Wake Forest University

Natural Hazards Engineering
Research Infrastructure (NHERI)

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SHAKE TABLE

Lesson Details

Grades This lesson has been designed for a high school level (9 – 12), but it can be adapted to lower grades by simplifying the information provided.

Key Words Large-Scale Mobile Shaker, P waves, S waves, Earthquake,

Topics Anatomy of an earthquake, Effects of an earthquake, Mitigation.

Objectives

Students will be able to:

- Understand the types of waves involved in an earthquake.
- Predict the effect of earthquakes over specific areas (urban & rural areas)
- Propose ways to mitigate the effects of earthquakes

Essential Questions

- What is the difference between P and S waves?
- What is soil amplification?
- What is stress and friction?

Materials

- 1 Roll of duct tape
- Shake Table (Appendix 4)
- Utility Cart (alternative to the Shake table)
- 3 Slinkies
- K'nex (popsicle sticks with silicone, or Legos are OK)
- 1 ½ Inch thick Gelatine Block (or silicone rubber)
- 1 ½ Inch thick wood block (or any other hard material)
- Accelerometer
- Wide Plastic Bottle
- Small, assorted weights
- Stopwatch (a cellphone is OK)

Introduction

You may have noticed that there are parts of the world where earthquakes tend to occur, but others where it rarely does. Knowing where and how strong one of these natural hazards would be is important to architects when creating houses, buildings, or bridges, to engineers when creating the tools required to mitigate their effects, and to people as a way to know how to react.

In this lesson we will learn how an earthquake is created, its parts, and the way it affects the surface and what is on it. We will study a bit of the ways in which mitigation is achieved and the science behind it.

The Lesson

Earthquakes are the consequence of the movement of the plates, so boundaries are important, since those places will suffer the most.

If you break an Oreo slowly in half, you will find that at first it resists being broken, if you apply more force it will start to show some cracks and finally, the cookie will tear, and crumble, and you will be able to see the cream in the inside. This is exactly how a divergent boundary works, just that the cream is actually the asthenosphere, and since it is pressurized below ground, it will rise, cool down and cover the crack, which we call a fault.

Image 1. Oreo Crack (*Taken from Oreo Isolated, n.d.)*

If you think you have a ball of playdough in one of your hands and you squeeze it with all your strength, you will find that it will come out through the spaces between your fingers. This is what happens is convergent boundaries, only that the only way the crust can go is up, which creates mountains.

Image 2. Squished Playdough (*Taken from About, 2013)*

Finally, think you have one hand against the other and you apply all the pressure you can. Know, you will try to move one of them up, while moving the other one down. You will find that the movement is not fluid, in fact, the hands will slip and get stuck several times while making a hissing sound. At the end you will see that one thumb is higher than the other, and the same with all the other parts of each hand. This is what happens in a transform boundary, just that each hand would represent a huge amount of land or mountain. Think that the thumbs were a mountain or a forest. Now, a piece of it is higher north and the other a bit south.


Image 3. Shear hand motion (Meigs, 2023)

Each of these movements would cause stress due to the compression, tension, or shearing motion. Once the stress is so big that the particles of matter involved can't take it anymore, the movement starts, but since it wasn't supposed to move, there will be another force involved called friction. When the motion starts, this creates waves.
If you have seen ripples in a pond, a waving flag, or the motion of a bouncing ball, you have seen waves. Waves are a disturbance that moves through space but they are not bound to matter, that is why sound and light are waves as well. There are two types of waves created by friction, The first wave is the Primary wave, so we will call them P waves. The second wave it creates is the Secondary wave, so we will call them S waves. These waves are the ones that cause an earthquake.

- P waves: These waves move back and forth which on the surface would feel like up and down. They are faster than the S waves.
- S waves: These waves move from side to side.

What we feel during an earthquake is actually the blend between waves, but scientists can decompose the movement and study it. What they have found is that the P waves don't cause major impact over the surface, but the S waves do (Set of pictures in folder, their details are in the Appendix 1).

S waves make structures move from side to side or vibrate, and if the vibration is too strong, it makes them break and now, without proper strength, they crumble to the ground. Each structure will have a specific speed or frequency of shaking at which their vibration is so intense that will make it break apart. This phenomenon is called resonance and it occurs at the natural frequency at which the structure vibrates (watch the video titled "Building Natural Frequency", further explanation in the Appendix 2). S waves could also be amplified by "soft soils", which makes studying the ground very important (more on ground composition in the Material Xylophone Lesson).

Houses, buildings, and other typical structures have been studied to find their natural frequencies and have been compared to thousands of earthquakes to be able to create a building code which will tell engineers the precautions they need to take in to account when developing a project in a specific place (like a specific type of building that would have a natural frequency that matches the vibrations of earthquakes recorded in the area). One way to study a structure's natural frequency is using the Large-Scale Mobile Shakers, trucks that have a mechanism that can mimic the waves of an earthquake but at a safe intensity. These Mobile Shakers are also used to identify the “soft soils” that can amplify the shaking of the ground.

Image 4. Large-Scale Mobile Shaker (*Taken from Putzer, 2022*)

In this way, the natural frequency is identified, and precautions can be made. The trucks work with a series of sensors that will interpret the vibration of the structure at different frequencies, so that engineers can compare the behavior of the structure and identify its potential weaknesses.

Image 5. Shaking Tool from a Large-Scale Mobile Shaker (*Taken from Putzer, 2022*)

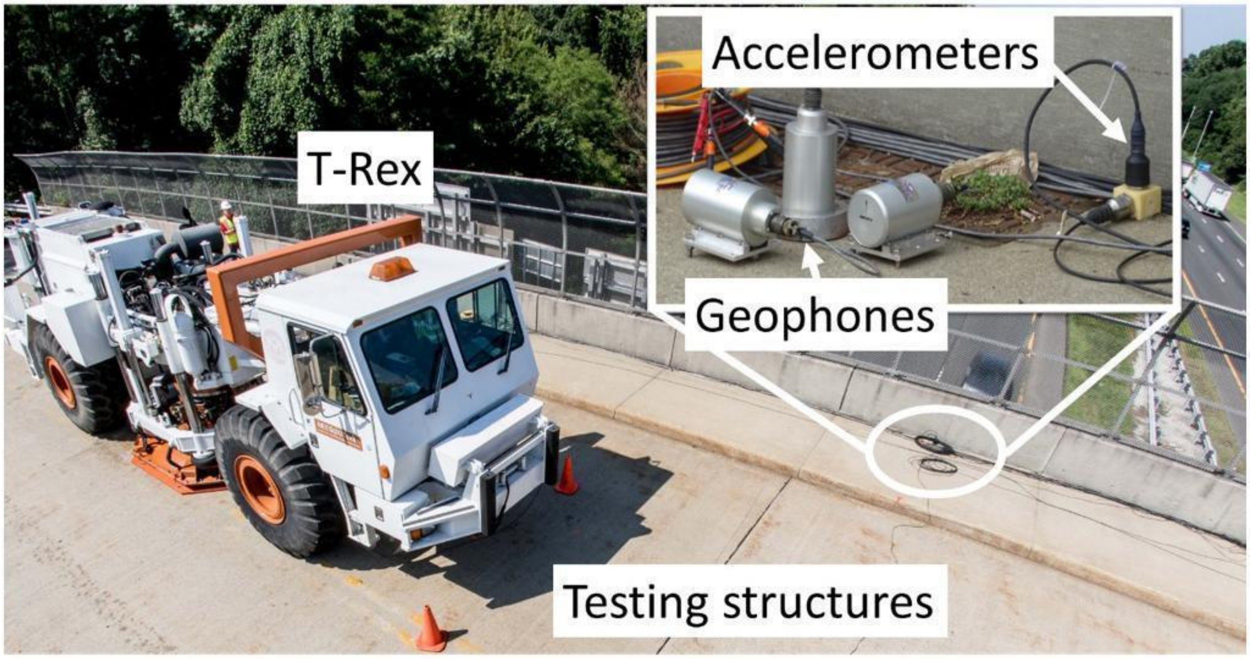

Image 6. T-Rex Shaker Truck Shaking a Bridge (*Taken from Stokoe II, 2020*)

However, if a structures has a natural frequency similar to the frequency of the waves created by an earthquake, it could cause lots of damage, so as an extra measure, mitigation techniques have been created. These are extra features of a building that will regulate the expression of the natural frequency of a building. In other words, they will make the building shake less if its natural frequency is met by the vibrations of an earthquake (watch the videos in folder titled "Mitigation", each video is explained in the Appendix 3).

Procedure

- Divide the class in groups (picked by teacher or by students). Try to have groups not bigger than 4 students per group and no less than 2.

P and S Waves

1. Take the slinky from one side and let it drop.
2. Have another team member sit on the floor and grab the other end (Side A). If necessary, make the team member holding the higher end (Side B) stand on a chair to make the slinky extend as much as possible.
3. Have the team member holding side A shake the tip up and down in one fast stroke. Repeat several times to understand what is going on. Discuss with the group what happens. Label this movement as P wave.
4. Have someone else set a stopwatch (cellphone). Coordinate with the one holding side A and record the amount of time that the wave takes to get from side A to side B.
5. Repeat 10 times and record the corresponding time. Calculate the mean.

6. Have the team member holding side A shake the tip from side to side in one fast stroke. Repeat several times to understand what is going on. Discuss with the group what happens. Label this movement as S wave.
7. Repeat steps 4 and 5 for the S waves.
8. Compare the means and conclude which type of wave is faster.
9. Analyze: If side A is the inside of the earth, and side B is the top layer of the crust, how would the waves affect the surface?

Natural Frequency and Resonance

1. Provide the K'nex (or any other building material you have) to the students and give them the creative freedom to build any building, as long as its three stories tall.
2. Using the shake table, clamp the building down in the center (as shown in image 12), attach the accelerometer at the top of the building, and proceed to do a "drum roll" on the wooden portion of the shake table to illustrate P-waves (depending on the type of accelerometer, different software could be used. Make sure the accelerometer has been installed and the corresponding software is running and ready for recording data).
3. Push the wood board of the shaker table forwards and backwards to simulate S-Waves and test if the buildings would resonate at that frequency. Try different frequencies.
4. Have students observe each building demonstration and determine which buildings they believe would sustain the most damage and which would not sustain much damage, if any.
5. Compare the movement of the building with its corresponding data obtained by the accelerometer. Compare this data with the data of other buildings.
6. Discuss the reasons behind building oscillation.

Soil Amplification

1. Set the gelatin on top of the shaker table (A silicone rubber block could be an alternative to the gelatin as a more permanent option. The way to prepare it is explained in the appendix 5).
2. Put the accelerometer on it and secure it (toothpicks and tape is a good option)
3. Shake the table, first replicating P waves and then S waves (make them emulate strong tremors for best results: here is an example https://www.youtube.com/watch?v=nuUaOXHqzec).
4. Take the accelerometer, get the gelatin off and put the piece of wood on top of the shaker table.

5. Using tape, secure the piece of wood to the table.
6. Put the accelerometer on top of the piece of wood and secure it with tape.
7. Repeat as close as you can step 3 for the piece of wood (if you have two accelerometers, you can test the gelatin and the wood at the same time).
8. Compare data obtained with the accelerometer for the gelatin and the wood.
9. Analyze and conclude what happened. Relate observations to what a building might feel if it is on top of soft vs. firm soil.

Image 7. Silicone rubber block

Mitigation

1. Using the buildings from each group, have students modify them to amplify their resonance on the shaker table (this means that if the building did not vibrate much, with the modifications will vibrate a lot).
2. Make groups use mitigation techniques to reduce the resonance of the building. The wide bottle can be used to make a tuned liquid damper, or the weights can be used to make a tuned mass damper. Other types of dampers can be made if resources are available.
3. Test on the shaker table. If resonance was controlled, then the damper is satisfactory.

Assessments

There are several ways in which this lesson could be assessed:

- Performance of buildings (without and with dampers)
- Identification of natural frequencies to make buildings resonate.

Interpretation of graphs obtained through the accelerometer (Identify resonant frequency, damping effect, soil amplification).

Appendix

Appendix 1. PICTURES

Images on the first slide are different areas of the same shoreline that was uplifted by an earthquake in Chile. The receding waters are evident from the before and after comparison. Images on the second slide show ground deformations from the 1906 San Francisco Earthquake. Top left shows a road that has been curved. The movement is evident in the road, and the fence. Center image shows a fence that is followed by a small set of trees. These trees and fence have been moved to the right by the earthquake. Top right image shows the length

of the movement experienced in the 1906 earthquake, measured by the arm's length of a person.
Images on the third slide are from the 2023 Turkey Earthquake.
References for all images are provided on the slides and in the reference section below.

Appendix 2. NATURAL FREQUENCY

In the video, you can identify three model buildings which have the same weight at the top. By changing the frequency at which the shake table is making the buildings vibrate, in this way each of the building's resonant frequency is matched to the natural frequency. A little more on the topic at this link: https://www.youtube.com/watch?v=dihQuwrf9yQ
Full video reference: SDOF Resonance Vibration Test (n.d.) www.youtube.com. Retrieved August 4, 2023, from https://www.youtube.com/watch?v=LV_UuzEznHs

Appendix 3. MITIGATION VIDEOS

Fluid Viscous Damper: This type of damper is like the one seen in a car or in some bicycles. The motion is attenuated by the pressures within the device, which makes the resonance less evident.
Full video reference: What is a fluid viscous damper? (n.d.). www.youtube.com. Retrieved August 4, 2023, from https://www.youtube.com/shorts/0Aa8c1taBr8

Tuned Mass Damper: This type of damper uses the weight of a heavy mass, that swings in the opposite direction as the building, to control the vibration of the building. It is installed at the top of the building since this is the part of the building that would resonate the most.
Full video reference: What is a Tuned Mass Damper? (n.d.). www.youtube.com. https://www.youtube.com/watch?v=f1U4SAgy60c

Tuned liquid damper: This type of damper is like the one that uses a mass, just that the liquid has taken its place. Water would be normally used but there are other types of liquids that could be used as well.
Full video reference: Tuned Liquid Column Damper Experimentation. (n.d.). www.youtube.com. Retrieved August 4, 2023, from https://www.youtube.com/watch?v=jL66oOADtVM

Base isolation: This type of damper tries to get rid of the vibration problem at the base instead of all the other alternatives. Basically, it isolates the building from the ground, which wants to remain still, due to inertia, when an earthquake occurs. I have edited the video so that it only shows the base isolation, but the link will take you to the original video that shows a bit more of Tuned mass dampers.
Full video reference: Simulating earthquakes with LEGO (how base isolation and tuned-mass dampers work). (n.d.). www.youtube.com. Retrieved August 4, 2023, from https://www.youtube.com/watch?v=RFqkNfx2Dm4

Compound Mitigation videos: These videos show the use of several mitigation techniques already described above and one not described. If seen with detail, you can appreciate how each level of the building has been isolated from the one above and below. It takes the idea of base isolation and is applied to each level of the building, which makes the whole structure shake in a balanced pattern (actually a sort of wave motion can be observed).

<u>Full video reference:</u> Effects of seismic Damper on a building during Earthquake. (n.d.). www.youtube.com. Retrieved August 7, 2023, from https://www.youtube.com/shorts/Xpa0jyKen-o
Seismic damper used in building | Earthquake resistant building. (n.d.). www.youtube.com. Retrieved August 7, 2023, from https://www.youtube.com/shorts/tU98UfGL-GQ

Appendix 4. SHAKER TABLE

The shake table used in this lesson was made following the prompt shown in this video: https://www.youtube.com/watch?v=ovjtEVbtPCo

The following are alterations made to the steps followed in the video:

1. Taking into account that rubber bands would be fragile and may not give enough tension, these were replaced with bungee cords (Image 9).
2. The eye bolts were not drilled into the PVC tube, rather installed on the board (Image 7). These made their height a possible issue since, with the tension, could lift the PVC frame, so they were put all the way down and the excess of the bolt was cut at the fixing nut (Image 10).
3. The frame was made with 2” PVC.
4. Instead of using the dowels to move the table, swivel ball caster rollers were installed so the table would have no limitation of movement.
5. Instead of using tape to fix the buildings to the table, two flat aluminum bars and small clamps (these clamps need to be small since bigger ones would have friction with the table or floor where the shaker table is placed) were used (Image 12).
6. The accelerometer was fixed to the top of the building using two zip ties (Image 11).

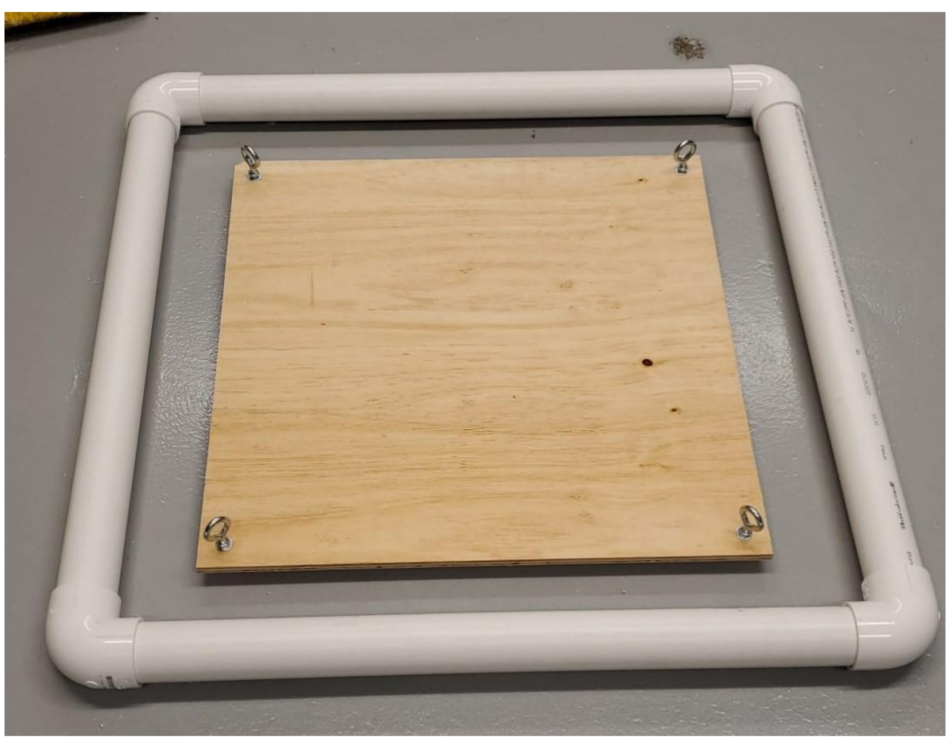

Image 8. Eye bolts installed in the table with a 2” PVC frame.

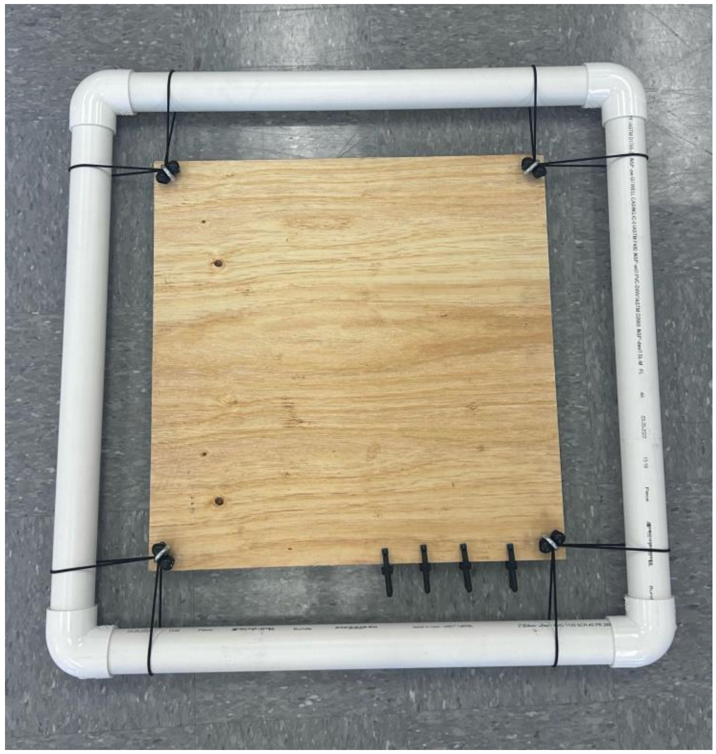

Image 9. Bungee cord installed and clamps.

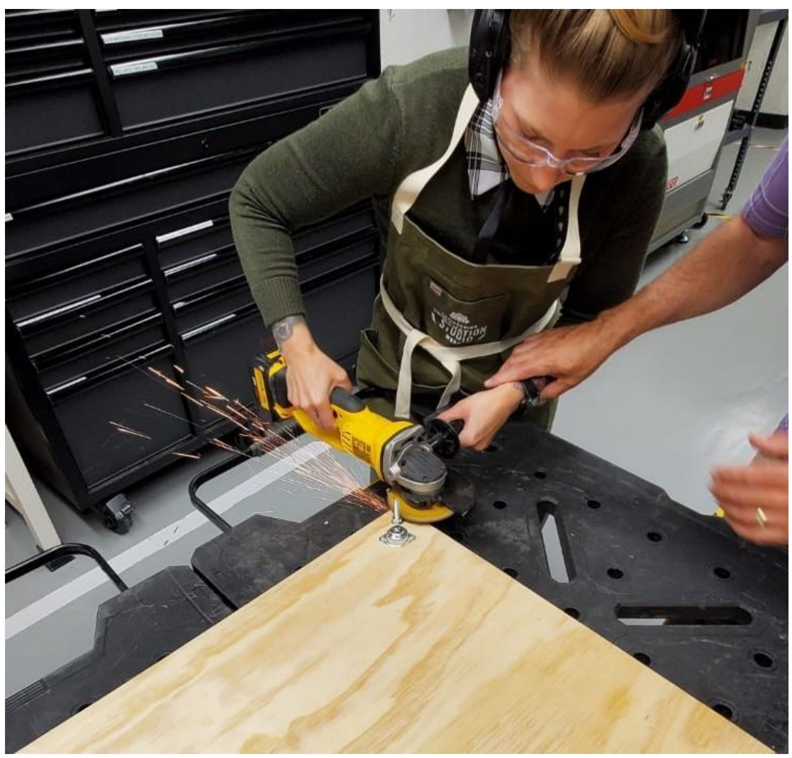

Image 10. Excess length cut from the eye bolts and swivel ball casters installed.

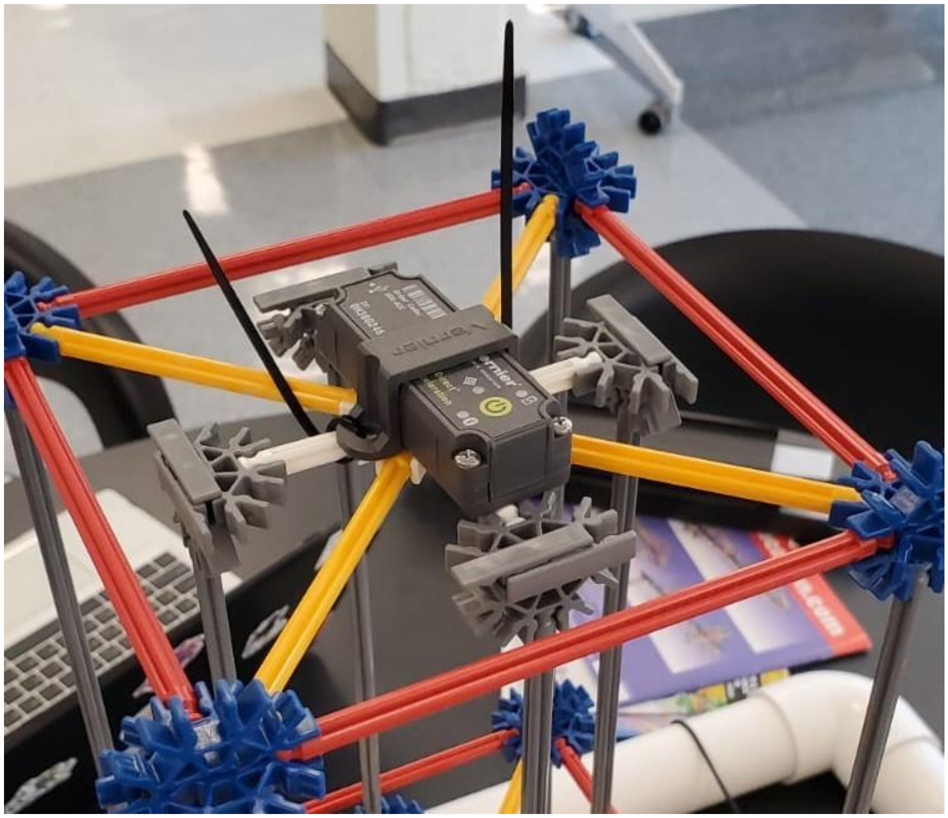

Image 11. Accelerometer installed at the top of building.

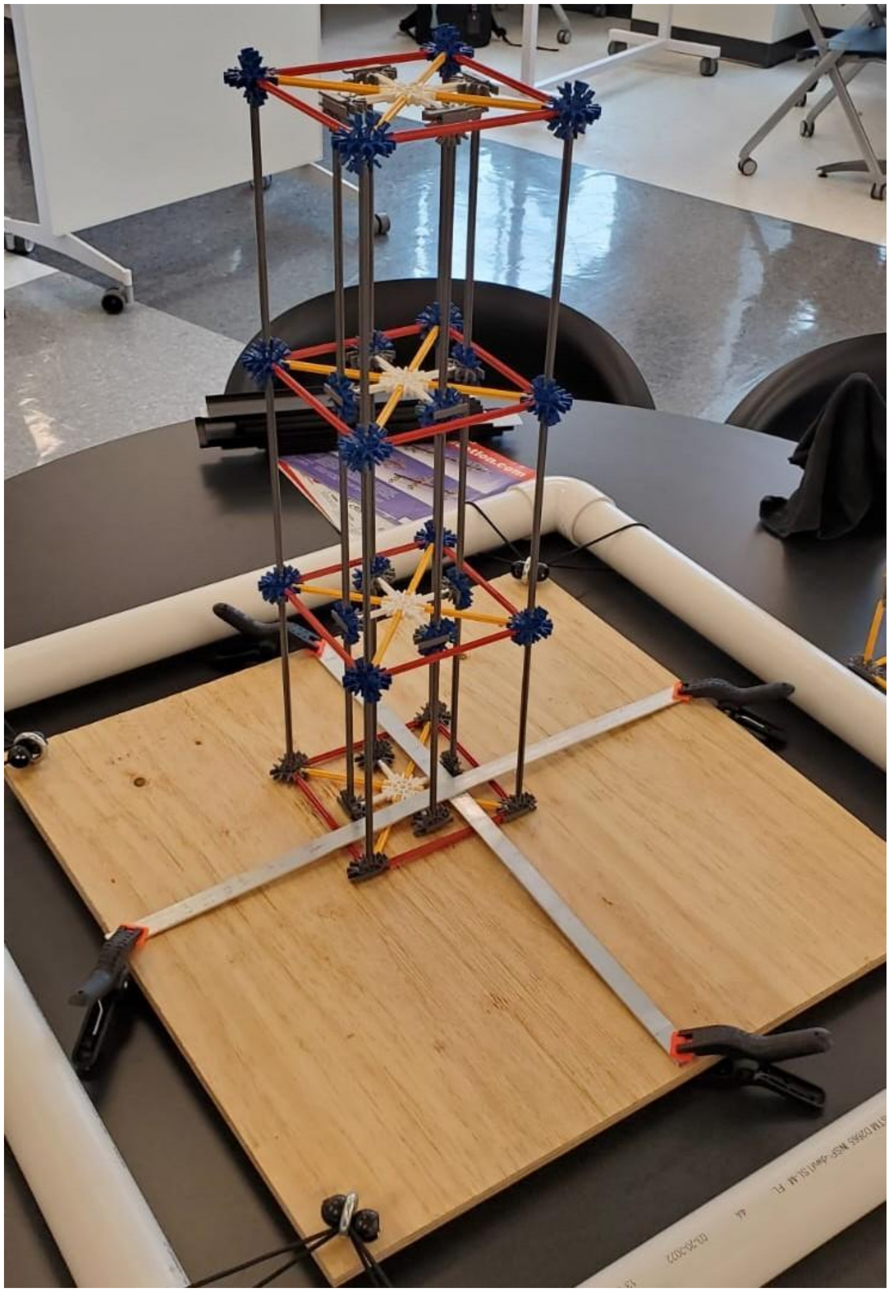

Image 12. Aluminum bars and clamps used to fix building to the shaker table.

If the resources to make the shake table are out of your possibilities, you can always use a utility cart to simulate the S waves. P waves can be simulated by the drumroll, but remember to hold the cart in place if you are using the accelerometer, so it won't record data in the X or Y axis.

Appendix 5 SILICONE RUBBER

To make this block, we used the EZ-SIL M30 Silicone. The one shown in image 7 is 6"X3.5"X1.5". Instead of following the proportions indicated by the manufacturer (1:1), the proportion used was 1:¼ of silicone rubber and curing agent, respectively. A mold made of cardboard was used to give it the desired shape.

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