ShakeAlert
Version of activity from:
IRIS
www.iris.edu/earthquake

Building Shaking —Variations of the BOSS Model*

Modeling the effect of resonance on buildings during an earthquake

Incorporated Research Institutions for Seismology (www.iris.edu/earthquake)
Activity modified with permission for ShakeAlert (www.shakealert.org).

Introduction

Why do buildings of different heights respond differently in an earthquake? All buildings have a natural frequency of oscillation. Shorter buildings have a different frequency than taller buildings. If a seismic wave has an extended rolling motion at the same frequency of a building, the structure will begin to sway back and forth with increasing amplitude. This effect is called resonance. The amplitude of building motion during an earthquake can increase to the point where the structural integrity of the building is compromised. Buildings can be engineered to withstand predicted oscillations without damage.

Building Oscillation Seismic Simulation (BOSS) is an opportunity for students to explore the phenomenon of resonance while performing a scientific experiment that employs mathematical skills. The students are intrigued by a discrepant event involving the BOSS Model, and are then set to work experimenting with the factors that affect the natural frequencies of structures.

The BOSS Model can be presented as a whole class demonstration, and/or used for a full student lab activity.

Objectives

Learners will:

- Explain the relationship between building height and natural frequency.
- Describe the phenomenon of resonance.

Time: 5-45 Minutes

Target: Grade Level: 6-12

Subjects: Natural Hazards, Earthquakes, Mitigation and Preparedness, Geoscience, Engineering

Materials: Resonance model (see p. 3 for options) timing device, ruler (optional), handout (Word version at https://serc.carleton.edu/ANGLE/educational_materials/activities/205641.html

Relevant Media Resources

Video:

Demo of the concept using BOSS Model **E**:
www.iris.edu/hq/inclass/video/183

How to Build the BOSS Model **E**:
www.iris.edu/hq/inclass/video/182

Animations:

Building Resonance: Why do certain buildings fall in earthquakes?"
www.iris.edu/hq/inclass/animation/224

How do we capture the motion of an earthquake?
www.iris.edu/hq/inclass/animation/115

Southern Mexico -- Earthquakes & Tectonics
www.iris.edu/hq/inclass/animation/235

***A.** Spaghetti & raisins* *B. Manila file and clips* *C. Construction paper rings* *D. Balls on dowels* *E. Blocks on dowels*

Figure 1 A–E: Five different models for demonstrating resonance in the classroom. The following pages will describe the preparation and includes external links to videos and lessons.

* Building Oscillation Seismic Simulation (Original activity from FEMA's Seismic Sleuths (link on next page.)
NOTE: This activity has been modified to include activities from several sources for ShakeAlert education and outreach.

Instructor Preparation

First, review Page 3 to decide which oscillation model fits both your class time, as well as preparation time. Although the **BOSS model "E"** takes the most time to construct, it is the most effective. You can do the activity as just a classroom demonstration (*practice before class!*), and/or as a student lab activity.

Second, assess what learners already know about the concepts of amplitude, frequency, and resonance. If they are not familiar with these terms, introduce them by building on what learners already know. A child's swing is a an effective common example to use to describe all of these terms.

Third, review the terms and concepts introduced in this lesson. Explain that seismic waves caused by earthquakes produce oscillations, or vibrations, in materials with many different frequencies. Every object has a natural rate of vibration that scientists call its natural frequency. The natural frequency of a building depends on its physical characteristics, including the design and the building material. Resonance is a buildup of amplitude in a physical system that occurs when the frequency of an applied oscillatory force is close to the natural frequency of the system. In the case of an earthquake, the ground shaking may be at the same frequency as the natural frequency of a building. Each vibration in the ground may come at or dangerously close to the natural frequency of the structure.

Fourth, ask the class to hypothesize what would happen when you oscillate the BOSS model. Learners invariably think the tallest building will wobble most. Wiggle the model so that the shorter building vibrates the greatest (practice a lot before demonstrating). Ask students to predict again, then make the middle-height building shake.

Fifth , discuss the model. Ask students: 1) What does the wooden base represent? 2) What do the standing blocks represent? 3) What does the shaking back and forth represent? Discuss how energy moves through the system: kinetic energy moves from your hand to the base, to the rods and blocks. As you demonstrate different frequencies, ask students to decide which building has the greatest amplitude? Which building resonates at the greatest wavelength, and which at the least wavelength?

Extensions:

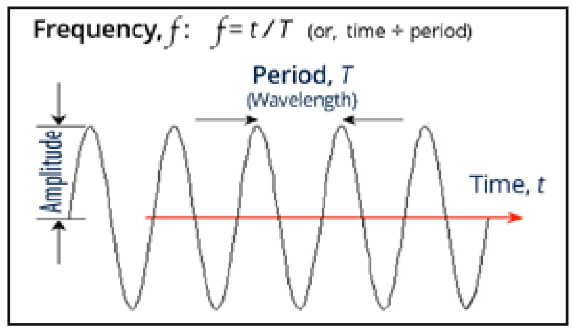
- Protecting buildings from resonance using ***Base Isolation*** (see https://serc.carleton.edu/ANGLE/educational_materials/activities/205647.html)
- Investigating better building design to include shear strength in the ***Build a Better Wall*** activity (see https://serc.carleton.edu/ANGLE/educational_materials/activities/205638.html)

VOCABULARY

(from FEMA's Seismic Sleuths)

Amplitude: a measurement of the energy of a wave. Amplitude is the displacement of the medium from zero or the height of a wave crest or trough from a zero point. (In this activity it's how far to the side the block moves.)

Frequency: the rate at which a motion repeats, or oscillates. The frequency of a motion is directly related to the energy of oscillation. In this context, frequency is the number of oscillations in an earthquake wave that occur each second. In earthquake engineering, frequency is the rate at which the top of a building sways. The natural frequency of a building depends on its physical characteristics, including the design and the building materials. mic waves that produce oscillations, or vibrations, in materials with many different frequencies.



Hertz (Hz): the unit of measurement for frequency, as recorded in cycles per second. When these rates are very large, the prefixes kilo or mega are used. A kilohertz (kHz) is a frequency of 1,000 cycles per second and a megahertz (MHz) is a frequency of 1,000,000 cycles per second.

Oscillation or vibration: the repeating motion of a wave or a material—one back and forth movement (period).

Period: the amount of time it takes one wave cycle to pass the given point. All buildings have a natural period, or resonance, which is the number of seconds it takes for the building to naturally vibrate back and forth.

Resonance: an increase in the amplitude (in this case, the distance the top of a building or other structure moves from its rest position) that occurs when the frequency of the oscillation of the seismic waves is close to the natural frequency of the system.

Resonant frequency: the frequency at which the maximum-amplitude oscillation occurs.

Figure 2 A–E: *Five demonstrations in order of ease of preparation; includes links to video demonstrations and as well as detailed descriptions the lessons.*

A: *The simplest and most spontaneous way to demonstrate the concept of resonance and building height uses uncooked* **spaghetti** *and small weights (raisins or marshmallows). This is the quickest to assemble.*

VIDEO: www.iris.edu/hq/inclass/video/184

LESSON: www.exploratorium.edu/snacks/spaghetti-resonance

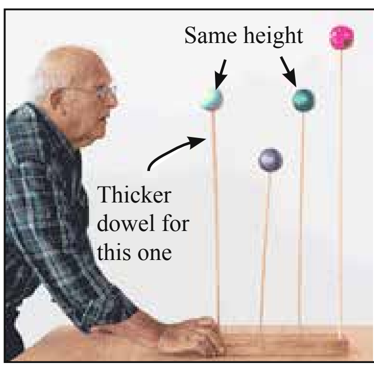
B: *This version from the* **Exploratorium** *in San Francisco uses rings of construction paper to graphically demonstrate that objects of different sizes and stiffness tend to vibrate at different frequencies.*

LESSON: www.exploratorium.edu/snacks/resonant-rings

C: *This "BOSS Lite" model uses manilla folders. This has the advantage of looking more like buildings; you could even draw windows on them. Because of the different weight of manilla folders, we found we had to experiment with doubling up the files as they were too floppy.*

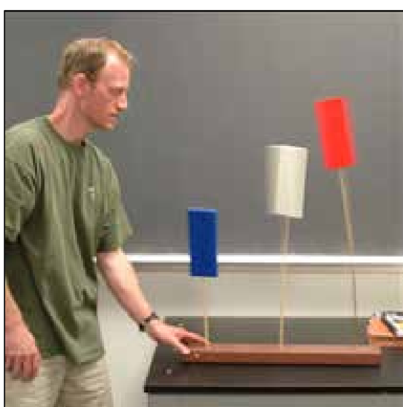
VIDEO: www.iris.edu/hq/inclass/video/185

LESSON: www.iris.edu/hq/inclass/lesson/373



D: *In this version from the* **Exploratorium**, *wooden dowels of varying lengths are used. One dowel is thicker than the other three, but the same length as the third dowel as shown in the photo. Each dowel is loaded with the same mass (ball). When the vibration matches the resonant frequency of a particular dowel (length & diameter), that dowel will vibrate with a greater amplitude.*

LESSON: www.exploratorium.edu/snacks/resonator



E: *This original "BOSS" model is more involved to construct, but will be a permanent tool for the classroom. Lesson includes a rigorous investigation wherein learners measure the natural frequencies of different height rod assemblies and correlate these motions to buildings and earthquakes. Learners use mathematical skills to perform a scientific experiment.*

VIDEOS: Demonstration: www.iris.edu/hq/inclass/video/183
How to Build the Boss Model: www.iris.edu/hq/inclass/video/182

LESSON: FEMA's Seismic Sleuths activity can be found in Section 4.3, page 247 of: www.fema.gov/media-library-data/20130726-1646-20490-4697/fema253.pdf

APPENDIX A—EXAMPLE OF RESONANCE

Tall and Short Buildings Stood—Middle-size Buildings Fell

1985 Mexico City quake kills 10,000

On September 19, 1985, a magnitude 8.1 earthquake occurred off the Pacific coast of Mexico. 350 km (217 miles) from the epicenter; damage was concentrated in a 25 km^2 ($9mi^2$) area of Mexico City. The underlying geology contributed to this unusual concentration of damage at this relatively far distance from the epicenter. An estimated 10,000 people were killed, and 50,000 were injured. In addition, 250,000 people lost their homes. The set of slides (link below), shows different types of damaged buildings and the major kinds of structural failure that occurred in this earthquake, including collapse of top, middle and bottom floors and total building failure.

Interestingly, the short and tall buildings remained standing. Medium-height buildings were the most vulnerable structures in the September 19 earthquake. Of the buildings that either collapsed or incurred serious damage, about 60% were in the 6-15 story range. The resonance frequency of such buildings coincided with the frequency range amplified most frequently in the subsoils.

To see a slide show for the earthquake, go to the NOAA website:
Earthquake Damage in Mexico City (https://tinyurl.com/y945a3uu)

Image of buildings that were vulnerable during the Mexico City earthquake (from the NOAA slide show; link at left). This is described in two IRIS animations:

- "*Southern Mexico—Earthquakes & Tectonics*" www.iris.edu/hq/inclass/animation/235.
- *Building Resonance: Why do certain buildings fall in earthquakes?*" www.iris.edu/hq/inclass/animation/224.

APPENDIX B—NGSS SCIENCE STANDARDS & 3 DIMENSIONAL LEARNING

Motion and Stability: Forces and Interactions

MS-PS2-2 Plan an investigation to provide evidence that the change in an object's motion depends on the sum of the forces on the object and the mass of the object.
http://ngss.nsta.org/DisplayStandard.aspx?view=pe&id=149

Science and Engineering Practices

Planning and Carrying Out Investigations

Planning and carrying out investigations to answer questions or test solutions to problems in 6–8 builds on K–5 experiences and progresses to include investigations that use multiple variables and provide evidence to support explanations or design solutions.

- Plan an investigation individually and collaboratively, and in the design: identify independent and dependent variables and controls, what tools are needed to do the gathering, how measurements will be recorded, and how many data are needed to support a claim. (MS-PS2-2)

Connections to Nature of Science

Science Knowledge Is Based on Empirical Evidence

- Science knowledge is based upon logical and conceptual connections between evidence and explanations. (MS-PS2-2)

Disciplinary Core Ideas

PS2.A: Forces and Motion

- The motion of an object is determined by the sum of the forces acting on it; if the total force on the object is not zero, its motion will change. The greater the mass of the object, the greater the force needed to achieve the same change in motion. For any given object, a larger force causes a larger change in motion. (MS-PS2-2)
- All positions of objects and the directions of forces and motions must be described in an arbitrarily chosen reference frame and arbitrarily chosen units of size. In order to share information with other people, these choices must also be shared. (MS-PS2-2)

Crosscutting Concepts

Stability and Change

- Explanations of stability and change in natural or designed systems can be constructed by examining the changes over time and forces at different scales. (MS-PS2-2)

Name: ____ Date: __________ Period: ______

Swaying Buildings

Using the BOSS Model to model the effect of resonance on buildings during an earthquake

Essential Question: How does rod (“building”) height effect the natural frequency?

Background Information

Earthquakes generate energy in the form of seismic waves. Like any mechanical wave, seismic waves are vibrations that can be described with quantities such as ***frequency*** (the number of vibrations per second), ***period*** (the seconds per vibration), and ***amplitude*** (the maximum displacement of the particles of the medium). These seismic waves travel for great distances before finally losing most of their energy. At some time after their generation, these seismic waves will reach the earth's surface, and set it in motion.

When an earthquake causes strong enough ground motion beneath a building, seismic waves will set the building in motion, starting with the building's foundation, and transferring the motion throughout the rest of the building in a very complex way. These motions in turn induce forces that can produce damage. The variety of ways a building responds to earthquake ground motion is the most important cause of earthquake-induced damage to buildings.

Every object has a natural rate of vibration that scientists call its natural frequency. The natural frequency of a building depends on its physical characteristics, mainly its height, but also including other design aspects and the building materials. When a building is set in motion by earthquake waves, it can sway from side to side, and that frequency of motion can be measured. If the building continues to receive an applied force from seismic waves that matches the natural frequency of the building, the amplitude of the swaying will continue to increase. This effect is called ***resonance***, when an object receives repeated pushes at its natural frequency, causing an increase in amplitude. Pushing a swing is a common example of resonance.

The characteristics of earthquake ground motions that have the greatest importance for buildings are the duration, amplitude (of displacement, velocity and acceleration) and the frequency of the ground motion. In particular, if the frequency of ground motions matches the natural frequency of a building, the amplitude of the building’s swaying motion can increase until the structural integrity of the building is overcome.

Materials:

BOSS model, timing device, *optional*: ruler to measure displacement when beginning oscillations

SAFETY NOTE: Be careful when handling the “buildings” in the BOSS model. Be careful not to break the dowel portions by pulling the blocks too far from their vertical position.

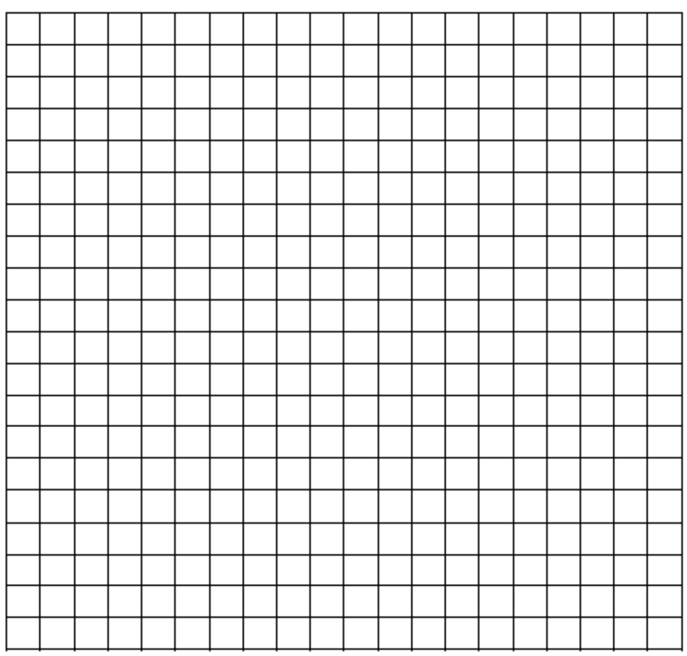
Write a hypothesis before beginning the activity:

Procedure:

1. Measure the height (cm) of each “building” from the base to the top, and record it in Table 1.
2. Hold the base stationary, pull the tallest “building” (wooden block) out several centimeters to the side, and release it. Be sure it does not hit the adjoining blocks as it oscillates. As the “building” oscillates, you will use a stopwatch to measure the time for 5 oscillations. Record this number in the correct column below. Practice this until your times for 5 oscillations are fairly close to each other.
3. Repeat step 2 two more times. Record your data in Table 1 below.
4. Calculate the average time for 5 complete oscillations, or cycles. Record in Table 1.
5. Calculate the period (seconds/cycle) by diving the total time by 5. Calculate the natural frequency of the building by dividing 5 by the average oscillation time (units are Hz, of 1/s). Note that these quantities are reciprocals. Record these values in Table 1.
6. Repeat steps 2-5 for the other two blocks.
7. Plot the building height versus natural frequency of each building on the graph provided. Consider which variable is the independent variable, and which is the dependent variable. Label the graph correctly and include a best-fit line.

Table 1

Building	**Building height** (cm)	**Time for 5 cycles** (oscillations)			**Avg. time for 5 cycles** (s)	**Avg. period** (s/cycle)	**Avg. frequency** (Hz = cycles/s)
		Trial 1	Trial 2	Trial 3			
Tall							
Medium							
Short							



Questions (*answer on a separate piece of paper):*

1. Identify and describe two variables that were controlled in this experiment.

2. Describe the relationship between the variables you plotted, citing evidence from the graph.

3. Write a conclusion statement, answering the essential question and citing your data. Evaluate your hypothesis.

4. Make a claim, based on evidence from your investigation, about how resonance can increase the damage done to buildings during earthquakes.

5. On September 19, 1985, a magnitude 8.1 earthquake occurred off the Pacific coast of Mexico. Extensive damage caused by this earthquake was concentrated in an area of Mexico City, 350 km from the epicenter. Interestingly, medium-height buildings were the most commonly damaged, while short and tall buildings remained standing. Citing evidence gathered in this investigation, explain why buildings of different heights standing next to each other could experience very different outcomes during an earthquake.

6. Read more about the damage caused by the 1985 Mexico City earthquake provided by National Oceanic and Atmospheric Administration (NOAA) at https://tinyurl.com/y945a3uu. Table 2 provides a summary of the natural period of typical buildings, based on their height in stories. Citing evidence from the NOAA website and Table 2, make a claim about the seismic waves that impacted Mexico City in 1985.

Table 2

Building Natural Periods	
Number of Stories	Natural Period (s)
2	0.2
5	0.5
10	1.0
20	2.0
30	3.0
50	5.0

Swaying Buildings – Rubric/KEY

Using the BOSS Model to model the effect of resonance on buildings during an earthquake

Essential Question: How does rod ("building") height effect the natural frequency?

Hypothesis: Example - If the height of the rod increases, then the natural frequency at which the rod resonates will increase. I predict this relationship will be linear.

Questions:

1. Controlled variables could include: the material rods are made of, diameter of rods, number of cycles/oscillations measured, the size and mass of the wooden block, the timing device, etc.

2. Students should graph building height (independent variable) on the x-axis and natural frequency (dependent variable) on the y-axis. The relationship should be fairly linear, that natural frequency is directly proportional to building height. Students can provide a best-fit line as evidence of this relationship.

3. Students cite the data in their table and graph to conclude that the natural frequency of buildings increases proportionally with increasing building height.

4. Example – Seismic waves will jostle buildings, but if the jostling is not at the natural frequency of the building, the amplitude of the resultant building motion is less likely to exceed the building strength. However, if a building receives repeated periodic pushes from seismic wavs at the natural frequency of the building, the building will begin to sway with greater and greater amplitude, which is resonance. The greater the amplitude of motion, the more forces are put on the building, and the more likely that the structural strength of the building materials will be overcome, causing the building to collapse. Since buildings will have different natural frequencies that depend on their height, it is possible for some buildings to resonate seismic waves of a certain frequency, while neighboring buildings of a different height do not.

5. According to the NOAA website, 60% of the most damaged buildings were in the 6-15 story range. The NOAA page states "the resonance frequency of such buildings coincided with the frequency range amplified most frequently in the subsoils." From this information, it appears that seismic waves in the period of 0.5 – 1.5 (from Table 2) were most amplified by the soils in the area, causing shaking at the frequencies that coincided with the natural frequency of the "medium" height buildings in the city.