Overview
During an earthquake, buildings move – or oscillate. If the frequency of this oscillation is close to the natural frequency of the building, resonance may cause severe damage. This lesson encourages students to observe how the mass, stiffness, and height of buildings affect their motion and how buildings respond to resonant motions.

Science Standards (NH Science Curriculum Frameworks)

ESS1 – The Earth and Earth materials (Processes and Rates of Change):
S:ESS1:6:5.3 Recognize that vibrations in materials set up wavelike disturbances that spread away from the source, as with earthquakes, convection in ocean currents, winds, weather and weather patterns, atmosphere, or climate. [ESS1(5-8)POC-3]

PS – Physical Science
PS4 - The growth of scientific knowledge in Physical Science has been advanced through the development of technology and is used (alone or in combination with other sciences) to identify, understand and solve local and global issues.
1. Design Technology
S:PS4:6:1.1 Understand that scientific principles are used in the design of technology.
S:PS4:8:1.1 Understand that design features, such as size shape, weight, and function, must be considered when designing new technology.

Focus Question
How do buildings of different heights and weights respond to an earthquake?

Objectives
Through this lesson, students will:
• Predict how a building will react to an earthquake;
• Perform an experiment to establish relationships between the height and weight of a building and its frequency;
• Describe resonance; and
• Record their observations.

Background
The most important variables affecting earthquake damage to buildings are (1) the intensity of the ground shaking, (2) the quality of the engineering design and construction, and (3) the response of the building to the earthquake motion. The focus of this lesson is on the third variable – how a building responds to the earthquake motion.
Vocabulary

- **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.
- **Hertz (Hz)**: the unit of measurement for frequency, as recorded in cycles per second.
- **Oscillation or vibration**: the repeating motion of a wave or a material—one back and forth movement. Earthquakes cause seismic waves that produce oscillations, or vibrations, 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 dimensions, design, and the building materials.
- **Resonance**: an increase in the amplitude (in this case, the distance the top of a building moves from its rest position) of a physical system (such as a building) that occurs when the frequency of the applied oscillatory force (such as earthquake shaking) is close to the natural frequency of the system.
- **Stiffness**: resistance to deformations. Stiffness is a function of material, size, shape, length or height, and mass.

Materials (for 20 people working in groups of 2)

- Clay (5 lbs),
- Wooden dowels (I used 1/8” diameter dowels – 8 each @ roughly 10”, 15”, 20” and 25”)
- 10 wood blocks (I used 2"x2" cedar boards – 18” long),
- Building Motions in Earthquakes Handout and pencils (20),
- Stopwatches (ideally one/group but groups can share),
- Scale to measure the weight of the clay balls,
- Rulers to measure the height of the dowels,
- Optional: sophisticated lollipop model (shown at the right).

Preparation

Collect materials. Measure and record the frequency of each mass in the ‘sophisticated lollipop model.’

Drill 1/8” holes (1” deep) in the wood blocks – I drilled 4 holes, spaced 4” apart in each 18” long block.

Cut the dowels to different lengths: 8 each @ 10”, 15”, 20” and 25”. Create a simple, single lollipop model with clay, one dowel (15” or 20” long), and a wood block and measure the frequency of this system as well as the weight of the clay ball, and the height of the clay ball, so that you can analytically determine the frequency.

Procedure

1. Research: Talk about my research and background – highlight dissertation research, seismic rehabilitation work, and recent trip to Haiti. Brief PowerPoint presentation. <5 minutes
2. Hook: Focus on the three most important variables affecting earthquake damage to buildings: (1) the intensity of the ground shaking, (2) the quality of the engineering design and construction, and (3) the response of the building to the earthquake motion. Show images from earthquakes giving examples of each of these three variables: Virginia, Japan, Haiti, and Mexico City. <5 minutes
3. Background: Discuss frequencies and periods of buildings. **Frequency** is the number of oscillations per unit time, or cycles per second. One oscillation is measured from the maximum position through the neutral position to the minimum position, back through neutral to the maximum position. The natural **period** of a building is the duration of one full cycle of response (from max displacement to the neutral position to the negative
displacement, back through the neutral displacement to the max displacement), so the period is the reciprocal of the frequency.

4. Lollipop Model: Introduce a simple lollipop model (see image at the right of three one-story ‘buildings’ or lollipops of different heights) and discuss the fact that engineers use lollipop models (lumped mass models) to represent buildings analytically. These models help simplify the analysis and are a fairly good representation since most of the mass in buildings is concentrated at the floor levels and the mass is what causes the shaking (F=ma). Clay balls represent the mass of the floors, the dowel represents the columns, and the wood block represents the foundation or ground.

5. Demonstrate: Demonstrate the frequency and period of a simple lollipop model by ‘plucking’ the clay ball and measuring with a stopwatch the time it takes to complete 10 full cycles (have students run the stopwatch and count the number of cycles).

6. Experiment: Form small groups (2-3 per group) and give each group a stop watch, ruler, block, dowel, and lump clay as well as a Building Motions in Earthquakes Handout. Ask each group to build their own simple lollipop model and measure the frequency multiple times and record the values. Also measure the height of the dowel and weight of the clay ball.

7. Extend the Experiment: Next have each group create a second lollipop model to investigate the focus question: How do buildings of different heights and weights respond to an earthquake? Change only one parameter for the study (i.e., change the height OR weight but NOT both). Determine the frequency of the new model and compare it with the first model. Measure the new height or weight.

8. More Experimentation: If there is time, groups may create additional lollipop models to test different parameters (or further test the same parameter).

9. Plot: plot the frequency results (on the y-axis) versus your variable (on the x-axis) – height or weight.

10. Share: Have groups share the results of their study.

11. Lesson: Define terms: frequency, period, and stiffness. Discuss the relationships between mass, height, stiffness, frequency, and period. Buildings have certain natural frequencies that depend on their mass and stiffness (which is a function of the height, diameter, and material used for the ‘columns’). Equations/relationships: \( f = \frac{1}{2\pi} \sqrt{\frac{k}{m}} \); \( \omega_n = \sqrt{\frac{k}{m}} = 2\pi f \); \( T = \frac{2\pi}{\omega_n} \).

12. Relate back to earthquakes: earthquakes produce motions or waves/oscillations at the ground level. How does that affect the response of buildings? Bring out the sophisticated lollipop model and ask the students to predict which lollipop (or numbered mass/rod assembly) will oscillate the most when you wiggle the base. Have them indicate their prediction by voting for number 1, 2, 3, or 4 (they will probably vote for number 1 because it is the tallest). Oscillate the sophisticated lollipop model so that some mass other than the one predicted oscillates. This may baffle the students so let them predict again. Again make a different mass resonate. Finish by making the mass that they predicted resonate. Invite discussion. Discuss the relationship between earthquake frequency content and building frequency and resonance. Example: 1985 Mexico City earthquake (8-10 story buildings were destroyed but other buildings remained intact).

13. Resonance: Have the groups try to induce resonance in their simple lollipop models. Resonance = the tendency of a system to oscillate at a greater amplitude at some frequencies than at others (typically at frequencies that match the natural frequency of the building or system).

14. Talk about the broader context of resonance: Tacoma Narrows (wind induced resonance), wine glasses (acoustic resonance), swings/pendulums.

Assessment

- Have the students demonstrate resonance.
- At the end of the lesson ask students to write down one thing they learned.
**Extensions**
Students could be encouraged to:
  - Experiment with different diameter dowels.
  - Experiment with multiple masses (clay balls) to extend to multi-story buildings and discuss modes and mode shapes.
  - Further understand earthquake motions and frequencies by studying different types of earthquake wave propagation, fault types, and soil conditions.
  - Design earthquake-resistant buildings
Build a ‘lollipop model’ of a building and record the amount of time it takes for your model to oscillate 10 times. Repeat the measurement four times. Calculate the average time by adding the four measurements and dividing by four. Calculate the frequency by dividing 5 cycles (since you measured 10 cycles) by the time for 5 cycles to get cycles/second. Average these values as well.

**Lollipop Model 1:**

<table>
<thead>
<tr>
<th>Trial</th>
<th>Time for 5 cycles (sec)</th>
<th>Frequency = 5 ÷ (time for 5 cycles) (Hz or cycles/sec)</th>
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**Lollipop Model 2:**

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**Lollipop Model 3:**

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**Lollipop Model 4:**

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Plot your average frequency results (on the y-axis) versus your variable – weight or height (on the x-axis) – for each of your lollipop models. Your variable should be height, weight, or wire diameter. Be sure to label the axes!

Consider your results:

- How much variation was there in your frequency measurements?
- What relationship do you notice, if any, between your variable (height or weight) and the average frequency?
- What other experiments could you run?
- Define frequency.
- What does it mean to oscillate or vibrate?