ShakeAlert® activities for formal and informal learning settings

Building Shaking—Variations of the BOSS* Model

Modeling the effect of resonance on buildings during an earthquake

Version 04/07/21

Pasta and paper rings activities modified with permission from the Exploratorium; BOSS Model modified from FEMA

This interactive activity explores how buildings *oscillate* during an earthquake (Vocabulary, Appendix A). If a seismic wave has a rolling motion at the same frequency of a building, the structure will sway back and forth during the seismic vibration. This phenomenon is called *resonance*, and the frequency at which this *oscillation* happens is called the *resonant frequency* (example in Appendix B). The *resonant frequency* of a building depends on its architectural design, height (how many stories), and construction materials. Buildings engineered with earthquake shaking in mind can better withstand resonance without serious damage.

In the 5-minute option, we use spaghetti as a medium to explore resonance and how an object can withstand shaking. In the 15-minute activity, learners explore how buildings can have more than one resonant frequency. Finally, in the 30- to 45-minute option, learners will determine the resonant frequency of buildings with different heights and then predict how that building would sway in an earthquake. For a quick overview of resonance, watch this short video (Figure 1) that uses the 30-min option.

Why is it important to learn about how human-made structures fare during an earthquake? More than 143 million people are exposed to potential earthquake hazards in the U.S. that could cost thousands of lives and billions of dollars in damage. An understanding of building resonance is fundamental to mitigating earthquake hazards. An important tool for mitigation is the ShakeAlert® Earthquake Early Warning System for the West Coast of the United States which detects significant earthquakes quickly so that alerts can be delivered to people and automated systems often before strong shaking arrives.

Beginner

5 min | 15 min | 30–45 min

Large Group

Demo | Materials

Time: 5-, 15- and 30- to 45-minute guided activities, which can be adapted for your audience.

Audience: Can be done with novice geoscience learning groups. It can also work for informal education or public outreach venues as a demo or interactive activity.

OBJECTIVES

Learners will be able to:

- Explore the concept of resonant frequency for different building heights.
- Investigate how seismic energy enters a structure and how resonance affects building oscillation.
- Explore how engineering design principles help mitigate damage to structures during an earthquake.

TABLE OF CONTENTS

* *Building Oscillation Seismic Simulation*

MATERIALS, TOOLS, AND CONSTRUCTION

You will need multiples of these materials depending on how many small groups of learners you have.

5-minute activity—for each learner or learner group:

- 5-8 strands of dry spaghetti
- 3 mini marshmallows, raisins, or small balls of clay

15-minute activity—for each learner or learner group:

- Large sheet of construction paper measuring about 14 × 20 inches (35 × 50 centimeters); alternatively, use strips of construction paper ranging in size from roughly 1 x 8 in (2.5 x 25 cm) to 1 x 20 in (2.5 x 50 cm) in a variety of colors
- Sheet of cardboard that is 12 in (30 cm) long and several inches (15–20 cm) wide or thick cardstock (manila file folder)
- Ruler
- Scissors
- Tape

30- to 45-minute activity—for each learner group:

- BOSS Model materials:
  - 2x4" wood, cut 24" long
  - 3 pieces of 1x4" wood, cut 8" long
  - 3 pieces of ¼" dowels cut 14", 18", and 22" long
  - 2 felt pads about 4" long
  - (Optional) Cut several extra dowels of each length for spare parts
  - (Optional) Paint (different colors for the 3 blocks)
- Tools to build the model:
  - Electric drill
  - ¼" drill bit (dowel size)
- Meter stick
- Stopwatch
- Graph paper, or use a computer graphing tool
- Poster of "*Violence of Ground Shaking Caused by 3 Types of Earthquakes*" in Appendix C. (Poster size is preferred, or a photocopied enlargement.)
- USGS publication "*Reducing Earthquake Losses Throughout the United States: Monitoring Earthquake Shaking in Buildings to Reduce Loss of Life and Property*"
- Learner Worksheets (additional copies if learners work independently) Appendix D.

Construction of BOSS Model

Each group of learners should have their own BOSS model. For more information, watch this video on BOSS model construction. See Figure 1 for completed model.

For the base:

- Drill a hole vertically one inch deep into the center of a 2x4", 24" length of wood.
- Drill two additional vertical holes 3" in from the ends of the board.
- On the bottom surface of the board, attach a felt strip crosswise on the board to allow the board to slide more easily on a table surface.

To complete the assembly:

- Drill a hole vertically one inch deep into the center of the 1x4" end of each of the three 8" painted wooden blocks. (These are the buildings.)
- (Optional) Paint the small blocks different colors.
- Insert each dowel of different lengths into the end of each block.
- Insert the dowel and block arranged by height into the wooden 2x4" base.

RELEVANT MEDIA SOURCES

Videos:

5-minute demonstration:

- Resonance: Modeling Resonance in Buildings using Spaghetti Noodles (start at 1:21)

30- to 45-minute activity:

- Building Resonance: BOSS model Construction & Use

Animations:

- Building Resonance: Why do certain buildings fall in earthquakes? (5:30)
- Buildings in Earthquakes: How does construction affect the shaking you feel? (6:29)
- How do we capture the motion of an earthquake? (2:53)

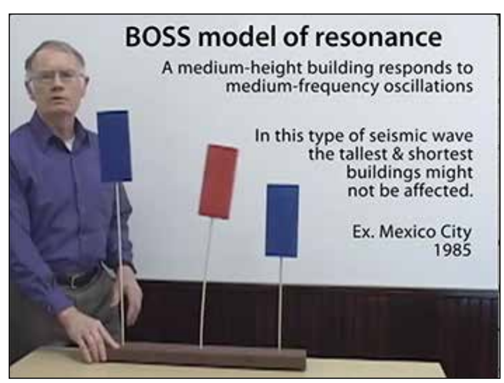


Figure 1 (right): Dr. Robert Butler demonstrates the BOSS model. Image is a screen capture from the "Building Resonance" video.

INSTRUCTOR PREPARATION

Please review the Instructor Background in Appendix E, which covers the basic concepts of resonance and frequency. Additionally, familiarize yourself with the model and concepts by watching the videos and animations listed in the "Relevant Media Sources" (previous page). NGSS standards for these activities are found in Appendix F.

For the 5- minute activity:

a) Gather the materials needed for each learner/learner group

b) Review the video resource

c) Review the vocabulary terms

For the 15- minute activity:

a) Gather the materials needed for each learner/learner group

b) Review vocabulary terms

For the 30- to 45-minute activity:

a) Construct each BOSS Model before class, enough for each learner group

b) Review video resources

c) Review vocabulary terms

d) Review background materials in Appendices C - F

ACTIVITIES AND DEMONSTRATIONS

IF YOU HAVE 5 MINUTES

Did You Know?

- Did you know that many objects will vibrate at specific frequencies?
- Did you know that an earthquake can make buildings sway back and forth?

We will use spaghetti as a medium to explore how buildings sway at specific frequencies (Figure 2).

Figure 2: A piece of spaghetti with a small marshmallow will oscillate (move side to side) at its natural frequency if the tip is pulled back and then released. Image modified from Pasta Resonance.

We will demonstrate how the resonant frequency of an object (the frequency at which an object sways, based on its height and other factors) can dramatically affect its ability to withstand shaking. Spaghetti will illustrate the principles that apply to buildings and bridges.

The effects of shaking on the spaghetti strand can be observed in the following ways:

1. If we apply the motion of an earthquake to the spaghetti strand, in sync with the spaghetti's natural frequency, the amplitude (or amount of swaying motion), will increase. This phenomenon is called resonance, and the frequency at which this oscillation happens is called the resonant frequency.
2. If the motion applied from an earthquake continues for a long time, the swaying will eventually exceed the material strength of the spaghetti and cause it to break.

The following two short demonstrations (Parts 1 and 2) illustrate an object's natural frequency of motion.

Part 1:

Explore how different lengths of spaghetti strands vibrate when you pull them. Compare your observations to what happens when buildings of different heights shake during an earthquake.

Directions

Note: Introduce new vocabulary (Appendix A) to meet your learner's needs.

1. Push a small marshmallow (or raisin or clay) onto the ends of three different lengths of spaghetti about 12", 10½" and 9" long. Each strand represents a building of different height.
2. Hold all three pieces of spaghetti together between your thumb and forefinger, with the end of the spaghetti with the marshmallows separated about an inch apart from each other (Figure 3).
3. With your free hand, and without breaking the strands of spaghetti, pull back

Figure 3: Hand holding 3 pieces of spaghetti with raisins on top. Screen capture from video demonstration.

the marshmallow end of each piece of spaghetti several inches and then release it. (Do not move the hand holding the spaghetti.)

4. Notice how far the end of each piece of spaghetti sways back and forth, at different frequencies (the number of times the spaghetti vibrates back and forth each second), revealing the natural frequency of each length of spaghetti.

Questions for Discussion:

- Which length of spaghetti swayed back and forth the farthest? (*The longest length swayed the farthest.*)
- Which length of spaghetti swayed the fastest or slowest? (*The shortest length swayed faster than the longer lengths. The longest length was the slowest.*)

Part 2:

Explore how the frequency of shaking can affect the amplitude of vibration for the spaghetti of different heights.

Directions:

1. Hold new long, medium and short pieces of spaghetti with small marshmallows on each (in one hand) as you did in Part 1, Step 2.
2. Gently, begin shaking the three pieces of spaghetti at varying speeds. Observe how each length of spaghetti responds. As you change the speed of shaking, you will notice the sway of motion increases and decreases on different strands of spaghetti.
3. See if you can make each piece of spaghetti sway, one at a time just by changing how fast you shake the pieces.

Questions for Discussion:

- If each length of spaghetti represents different heights of buildings in an earthquake, which height would be most affected by slower moving seismic shaking? (*The longest piece of spaghetti, or taller buildings.*)
- Which buildings would be most affected by faster moving seismic shaking? (*The shortest piece of spaghetti, or shorter buildings.*)
- As the speed of shaking changes, one length of spaghetti, which had been swaying back and forth slows or stops moving even though energy is still entering the system. Why is this happening? (*Shaking the spaghetti in sync with that strand's natural frequency will cause it to sway more. This effect is called resonance. Shaking the spaghetti out of sync with that strand's natural frequency will cause it to sway less. This effect is called dampening. See inset upper right.*)

Tuned Mass Dampers

The principle of dampening is demonstrated in seismic engineering design with a system known as a Tuned Mass Damper (TMD; Appendix A and Figure 4). For more information about a TMD system watch this video: Seismic Engineering: What is a Tuned Mass Damper? (to view the dampening effect, start at 4:06)

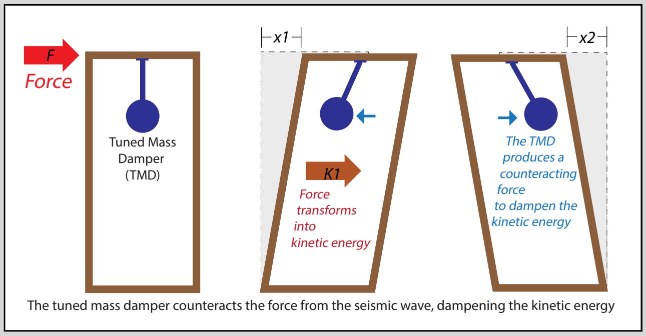


Figure 4: Tuned Mass Damper (TMD) in a high-rise building. The TMD counteracts the force (F) from the seismic waves dampening the kinetic energy. The damper will resonate out of phase with the structural motion to attenuate the vibrations providing seismic resilience. When the structure starts to sway (displacement x1), it generates energy (K1). That sets the TMD in motion and makes the building respond in the opposite direction (x2).

Going Further

Try shaking a single piece of spaghetti to make it vibrate.

Continue to add more energy to the spaghetti and observe how the swaying motion (or amplitude of shaking) increases. The continued shaking increases the amplitude of oscillation, making it respond at a resonant frequency of the strand.

Continue to shake the spaghetti strand until it breaks. This happens because the motion continues, weakening the pasta until its material strength is exceeded and the spaghetti strand breaks.

Did you know that the ground also has a specific resonant frequency when seismic waves pass through it? Hard bedrock has higher resonant frequencies than softer sediments. If the ground is moving in sync with the building's natural frequency, then the amplitude of the back-and-forth swaying of the building will increase, eventually causing damage. The natural frequency of a building will differ depending on its height, size, shape, and construction.

IF YOU HAVE 15 MINUTES

Did You Know?

- Did you know that an object can have more than one resonant frequency?

Learners now create a series of rings that increase in size and are made from construction paper. Tape each ring to a cardboard base from smaller to larger diameter (Figure 5). When the rings are shaken back and forth, each ring will vibrate at more than one frequency, but the shape of each ring will differ for each resonant frequency. Taller buildings also will undergo several modes of vibration (Figure 5-7).

Figure 5: Resonance Rings made from construction paper. Image from the Exploratorium.

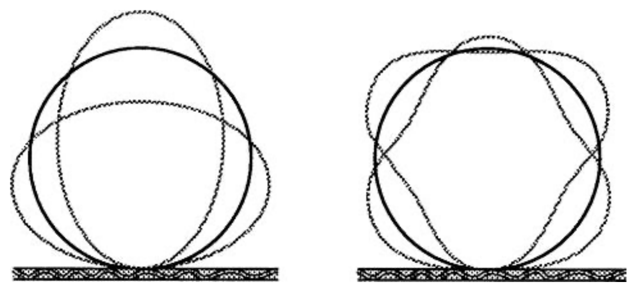


Figure 6: The speed of shaking or oscillation causes the shape of each ring to be different for each resonant frequency.

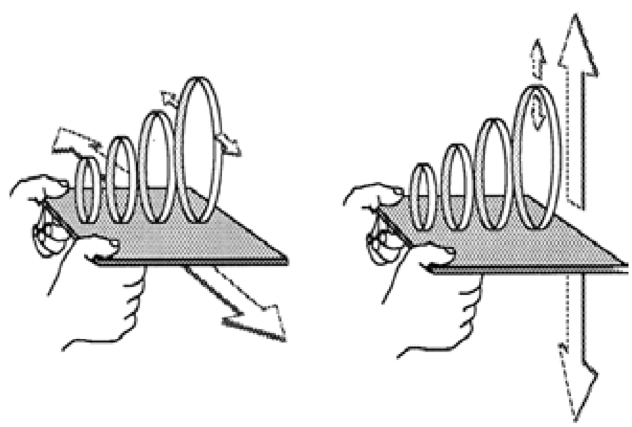


Figure 7: The direction of shaking will also cause the shape of each ring to be different for each resonant frequency.

Directions:

1. Cut four or five 1″ (2.5-cm) wide strips from the construction paper. The longest strip should be about 20″ (50 cm) long, and each successive strip should be about 3″ (8 cm) shorter than the preceding one.
2. Form the strips into rings by taping the two ends of each strip together.
3. Tape the rings to the cardboard sheet as shown in Figure 5.
4. Shake the cardboard sheet back and forth. Start at very low frequencies and slowly increase the frequency of your shaking. Point out that buildings actually have multiple resonant frequencies.

   Questions for Discussion:

   - What do you notice about how the rings vibrate or oscillate at different frequencies? (*Each ring oscillates at a different frequency*.)
   - Which ring oscillates first (at the slowest speed and frequency)? (*The largest followed by the second largest until the smallest ring*.)
   - Which ring oscillates at the highest frequency? (*the smallest ring*)

5. Keep shaking the cardboard faster and faster while observing the shape of each ring as it oscillates at a speed faster than in Step 4.

   Questions for Discussion:

   - What did you notice about what happened to the largest ring? (*The largest ring started to oscillate again, at about twice the speed of shaking.*)
   - What did you notice about the shape of each ring as you increased the speed of shaking (Figure 6)? (*The shape of each ring was different for each resonant frequency*.)

6. Now, shake the board up and down instead of sideways (Figure 7).

Questions for Discussion: (See inset below.)

- In what ways did the rings move differently when shaken up and down? (*Each ring still had a different resonant frequency depending upon the speed of shaking*.)
- In what ways is shaking the board up and down or sideways similar or different to the way seismic waves would shake a building? (*Buildings can shake up and down as well as side to side during an earthquake*.)
- What other factors do you think would affect the amount of shaking to a building? (*The distance from the epicenter, the ground under and around it, and the construction materials that are used in the building.*)

What's Going On?

The resonant frequency of each ring is determined by its mass and stiffness, which is determined by the construction materials and design. The biggest ring has the largest mass and the least stiffness. The mass and stiffness are determined by the lowest resonant frequency. The largest ring takes more time than the smaller rings to respond to an accelerating force. During earthquakes, two buildings of different sizes may respond very differently to the earth's vibrations, depending on how well each building's resonant frequencies match the "forcing" frequencies (the frequencies that are causing the buildings to sway) of the earthquake.

IF YOU HAVE 30 TO 45 MINUTES

Did You Know?

- Did you know that you can determine the resonant frequency of buildings with different heights and then anticipate how that building would sway in an earthquake?

In this version of the BOSS model, mount three wooden blocks on dowels of different lengths and secure them to a wooden base (Figure 1). Learners work in small groups and explore the concept of resonance with activities that quantify the resonant frequency of buildings of different heights. Learners also explore how different types of earthquakes that range from shallow crustal earthquakes to deeper subduction zone earthquakes affect different building heights.

Additionally, learners investigate base isolation as an engineering design solution in which buildings remain in place during an earthquake as the ground moves beneath the foundation system.

Activity Sequence:

1. Demonstrate the BOSS model for the class.

Questions for Discussion:

- In this model, what does the wooden base represent? (*the surface of the earth*)
- What do the standing blocks on the dowel rods represent? (*buildings and other structures, such as water towers and bridges*)
- What does the shaking back and forth of the model represent? (seismic waves, and wind shear for taller buildings)
- How is energy moving through this system? (*kinetic energy transfers from your hand to the base of the model, then to the rods, and then to the blocks causing the blocks to sway back and forth*)

As you demonstrate several different shaking frequencies, discuss:

- Which building has the greatest amplitude of shaking? (*Tallest.*)
- What musical instruments illustrate resonance? (*Piano, harp, guitar, drums, wind chimes, etc.*)

2. Distribute the learner worksheet (Swaying Buildings–The BOSS Model; Appendix D) and reference materials: Violence of Earthquake Shaking Poster (Appendix C) and USGS publication: "Reducing Earthquake Losses

Throughout the United States: Monitoring Earthquake Shaking in Buildings to Reduce Loss of Life and Property".

3. Introduce the lab to learners before distributing the BOSS model:
   a. Review the Background Information found on the first page of the lab packet (page 16).
   b. Describe the poster "Violence of Ground Shaking Caused by 3 Types of Earthquakes" (Appendix C).
   c. Describe the USGS publication: "Reducing Earthquake Losses Throughout the United States: Monitoring Earthquake Shaking in Buildings to Reduce Loss of Life and Property"
   d. Describe the sequence of the lab. Check with learners for understanding.
   e. Set time to complete the lab and next steps for completing the lab packet before turning in.
   f. Distribute the BOSS models*
   **NOTE*: Warn learners that the wooden dowels are fragile and will break with rough handling. Avoid excessive shaking!
   g. Show animation, Buildings in Earthquakes: How does construction affect the shaking you feel? (6:29), after learners conduct their explorations. Discuss insights learned and the implications to buildings in earthquake prone communities
   h. At the conclusion of the lab activity, collect supplies and reference materials and discuss new insights discovered in the activity.

Extension

A logical extension to the BOSS Model would be to begin an exploration of how buildings can be strengthened by engineering seismic design principles. "Build a Better Wall" is a hands-on model that allows learners to experiment with different types of building reinforcement elements.

Lesson:

Build a Better Wall: How can we make a building more earthquake proof?

Videos:

Build a Better Wall Demo: Parts and Construction (6:05)

Build a Better Wall Demo: Why Buildings Fail

Amplitude: 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.) The amplitude depends on the amount of energy put into the system. See graphic below.

Base Isolation: a collection of structural elements which should substantially decouple a building from its foundation. If the building rests on potentially shaky ground, base isolation protects the structure's integrity. See photo below.

Frequency: the rate at which a motion repeats, in units of cycles per second, or Hertz. The frequency of motion is directly related to the energy of oscillation. In earthquake engineering, frequency is the rate at which the top of a building sways. See graphic below.

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.

Natural frequency: when a single pulse of energy is applied to an object, it will sway back and forth (oscillate) at a specific frequency, its natural frequency.

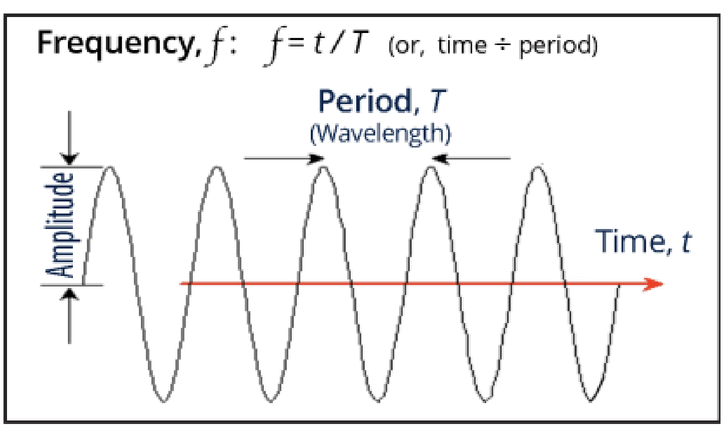
Oscillation or vibration: the repeating motion of a wave or a material—one back and forth movement (period).

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. See graphic below.

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 frequencies at which an elastic system, such as a building, vibrates when it is set in motion by an oscillating force, like seismic waves. When the frequency for one of the seismic waves is close to that of a building's natural frequency, the continued shaking increases the amplitude of oscillation of the building making it respond at a resonant frequency of the building. The resonant frequency of a building will differ depending on its size, shape, and construction. (Animation: Building Resonance: Why do certain buildings fall in earthquakes?)

Tuned Mass Damper: a device with a suspended mass within a high rise building that reduces the amplitude of vibration or swaying motion by absorbing kinetic energy from the system.



A wave as a function of time. The definitions for amplitude, period, and frequency are provided here. (Discussed in this animation: Building Resonance: Why do certain buildings fall in earthquakes.)

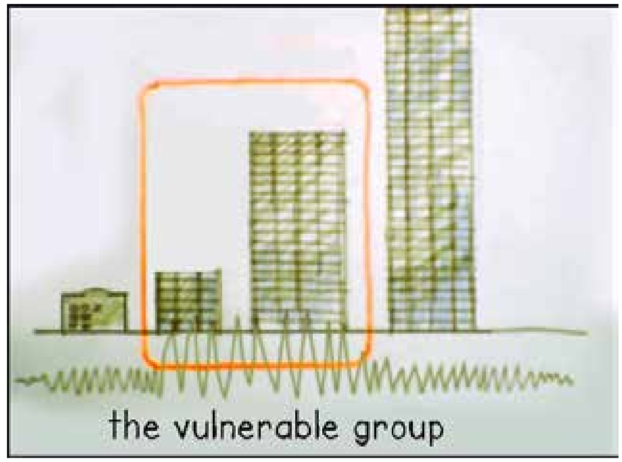
Base isolators at the Washington Emergency Management Division building. Photo courtesy of Washington State Military Department Emergency Management Division

APPENDIX B—EXAMPLE OF RESONANCE DURING AN EARTHQUAKE

1985 MEXICO CITY EARTHQUAKE

On September 19, 1985, a magnitude 8.1 earthquake occurred off the Pacific coast of Mexico. 350 km (217 mi) from the epicenter, damage was concentrated in a 25 km^2 (9 mi^2) area of Mexico City. The underlying geology contributed to this unusual concentration of damage at this 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 major kinds of structural failure that occurred in this earthquake include collapse of top, middle, and bottom floors, plus total building failure (see photo below).

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



The circled buildings were vulnerable during the 1985 Mexico City earthquake. Image courtesy of NOAA

This event is described in two IRIS animations:

- Mexico—Earthquakes & Tectonics
- Building Resonance: Why do certain buildings fall in earthquakes? (For the Mexico story, begin at 3min 9sec into the animation.)

Mexico City - Building collapsed. Photo courtesy of the U.S. Geological Survey.

APPENDIX C — VIOLENCE OF GROUND SHAKING CAUSED BY 3 TYPES OF EARTHQUAKES

QUAKE SCENARIOS: TYPE DETERMINES EXTENT OF DAMAGE

Last year's Nisqually Quake was a deep earthquake that caused some damage but is the least destructive of the three types of quakes possible in the Northwest. The two other types — shallow and subduction — are potentially much more destructive. The scenarios below illustrate why magnitude estimates alone do not fully represent the threat an earthquake may pose or type of shaking it can generate.

DEEP QUAKES

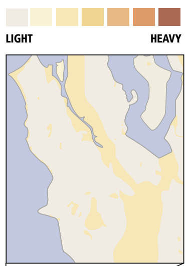
Fracturing occurs within the Juan de Fuca plate 30 to 40 miles underground. The Juan de Fuca plate dives under, subducts, North America. The intensity of a deep quake often dissipates before hitting the surface.

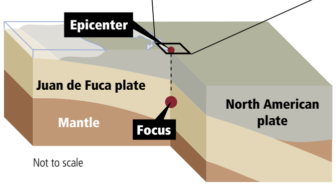
Largest recorded in Washington: 7.1M in 1949, Olympia

Frequency: Every 30 or 40 years

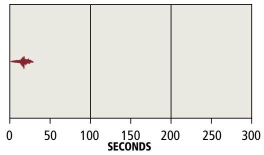
Possible shaking scenario

If a 7.1M (magnitude) quake hit Seattle



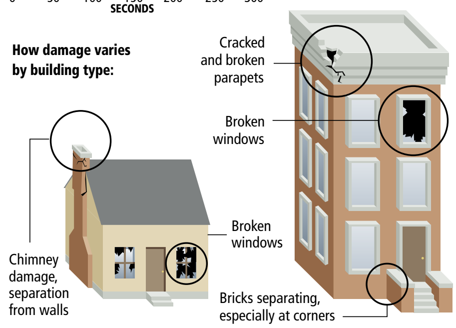


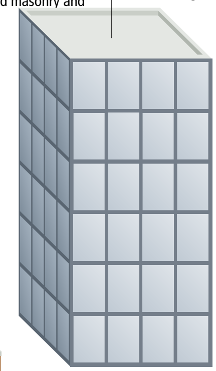
DURATION, INTENSITY AND STRUCTURAL DAMAGE



Duration: Roughly 15 to 30 seconds
Intensity: Moderate ground shaking
Damage: Most likely only the weakest parts of structures, such as unreinforced masonry and windows, will be damaged. Foundations will endure in most situations.

How damage varies by building type:





SHALLOW QUAKES

Crustal stress causes fracturing within the North American plate less than 15 miles below the surface.

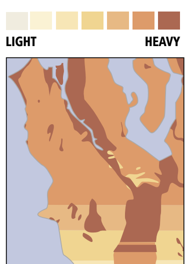
Largest known in Washington: 7.4M in 1872, North Cascades

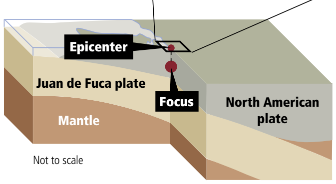
Frequency: Unknown

The Seattle Fault Zone is a shallow fault. Scientists suspect there are similar faults in Tacoma, Olympia and Portland.

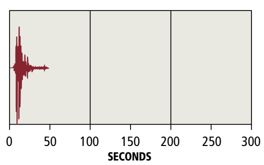
Possible shaking scenario

If a 7M quake hit Seattle



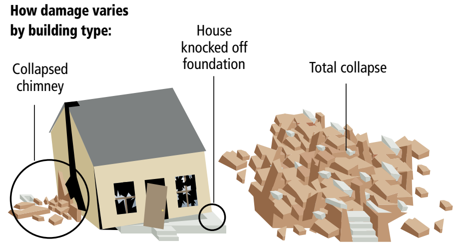


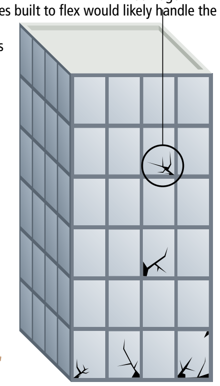
DURATION, INTENSITY AND STRUCTURAL DAMAGE



Duration: Roughly 20 to 60 seconds
Intensity: Violent ground shaking
Damage: Taller, newer structures built to flex would likely handle the shaking best. Brick or other unreinforced masonry buildings would do poorly, as would woodframe structures.

How damage varies by building type:





SUBDUCTION QUAKES

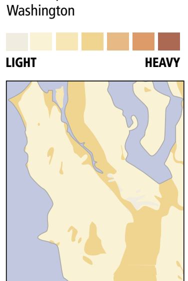
Over time, the North American plate builds stress as it locks up against the Juan de Fuca plate. When the subduction boundary slips, releasing the stress, scientists say it will produce one of the world's largest earthquakes.

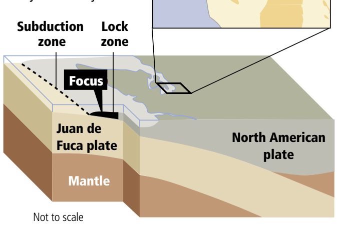
Largest known in Washington: 9M in 1700

Frequency: About every 400-600 years

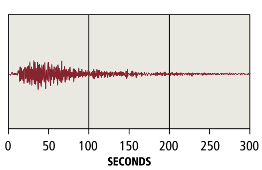
Possible shaking scenario

If a 9M quake hit Western Washington



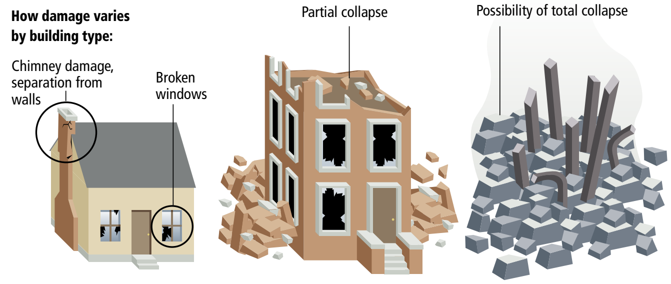


DURATION, INTENSITY AND STRUCTURAL DAMAGE



Duration: Roughly 1 to 5 minutes
Intensity: Moderate ground shaking
Damage: This is the scenario scientists know least about. Some say the long duration of shaking could start modern skyscrapers and bridges swaying back and forth until they collapse because many structures have only been engineered to withstand shaking for seconds rather than minutes. Others think the damage might not be as severe because the shaking is not as violent as a shallow quake.

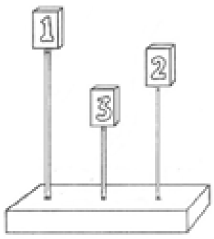
How damage varies by building type:



Sources: U.S. Geological Survey, University of Washington, California Institute of Technology

SEATTLE POST-INTELLIGENCER

Name: ________________________________ Date: ______________ Class session: ______



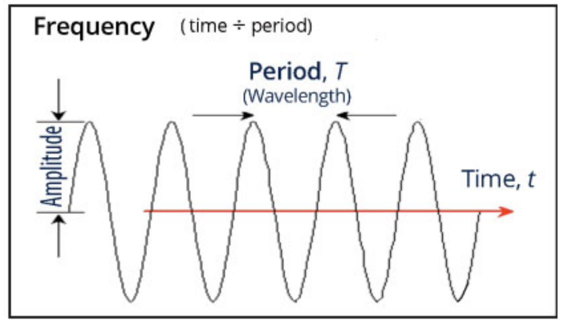
Swaying Buildings: The BOSS Model activity

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

Essential Question: How does rod ("building") height affect 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 dividing 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. 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: Data

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 (use additional page if needed)**:**

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 the Berkeley Seismology Lab blog, or watch this video that describes why that earthquake caused so much damage. Table 2 provides a summary of the natural period of typical buildings, based on their height in stories.
Citing evidence from the blog or movie, and from Table 2, make a claim about the seismic waves that impacted Mexico City in 1985.

Table 2: Relationship between the number of stories a building has, and the natural period of the building.

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

INSTRUCTOR KEY:

Swaying Buildings Learner Activity – 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 vibrates 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. Learners 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. Learners can provide a best-fit line as evidence of this relationship.

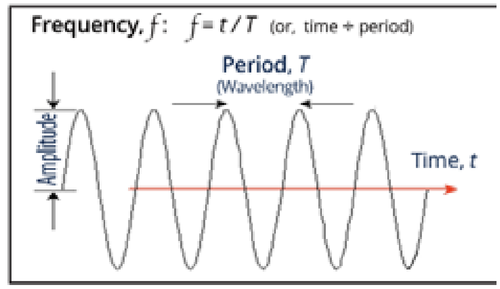
3. Learners cite the data in their table and graph to conclude that the natural frequency of buildings increases proportionally with increasing building height.

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 waves 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 with 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.

Once set into motion, guitar strings, tuning forks, buildings, and many other objects will spring back and forth for some time by themselves (see Animation on "Building Resonance"). This back-and-forth motion is called oscillation. The rate of vibration (the number of times something oscillates back and forth in a second) is called frequency. When an object is allowed to vibrate freely (one pulse of energy is applied, such as plucking a guitar string), it will do so at its own natural frequency.

The amount of time (usually seconds) it takes to complete one oscillation is called the period and is inversely related to the frequency. As the period increases, the frequency decreases (period =1 /frequency; 1 Hz = 1 second period; 10 Hz = 1/10 second period). Long-period shaking (with a period of many seconds) is low frequency while short-period shaking (1-2 seconds) is high frequency.



Earthquakes produce a broad spectrum (or 'symphony') of seismic waves at many frequencies. When the frequency for one of the seismic waves is close to that of a building's natural frequency, the continued shaking increases the amplitude of oscillation of the building and it responds with the resonant frequency of the building. Buildings can have more than one resonant frequency (explored in the 15-minute activity).

The resonant frequency of a building will differ depending on its size, shape, and construction. In general, small buildings (e.g. single-family homes) will shake more violently during short-period (higher frequency) ground shaking (~1-2 s). This short-period ground shaking is a characteristic of earthquakes on crustal faults, like the Seattle or Portland Hills Faults. Small structures, like single-family homes, would sustain significant damage, if located near the epicenter. The ground shaking from earthquakes located on crustal faults will typically last for about 10 to 20 seconds.

Taller buildings (e.g., skyscrapers and bridges) will shake more violently by long-period, low-frequency ground shaking in which the ground oscillates back-and-forth every 10 to 20 seconds. If resonance continues for an extended duration, the building may sway until its structural integrity is compromised and cause severe damage. This long-period ground shaking is characteristic of surface waves produced by a great subduction zone earthquake, such as along the Cascadia Subduction Zone in northern CA, OR, and WA. Plus, the duration of ground shaking will be four to six minutes!

Long-period ground shaking combined with long-lasting ground shaking (minutes duration), such as during a great earthquake, will cause even very large structures to violently shake for several minutes. Seismic wave oscillations lasting several minutes can build the amplitude of the shaking and cause damage to large structures. Designing bridges and large buildings to withstand such ground shaking is a major engineering challenge.

APPENDIX F – NGSS SCIENCE STANDARDS AND CROSS CUTTING CONCEPTS

https://www.nextgenscience.org/pe/ms-ess3-2-earth-and-human-activity

Students who demonstrate understanding can:

MS-ESS3-2. **Analyze and interpret data on natural hazards to forecast future catastrophic events and inform the development of technologies to mitigate their effects.** [Clarification Statement: Emphasis is on how some natural hazards, such as volcanic eruptions and severe weather, are preceded by phenomena that allow for reliable predictions, but others, such as earthquakes, occur suddenly and with no notice, and thus are not yet predictable. Examples of natural hazards can be taken from interior processes (such as earthquakes and volcanic eruptions), surface processes (such as mass wasting and tsunamis), or severe weather events (such as hurricanes, tornadoes, and floods). Examples of data can include the locations, magnitudes, and frequencies of the natural hazards. Examples of technologies can be global (such as satellite systems to monitor hurricanes or forest fires) or local (such as building basements in tornado-prone regions or reservoirs to mitigate droughts).]

The performance expectation above was developed using the following elements from the NRC document *A Framework for K-12 Science Education*:

Science and Engineering Practices

Analyzing and Interpreting Data
Analyzing data in 6–8 builds on K–5 and progresses to extending quantitative analysis to investigations, distinguishing between correlation and causation, and basic statistical techniques of data and error analysis.

- Analyze and interpret data to determine similarities and differences in findings.

Disciplinary Core Ideas

ESS3.B: Natural Hazards

- Mapping the history of natural hazards in a region, combined with an understanding of related geologic forces can help forecast the locations and likelihoods of future events.

Crosscutting Concepts

Patterns

- Graphs, charts, and images can be used to identify patterns in data.

Connections to Engineering, Technology, and Applications of Science

Influence of Science, Engineering, and Technology on Society and the Natural World

- The uses of technologies and any limitations on their use are driven by individual or societal needs, desires, and values; by the findings of scientific research; and by differences in such factors as climate, natural resources, and economic conditions. Thus technology use varies from region to region and over time.

Incorporated Research Institutions for Seismology

IRIS

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