Wake Forest University

Natural Hazards Engineering Research Infrastructure (NHERI)

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MATERIAL XYLOPHONE

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 Resonance, Large-Scale Mobile Shaker, Waves, CPT (Cone Penetration Testing), Soil Core, Cross Hole Test method.

Topics Soil Composition, Effects of layers

Objectives

Students will be able to:

- Understand what is natural frequency and how it relates to object vibration.
- Understand that stiffness affects the natural frequency of materials.
- Predict the relative stiffness of materials based on the sounds they produce when struck.

Essential Questions

- What is natural frequency, and how does it relate to the sound produced by an object when struck?
- How can we predict the relative stiffness of materials based on the sounds they create?
- What is resonance and why is it important to understand?

Materials

- A piece of Styrofoam
- A piece of hard foam
- A piece of wood
- A piece of metal

Try to have all pieces match the same size.

- Material Xylophone (appendix 1)
- Rubber Mallets (one per group)
- Plastic or metallic ruler
- Flexible ruler

- Other prepared resonant samples (these are some examples; you can make your own):
    - Filled box
    - Empty box
    - Tube
    - Solid plastic rod

Introduction

I bet you have been to a concert at least once. When you feel that low vibration coming most possibly from the bass, you are actually experiencing the effect of waves. Everything can vibrate, your car, the floor, buildings, anything you think of, but humans like to modulate vibrations to make music. The thing is that vibrations by themselves are not what we call music, we need to find the vibration that the object "likes", and if we do so, then we have a musical note.

Instruments are complex tools due to the exploration of materials and conditions required to be able to have several "liked" vibrations in the same object, and that would be the range of the instrument, from the highest note to the lowest. In this lesson we will explore how waves can be used to better understand matter.

The Lesson

If a force affects an object (living or not), this object will vibrate. The force can be coming from any source, a punch, an explosion, sound, you name it. Now, if this object is affected by a force that makes it vibrate at the frequency that it "likes" (its natural frequency), resonance occurs and vibration is amplified. Two kids jumping on the trampoline at the same time will go higher than if each one jumps at their own different timing. You can find further information about these phenomena in the following YouTube video:
https://www.youtube.com/watch?v=6IJ99phNArM.

As mentioned before, everything has its own natural frequency under given circumstances. For instance, if you strum a chord from a tuned guitar, you will hear a specific sound. This sound, because it is tuned, can be called a note. Notes are actually natural frequencies. In this case, the chord, depending on the string's specific material density, length, and stiffness/limpness will have a specific sound. If you press one of the frets in the fretboard and strum it again, you will hear a new natural frequency (new note). Same thing happens with a piano, just that in this case you hit the strings within the piano to make the sound. Some instruments are not that easy to play, for example a trumpet. This one depends on the air pressure and the vibrations produced by the mouth.

Music is built on natural frequencies that are excited by the forces we make so that each instrument resonates, making vibrations go wild and giving that beautiful sound. On the other end, if the ground were to shake at its natural frequency you would feel that vibration at the surface. However, if something were to make it vibrate constantly at its natural frequency, that would make the ground resonate, and it's not that pretty anymore. That could be the case of an earthquake. This issue of earthquakes causing resonance resulted in massive damage in the 1985 Mexico City earthquake, which you can read about in Appendix 2.

Thankfully earthquakes don't tend to do this to a full degree, but it can always happen. This, added to the fact that the ground itself is made of many different layered materials, means that there are many different factors that could affect the shaking we feel on the ground from an earthquake.

Up until now, we know the ground is made of different layers of weathered materials of different sizes, organic materials at different levels of decomposition and/or size, and water. The different amount of each would give the ground at a particular spot its properties such as its density and stiffness (how much it deforms when a force is applied). Thus, it will vibrate in a different way depending on these properties. There is a particular type of layer in the ground that is of special importance to engineers. Sandy soils that are saturated with water (a fancy way of saying that are filled with water), tend to separate from water if they are subject to vibrations, which makes them really unstable. If these soils are at the surface, they could easily eat up a car or house. If they are within the layers close to the surface, they could make water pressurize so high that water drills through the upper layers and causes a flood. This is called liquefaction (to learn more about liquefaction, refer to the lesson on Liquefaction).

As you can see, if you are going to make a structure at a given place, you really want to know what is below the surface. This is why scientists and engineers have developed several ways to identify the layers within the ground:

- Soil Cores (Image 1): This is a technique where a machine would puncture the ground with a hollowed rod that gets filled up with each layer as it goes down. Then, the rod is taken out of the soil and the sample is carefully extracted. This sample, as you may imagine, has each layer at its precise location and its composition can be studied. Soil cores are expensive and take out a sample, which makes a hole you may not want around, so they are not used often.

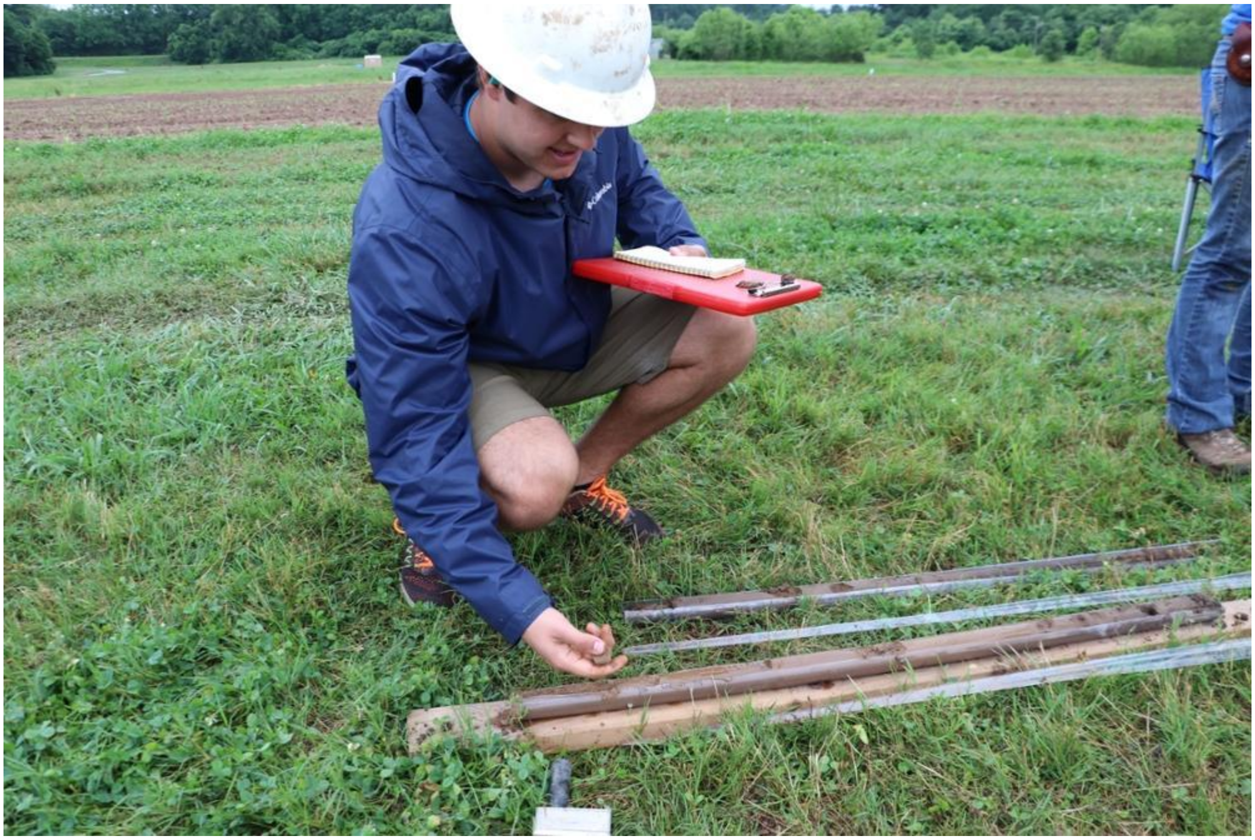

Image 1. Soil cores collected with geoprobe. (*Clemson University, n.d.*)

- Cone Penetration Test (CPT, Image 2): This technique is similar to the Soil Cores but instead of obtaining a sample of the ground, the rod would have a sensor at the tip which measures the pressure required to puncture each layer of the soil. This is sent to a software that helps researchers identify the composition of the soil. This is one of the ways commonly used to characterize the ground.

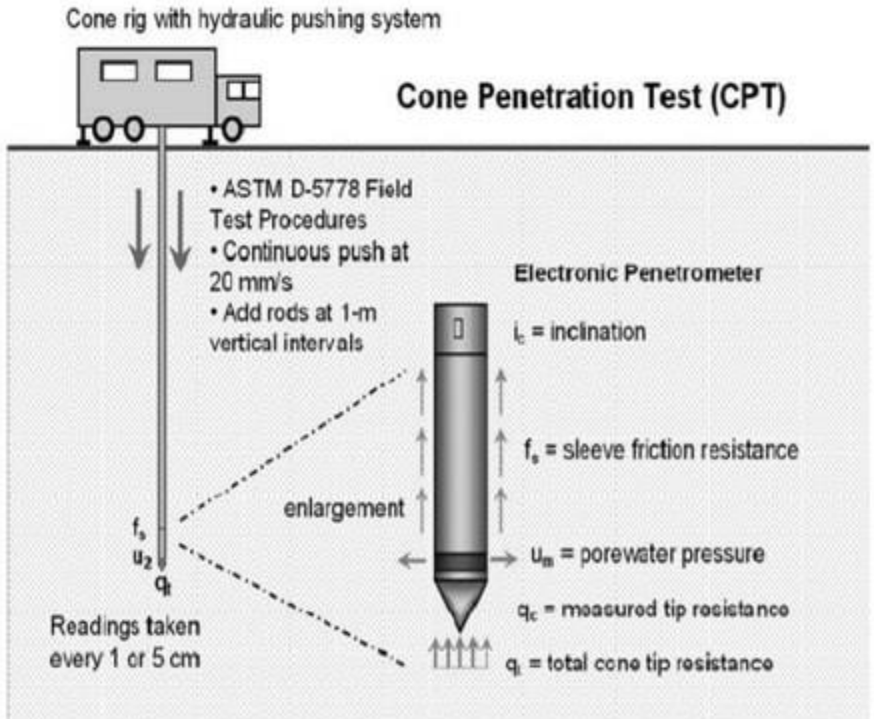

Image 2. Diagram of CPT testing. (*Cone penetration test, n.d.*)

- Cross Hole Testing (Image 3): As mentioned before, every material has its own natural frequency, so if we know this frequency, we can know the material. Remember that the vibration can be affected by the density, stiffness, and length of the material, so this technique would use two rods instead of one to keep the length controlled. One of the rods is struck with a hammer and sensors attached to the other rod would analyze the speed of the vibrations within the specific layer. Afterwards, the bars are pushed farther down and hammered again. This is another widely used way to characterize the ground.

in it.

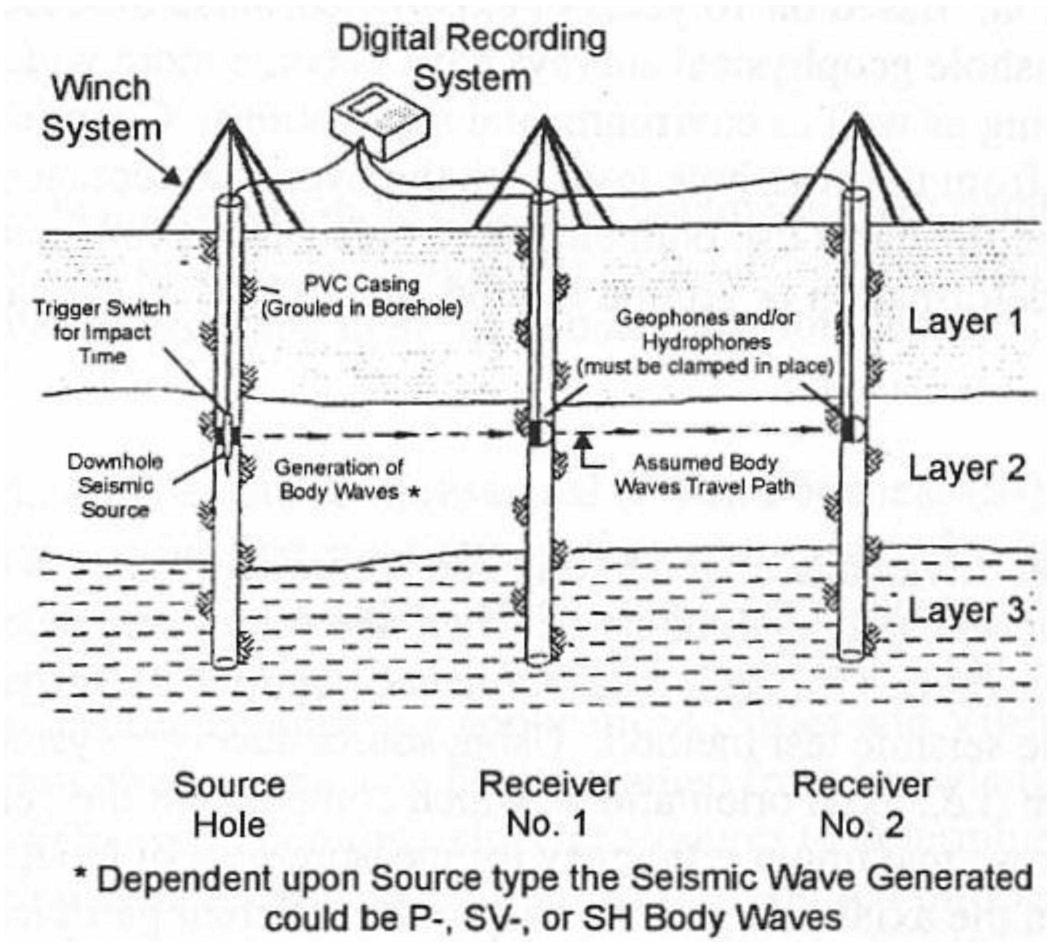

Image 3. Depiction of cross hole soil testing (*Cross Hole Testing, n.d.*).

These techniques have several complications, one of them being the holes left after the test, so engineers are studying a way to be able to characterize the ground without puncturing it. To achieve this, they have created the Large-Scale Mobile Shakers (see Image 4), trucks that have attached a device that can make the ground vibrate. Using the same principle that doctors use to see babies in the womb (ultrasound), an engineer would make the truck shake the ground and study the reflection of the vibrations back up to the surface(like a bat uses echolocation). This is still a technique in research, but once it's standardized (when researchers find a specific way for it to work every time), it would help a lot to identify the ground and not make any holes in it.

Image 4. Photo of Large-Scale Mobile Shaker (*UT Austin, n.d.*)

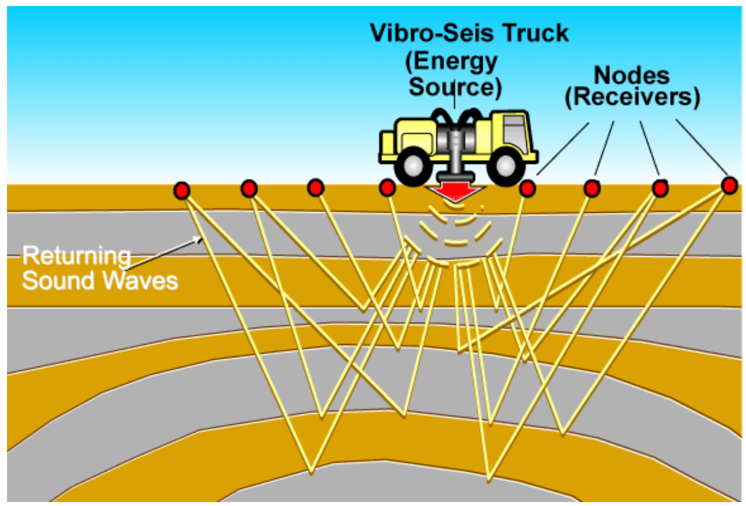

Image 5. Ground Layers Identified by Mobile Shaker (*Seismic Reflection Survey, n.d.*)

Procedure

Natural Frequency

1. Play the videos in the folder named "Natural Frequency" in order. They will show how a yard stick made of metal, wood, and plastic vibrate at 10", 15", 20", 30" mark (this is the measurement of the part that is being held on top of the table). The last one, will show a small wooden ruler vibrating at 10" and 5" mark.
2. Analyze with the students how the natural frequency changes. You can study this with the way it moves (the up and down motion), and the sound it makes.
3. Using the flexible ruler, put the mark at 10" at the border of the table (from 1 to 10 should be on the outside of the table, the rest on top of the table) and pluck the free end. Analyze the vibration.
4. Move the ruler to the 5" mark and pluck it again. Analyze the vibration.
5. Conclude how the stiffness and length of the rulers affects the natural frequency at which it vibrates and the sound it produces. (Stiffer materials and shorter lengths produce faster vibrations, or higher natural frequencies, and higher pitches)

The Material Xylophone (check how to make it in the appendix 1)

1. Using the mallet, hit the foam key. Analyze the sound. (Tip: since the foam has a lot of bubbles in the inside, they act as a damper and affect the stiffness of the material and its density, which in turn affect the way it vibrates).
2. Using the mallet, hit the Styrofoam key. Analyze the sound. (Tip: although the Styrofoam has a lot of air inside, these bubbles are smaller, which makes it stiffer, which lets it vibrate more and at a slightly higher pitch than the foam).
3. Using the mallet, hit the wooden key. Analyze the sound. (Tip: this would be the first real solid material, although wood has bubbles as well, but they are the size of cells, producing a stiffer material, and thus a higher pitch than the foams).
4. Using the mallet, hit the metal key. Analyze the sound. (Tip: depending on the type of metal you have used, you will get a different pitch, but all of them will be higher than the wood. This is because metal doesn't have bubbles).
5. Each group, using the mallets provided and the prepared resonant samples, will need to hit each of them and analyze the sound.

Ground Layers

1. Take each key of the material xylophone and stack it. Tell students that each key represents a layer of the soil.
2. Using the handle of the mallet, show how would a Soil Core be taken (explain that the machine makes the rod go through the ground getting a sample of it in the same order as is seen in the stack).
3. Using the handle of the mallet, show how a CPT test would be done (explain that as the machine makes the rod go through the ground, the tip of it hits each of the layers, which depending on their puncture resistance, would help identify the soil type).

Image 6 Identifying soil layers by the Cross-hole technique.

4. Using the handle of two mallets, show how the Cross-hole testing would work (putting the handle of both mallets at opposite ends of the same layer explain that when one rod is hit by the hammer, it is as if the material layer was hit from one side and the other mallet would record the wave).
5. Show that the stack can change, which represents the different layers in the ground that can be found at different locations. Highlight the importance of identifying water saturated sandy soils, represented by the foam layer and their liquefaction effect (to better explain this effect, refer to the Liquefaction lesson).

Assessments

Assessment can be found, along with required sound recordings, within the “Material Xylophone” folder.

Students will have successfully understood the lesson if they are able to properly identify that high pitches relate to higher stiffnesses and lower pitches will relate to lower stiffnesses.

Appendix

Appendix 1. MATERIAL XYLOPHONE

We will use aluminum, wood, Styrofoam, and a stiff foam. If you have materials of similar consistency, it is fine to swap them. Each material was obtained/cut to a thickness of 3.1 cm or 1.2 inches, 5,2 cm or 2.05 Inches, and a length of 25.2 cm or 10 inches. This will give you a rectangular bar similar to that of a xylophone.

The base in this case was built using plywood for the frames and a wood bar for the rails with the following measurements:

- Frames (27.8 cm or 11 inches long, 6.3 cm or 2.5 inches tall, using a 1.8 cm or 0.7 inches thick board)
- Rails (25.5 cm or 10 inches long, using a 3.3 cm or 1.2 inches thick and tall bar)

Each rail had small dents made with a drill which were filled with hot glue. This process helps to ensure that each bar would rest on four dots of hot glue at the position that it was going to be placed (image 7).

 

Image 7 Resting silicon dots for bars **Image 8** Platform, bars, and mallet for xylophone

Once the bars and base are finished, place the bars following the the pattern shown in image 9.

Image 9 Material xylophone

Appendix II. 1985 MEXICO CITY EARTHQUAKE

Although the epicenter of the Mexico City earthquake was over 200 miles away, the damage that occurred to the city was devastating. Due to Mexico City being built on an old lake bed with loose sediments, the ground motion measured “five times the movement as the outlying cities of different [firmer] soil type.” (Britannica, n.d.). The soft soil beneath Mexico City shook with a natural period of around 2 seconds (note, natural period is related to the inverse of natural frequency). The shaking of the ground caused resonance in buildings with the same 2 second natural period as soil, which led to lots of damage. Buildings that were 5-15 stories tall were the most affected by the earthquake, as they had natural periods similar to the period of the ground shaking, while buildings that were smaller and larger were largely unaffected due to the difference in natural frequency.

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