

The Physics of Seismic Waves

For years scientists have tried to learn as much as they can about the Earth's interior. Earthquake seismology is one of the best tools for them to do this. From the many studies they have done, a better idea about how to predict future earthquakes and the effect they may have is known.

Seismology is the study of the elastic waves that pass through the earth. When an earthquake or explosion occurs it causes two types of deformation: static and dynamic. Static deformation accounts for about 90% of the energy. This is produced when, an earthquake fault ruptures. It progresses from a fault in the plate tectonics, which is under stress in an earthquake, and gives rise to the permanent displacement of the ground.

The dynamic deformations from earthquakes are essentially elastic sound waves that radiate out and get transmitted through the earth when it ruptures. These are known as seismic waves. There are several types of these waves, which all move and behave in different ways. The two main types are body waves and surface waves.

Body Waves

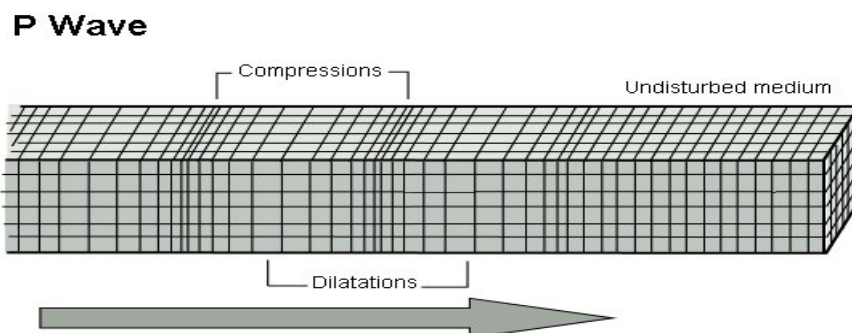
These are seismic shock waves that travel through the inner layers of the earth. They can be reflected and transmitted with density or velocity changes and all obey Snell's Law. This states that:

$$n = \sin i / \sin r$$

where i = angle of incidence
 r = angle of refraction
 n = refractive index

There are two types of body waves.

1. **P waves** – Known as primary, or push-pull waves, they are the fastest kind of seismic wave. A P wave can travel through solids and fluids pushing and pulling the particles in the material as it moves through it. They are similar to sound waves in that they are longitudinal and involve compression and rarefaction of the material along the direction of propagation of the wave.

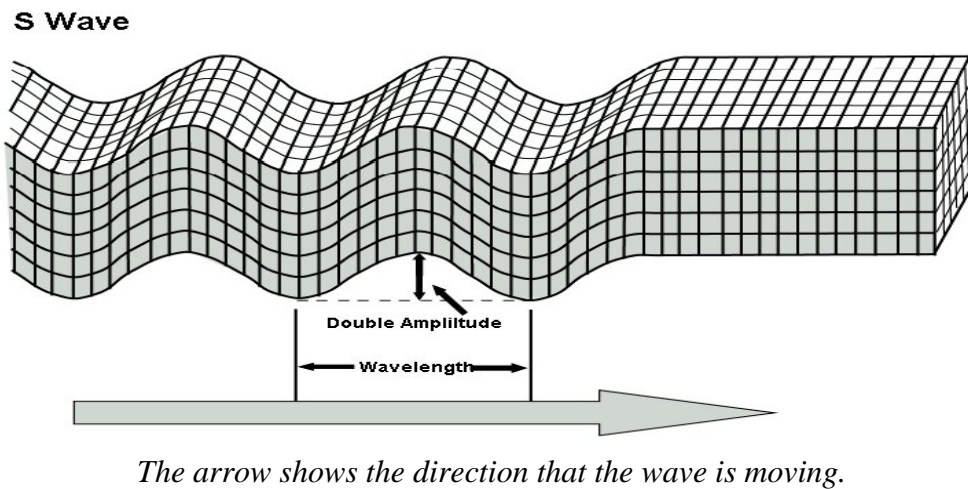


The arrow shows the direction that the wave is moving.

Source 1

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2. **S waves** – These are the second kind of wave to be felt in an earthquake. They are known as secondary or shear waves, as they involve shearing and rotation of the material that the wave passes through, moving it up and down or side-to-side. There is no volume change of the rock. S waves are transverse, moving particles transverse to the movement of the wave front and perpendicular to the ray. They travel slower than P waves and can only pass through solid rock in the earth. The fact that S waves cannot travel through a liquid and are not observed on the far side of earth from an earthquake is evidence for the fact that the Earth's outer core is liquid.



Source 1

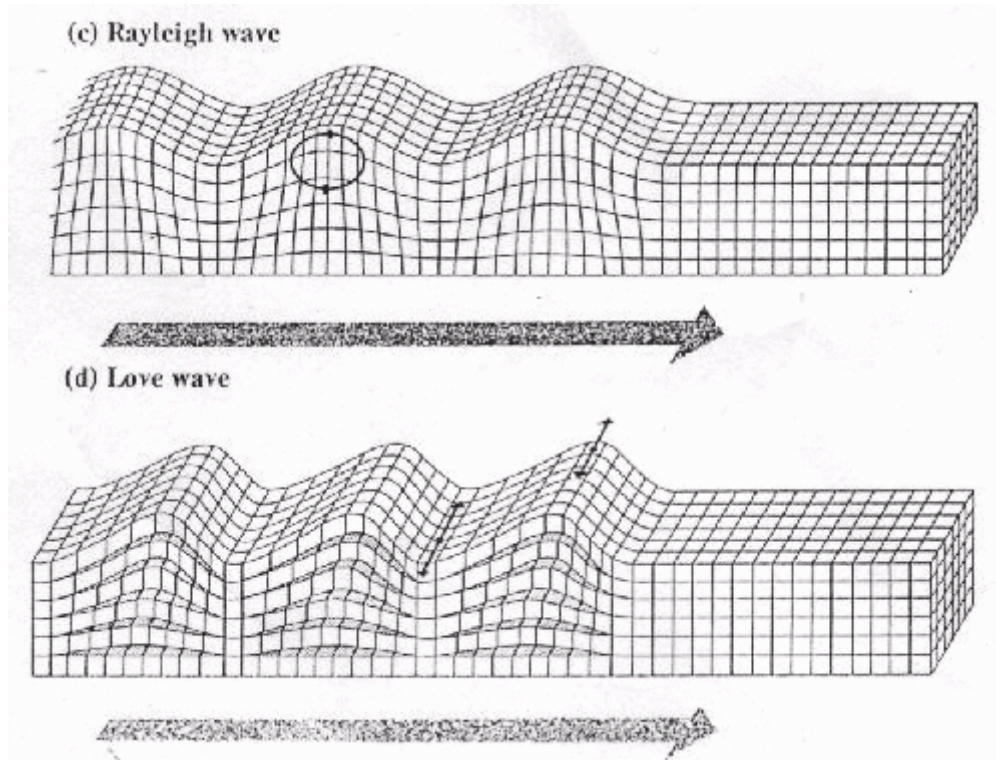
Surface Waves

Surface waves oscillate slowly along the surface of the planet like ripples of water. Normally generated by shallow earthquakes, they do not deeply penetrate the interior of the earth. They have larger amplitudes and a longer period (T) than body waves and therefore slower velocities. There are two types of surface wave:

1. **Rayleigh waves** – Also known as ‘ground roll’, these waves were named after the scientist who mathematically predicted the existence of them. They roll along the ground in a similar way to how ocean waves propagate. As it rolls it moves the ground up, down and sideways in the direction of motion of the wave. The displacements are larger at the surface and decrease exponentially downwards, with the waves showing dispersion, and a velocity that varies with wavelength. The shaking felt from an earthquake is mainly due to Rayleigh waves.

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2. **Love waves** – Named after the mathematician who worked out the model for these kinds of wave, Love waves are the fastest surface wave travelling in a transverse motion which is parallel to the ground surface. They are similar to S waves and move the ground in a side-to-side motion.



Source 2

Wave Velocities

The velocities of P and S waves can be determined from the density (ρ) and elastic coefficient of the material they travel through.

Elastic Coefficient

If we consider the rock through which a seismic wave travels, we find that it is subjected to a stress, which is defined as force/area and a change in shape, or a strain. How fast the wave travels through the medium is controlled by their elastic properties. Young's modulus is the constant of proportionality, which defines the linear relationship between stress (σ) and strain (ϵ).

$$\sigma = E\epsilon$$

The ratio of extension in the material in each direction can be calculated. This is referred to as Poisson's ratio (μ).

$$\mu = \frac{-\epsilon_1}{\epsilon_2} \quad \text{where } \mu \leq 0.5$$

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If we then consider the original pressure (P_0), volume (V_0) and therefore density of the material that define its equilibrium state, we can look at how the compressions and rarefactions of the seismic waves affect the material. Under the influence of the waves:

$$\text{Bulk modulus } K = \frac{\Delta P}{\Delta V/V_0}$$

Where the bulk modulus is a measure of the compressibility of a material.

This can also be defined in terms of Young's modulus (E) and Poisson's ratio (μ):

$$K = \frac{E}{3(1-2\mu)}$$

Another thing to define before looking at the velocities of waves is the rigidity modulus (G), which is the ratio of sheer stress (σ_s) and sheer strain (γ).

$$G = \frac{\sigma_s}{\gamma} \quad \text{or} \quad \frac{E}{2(1+\mu)}$$

From these equations an expression for the velocity of a P wave and of an S wave can be obtained. The final results are as follows:

$$\begin{aligned} V_p &= \sqrt{\frac{K + 4/3G}{\rho}} = \sqrt{\frac{E(1-\mu)}{\rho(1-2\mu)(1+\mu)}} \\ V_s &= \sqrt{\frac{G}{\rho}} = \sqrt{\frac{E}{\rho 2(1+\mu)}} \\ \frac{V_p}{V_s} &= \sqrt{\frac{1-\mu}{1/2-\mu}} \end{aligned}$$

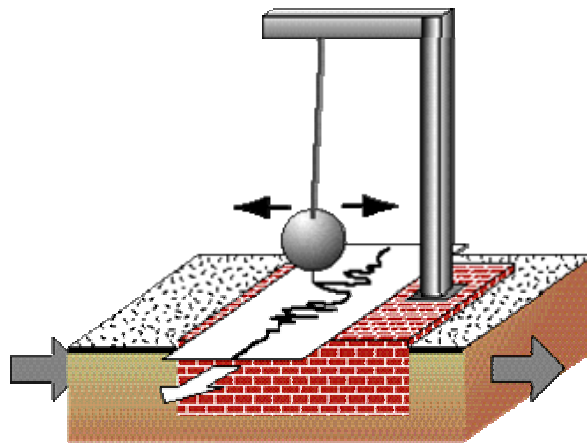
Where:
 V_p = velocity of a P wave
 V_s = velocity of an S wave
 K = bulk modulus
 G = rigidity modulus
 E = Young's modulus
 ρ = density
 μ = Poisson's ratio

The bulk and rigidity modulus are always positive values and $\mu \leq 0.5$, which shows that P waves are of much greater magnitude than S waves. Also, S waves can't travel through liquid, so if $G = 0$ is substituted for liquid, the S wave velocity is zero.

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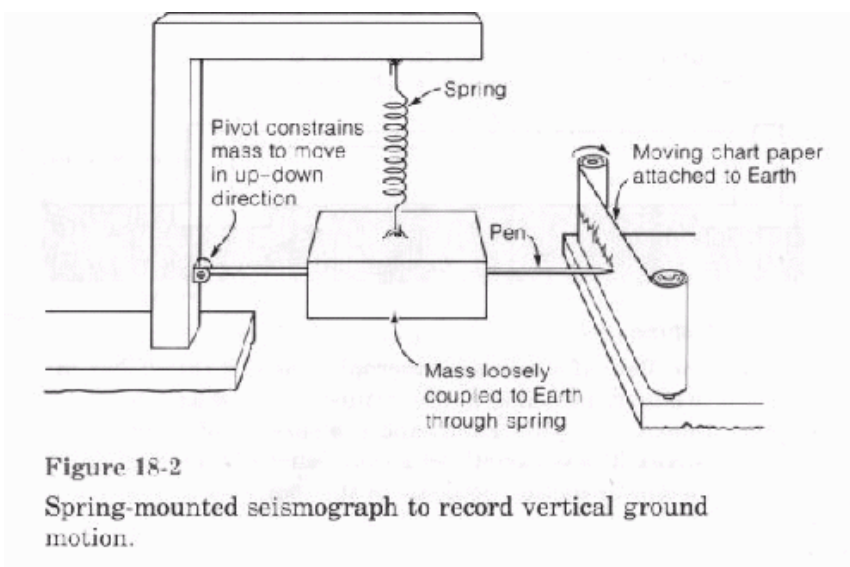
Detecting Earthquakes

Seismographs are the tools used to measure earthquakes. There are thousands of stations in operation around the world processing information to try to determine the locations and scale of them. Horizontal motion of the ground is detected by what is essentially a simple pendulum. The base and frame of the instrument move with the ground as it shakes, but inertia keeps the pendulum bob in place. It then records the displacements of the ground as they change with time, tracing a pattern called a seismogram. An example of a seismograph is shown below.



Source 3

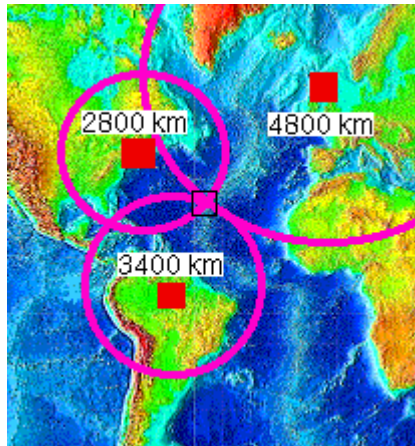
Vertical motion can also be measured using a spring-mounted seismograph as shown below. A spring is attached to a mass and moves up and down as the ground moves.



Source 2

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The use of seismographs to locate an earthquake is most effective if at least three seismic stations are used. Each station records measurements that can determine how far away the seismic waves came from. A circle with a radius equal to this distance can be drawn around the station's location, and if more than one station is used, the circles will pin point the epicentre (point on the surface above the focus of an earthquake). The diagram below shows how the epicentre is found.



Source 3

Magnitude and intensity

Richter Magnitude

Earthquake magnitude is most commonly reported using the Richter scale. It was named after Charles F. Richter, who developed it by collecting readings of seismic waves from a large number of earthquakes and calibrating a system. Magnitude expresses the seismic energy released from the amount of ground displacement. The larger the energy from an earthquake, the greater the amplitude of ground motion.

Seismic Moments

More recently, scientists have developed another standard magnitude scale called the moment magnitude. It is derived from the concept of torque, a force that changes the angular momentum of a system. It is defined as the force times the distance from the centre of rotation. The interactions of blocks of earth in the faults during earthquakes causes internal torques which can be found by the following equation:

$$\text{Moment} = (\text{Rock rigidity}) \times (\text{Fault area}) \times (\text{Slip distance})$$

$$M_0 = \mu A d$$

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From this formula for moments, a seismologist can assess how dangerous a certain fault can be. The moment can now be converted into a Richter magnitude by the following relationship:

$$\text{Magnitude } M = \frac{2}{3} [\log_{10} M_0 - 16.0]$$

M_0 must have units of Dyne-cm

The amount of energy radiated from the earthquake as seismic waves can then be found (in ergs) from the magnitude and moments in the following formulae:

$$\text{Log } E_s = 11.8 + 1.5M$$

Where M = magnitude
 E_s = energy

$$E_s = \frac{\text{moment}}{20,000}$$

Intensity

One other method of describing the size of an earthquake is intensity. This method is an estimate of the effects on humans and the environment. The effects produced by an earthquake of a given magnitude can vary considerably as a result of factors such as population density, quality of construction and distance from epicentre. The most commonly used intensity scale is the Mercalli scale.

Perhaps one of the most important reasons to study earthquake seismology is the devastation that can be caused from seismic waves. Scientists are learning more and more about the cause and effects of earthquakes every day, from the types and mechanics of the waves, to how they can detect and measure them, all of which I have discussed in this article. The better these things are understood, the better we can predict what will happen in the future.

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