus could inspire new classes at Linfield College. Since the Linfield Research Institute will now have a working and reliable earthquake shake table, classes could be constructed to incorporate this apparatus. A structural design class could have a project where students test structural models on the shake table. A CAD class could also be incorporated to draw a new design of an earthquake shake table or use the CAD program to draw the existing apparatus that was tested in this experiment.
6 Acknowledgements

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7 References


