EARTHQUAKES – Tutorial Script

Earthquakes can have large and deadly impacts on communities worldwide. Many of the world's major population centers, such as San Francisco and Tokyo, experience earthquakes on a regular basis. In this video tutorial we will discuss the locations, patterns, causes, and consequences of earthquakes worldwide.

As discussed in the Folds & Faults Video tutorial, faults are planes along which rocks under stress have broken and moved. After a fault has formed, successive application of stress can cause continued movement of the rocks along each side of the fault. If that stress is released through continual movement, we say the fault creeps. However, when friction causes the fault to stick, stress will build, and the rocks on either side of the fault will deform elastically under that stress. When eventually the stress is high enough to overcome the friction, and the fault slips, the release of the built-up stress energy causes the Earth to shake: an **earthquake**. The spot along the fault where the friction is first overcome and the slip happens is called the **focus** of the earthquake. The spot on Earth's surface directly above the focus, the place that will first receive the energy waves that emanate out of the focus, is called the **epicenter**. The energy that is released as the fault slips and the rocks rebound back to their original shape moves in the form of waves that travel outward in all directions. We call the waves that travel through the solid rock, **body waves**, and these can travel all the way through the Earth to be picked up by seismic stations on the other side of the planet. When these body waves arrive at the surface they will generate **surface waves,** which move outward from the epicenter in all directions along Earth's surface (the boundary between the rock surface and the atmosphere or water).

As discussed in the Plate Tectonics and Global Impacts and Folds & Faults video tutorials, plate boundaries are regions where stresses, such as compression, tension, and shear, are continually applied. Extensive fault systems exist along all these boundaries, and earthquakes concentrate here globally. These earthquakes nicely outline the edges of plates and let us see the various shapes and sizes of plates globally. What we can also see in these images is that earthquakes at divergent plate boundaries where oceans are opening up or along transform plate boundaries where plates slide past each other are a bit different than those happening where plates converge. Convergent plate boundaries have much wider zones of earthquake activity. And when we color code earthquakes based on depth, we can see why. Over subducting plates, we would expect shallower earthquakes near the top of the subducting plate, near the trenches, and progressively deeper and deeper focus earthquakes as the plate descends. In fact the earthquake data confirm this, and maps like these provide an image of the location of the subducting plate and the geometry of the subduction zones.

We can determine how much stress builds up and is released during an earthquake by studying the way the ground moves after the rupture. Scientists who study earthquakes are called seismologists and record the ground movement using instruments known as **seismographs**. These devices can measure movement in three directions and record that motion as a two-dimensional wave form on a piece of paper called a **seismogram**. A simple seismograph can be described as a hollow box attached to the ground so it moves in exactly the same direction and motion as the ground. Dangling in the middle of the box from the top is a heavy weight that is attached to a thin line. The weight is pulled towards Earth's center by gravity and because of its mass will stay in place during an earthquake while the box moves with the Earth around it. We can then measure how much distance is created in each dimension of the box between the weight and the sides of the box as the box moves with the Earth. Thus we can record accurate motion of the Earth.

Here is a sample seismogram from an earthquake. What do we see? The first wave to appear, here, causes a different intensity ground shaking than the second wave, which appears here. After a fault ruptures at depth, there are two body waves that emanate outward. The fastest body waves are the first to arrive at the seismograph stations on the surface and are called **primary waves** or **P waves**. They are compressional waves that travel on average 7 km/s. These energy waves are transmitted as the material through which they're traveling alternately compresses and expands. Sound waves are also compressional waves. Because all substances (solids, liquids, and gases) are capable of compression and expansion, compressional waves can travel through all materials. We can hear sound traveling through the air, water, or solid rock.

The second type of body waves are shear waves and slower, on average 3.5 km/s. These waves arrive second at the seismograph station and are called **secondary waves or S waves**. As you see here with the slinky, shear waves cause the individual slinky pieces to move up and down relative to each other as the energy passes through. Because only solid materials are capable of shear, S waves can travel only through solids.

Going back to the seismogram, what we see here is the arrival of the compressional P wave, which is like a hammer punching up out of the ground. Following behind is the S wave. Both of these waves will produce surface waves that emanate outward from the epicenter. The surface waves move along Earth's surface and cause the Earth to move up and down and sideways in three directions. It's the motion of the surface waves that cause the greatest amount of damage to buildings during earthquakes.

In general, surface waves will dissipate the further one gets from the epicenter of an earthquake. However, surface wave intensity is impacted by the type of material they travel through. For example, as this shake map of San Francisco shows, when each of these rock materials is subjected to earthquake waves, different amounts and types of shaking result. Solid bedrock shakes least – unconsolidated sand shakes more – and unconsolidated mud, bay fill, shakes the most (like jello). Finding the most stable ground to build on is a key part of minimizing damage during earthquakes. It's also important to prevent structures from being built across multiple materials that shake differently. For example, during the 1989 Loma Prieta earthquake in California, for one of the highways that fell down in the East Bay, one support was built on sand, and the other on mud. The two supports shook with different motions during the earthquake and pulled the material supported between them apart.

In addition to the ground material impacting the intensity of shaking, sometimes the geology of an area can intensify shaking through **interference**. Interference is the meeting of two waves arriving from different directions. When the two waves meet, they add to each other. If they meet crest to crest, or trough to trough (in phase), they increase the overall wave height. For earthquakes that increase means more shaking. When the two waves meet crest to trough (out of phase), they decrease the wave height. That decrease means less shaking. Interference happens during an earthquake when the seismic waves bounce off a hard object underground, like the edge of a basin, or the side of a granite intrusion. Areas between the epicenter and the reflection surface will experience two waves arriving from different directions – the original earthquake waves and the reflected waves. The pattern that interference makes on the surface is similar to a checkerboard – in black squares waves meet out of phase and shaking is reduced; in white squares waves meet in phase and shaking is increased. In the center of black squares people may not feel any shaking at all. In the center of white squares, shaking may be so intense that structures fall. Evidence that interference has occurred can be seen when you view this checkerboard pattern of destruction in an area, like a housing development, where all structures and ground material are similar.

In addition to the local soils, rocks, and geology, the type of building material will also impact how severely a particular earthquake is experienced by the people living in an area. Urban areas prone to earthquakes will often develop strict building codes to minimize these impacts. For example, if a building's foundation is sunk deep and solidly into the bedrock, it will move with the ground and be less likely to break apart. If the walls of the house are bolted to the foundation, they'll move with the foundation. If the walls are bolted to each other, it further connects everything so it all moves as one. If we build houses out of flexible material, like wood, they're less likely to break as they bend. If we minimize the use of rock tiles and ornamental door headers, we're less likely to have these fall and cause damage during an earthquake.

Sometimes it's not the way a building is built, but the size of the building that impacts the amount of damage during an earthquake. **Resonance** is the matching of the period (or frequency) of an earthquake wave with the natural vibrational period (or frequency) of an object, like a building. All buildings vibrate at a period (number of seconds per vibration) that depends mainly on the height of the building. If the period of an earthquake is the same as the natural period of the building structure, shaking increases more and more with each wave's arrival, until the structure falls apart. You can see examples of resonance when you push a child on a swing (if your pushing period matches the child's swinging period, the child will swing higher and higher) or when an opera singer matches the frequency of a sound wave to the frequency of a wine glass and makes it shatter. After an earthquake, you would see evidence of resonance if you noticed that all buildings of a particular height experienced more damage than other buildings, shorter or taller.

What are some other things that contribute to damage during an earthquake? Unconsolidated sands and muds can behave like liquids when shaking and heavy buildings on top can sink into them, a process called **liquefaction**. Fires spread easily when folks are cooking over open flames and buildings are made of wood. Seiches or large standing waves can form in lakes or pools or lagoons and flood the surrounding land. Landslides can be triggered. And if the earthquake happened underwater at a fault that experienced vertical displacement of the seafloor, like at subduction zones, then it's possible to create a **tsunami** or splash wave that emanates out and can travel thousands of kilometers across the ocean. Tsunami can also be created by landslides that fall into the ocean thus creating a vertical displacement of seawater and a splash.

Since the amount of damage done during an earthquake can be impacted by ground material and building design, how do we accurately measure the amount of energy released in an earthquake and assign a particular earthquake a measurement that we can compare globally with other earthquakes? The first scale devised to measure earthquake intensity was the **Mercalli Intensity Scale**, and it provided a scale based solely on the subjective experience of the people in the area of the earthquake. So even though the actual energy release and size of the body waves might be the same from one location to the other, if there were no people living in one area and no buildings, it would not even appear on the scale; if ground material amplified shaking and building design was not engineered for earthquakes, then it would appear very high on the scale. This scale is very useful for comparing damage from one part of the planet to the other, but not for comparing energy release. In 1935, Charles Richter and others at Caltech in Pasadena, California, devised a new scale, the **Richter Scale**, which measured the amplitude of arriving earthquake waves on a seismogram recording. Based on the local rocks of Southern California and the type of seismograph instrument used, seismologists developed a paper scale that allowed them to calculate the energy released in an earthquake based on its distance away and the amplitude on the seismogram. In the Richter Scale, for each approximately 33-fold increase in energy, we move up 1 number in magnitude. So a magnitude 7 earthquake represents a release of approximately 33 times more energy than a magnitude 6 earthquake and 33 x 33 or approximately 1000 times more energy than a magnitude 5 earthquake. In other words, it would take 1000 magnitude 5 earthquakes to release the same amount of energy as one magnitude 7 earthquake. *Note: the amplitude of the seismogram wave increases 10 times for each magnitude, which means of course that not all earthquakes can be recorded on a single seismograph. Some will be too big and run off the drum – others too small to see – so multiple seismograph instruments would be needed to record the various magnitude earthquakes that would exist in any one area. The benefit of the Richter scale is that earthquake magnitude can be determined quite quickly after an earthquake just by measuring the amplitude on the seismogram recording and calculating as well how far away the earthquake was.

The drawback to the Richter scale is that it was designed around a particular instrument and location and thus doesn't translate uniformly to other earthquakes elsewhere in the world that might have different rocks and different instruments. It also loses its accuracy for high magnitude earthquakes. As a result, the **Moment Magnitude Scale** was developed and is the one now used by seismologists around the world. The Moment Magnitude Scale calculates magnitude from amount of slip along the fault, depth and length of fault rupture, and strength of rocks that broke. With this new scale, a magnitude 7.1 from one location represents the same energy release as another location. However, it does take time to gather the data necessary to calculate the moment magnitude. As a result, usually after an earthquake, the first magnitude given right away is the Richter magnitude, based on the seismogram recording, and then a few days or weeks later that number is refined to the more accurate moment magnitude.

To determine the exact location of an earthquake, we look at the arrival time difference of the P and S waves. Because we know the speed of each, we also know how far away we have to be from the epicenter of an earthquake to get a particular time difference in their arrival – the further away, the larger the arrival time difference, the closer, the smaller the arrival time difference. Once we determine the exact distance, we can draw a circle around the seismic station with a radius equal to that distance. The earthquake happened somewhere on that circle. What else to we need to pinpoint the exact location? Two more seismic stations reporting their data, so we have three circles, which will intersect in only one location, the epicenter of the earthquake.

One of the common comments I receive from students the week we study earthquakes in class is surprise at the "coincidence" that while we're studying earthquakes, there happens to be an earthquake somewhere in the world that impacted an urban center and is written up in the news. Is it really a coincidence? From the USGS Earthquake Hazards Program website, from 2000 to 2018, there have been on average 1-2 magnitude 8 earthquakes per year; 14 magnitude 7-7.9, approximately 140 magnitude 6-6.9; and approximately 1600 magnitude 5-5.9. You can see that the annual number seems to jump 10 times for each magnitude drop. So 4-4.9 would be about 16,000; 3-3.9, 160,000; and less than 3.0 is over 1.6 million. On any given week (7 days), the planet will experience thousands of earthquakes, and there's bound to be one of those that makes the news.

[end credits]

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