Chapter 1

Seismology

1.1. Introduction

A study of earthquake engineering calls for a good understanding of geophysical process that causes earthquakes and various effects of earthquakes. Seismology is the study of the generation, propagation and measurement of seismic waves through earth and the sources that generate them. The word seismology originated from Greek words, ‘seismos’ meaning earthquake and ‘logos’ meaning science. The study of seismic wave propagation through earth provides the maximum input to the understanding of internal structure of earth.

1.2. Internal Structure of Earth

The earth’s shape is an oblate spheroid with a diameter along the equator of about 12740 km with the polar diameter as 12700km. The higher diameter along equator is caused by the higher centrifugal forces generated along the equator due to rotation of earth. Though the specific gravity of materials that constitute the surface of earth is only about 2.8, the average specific gravity of earth is about 5.5 indicating presence of very heavy materials towards interior of earth. The interior of the earth can be classified into three major categories as Crust, Mantle and Core (refer Figure 1.1).

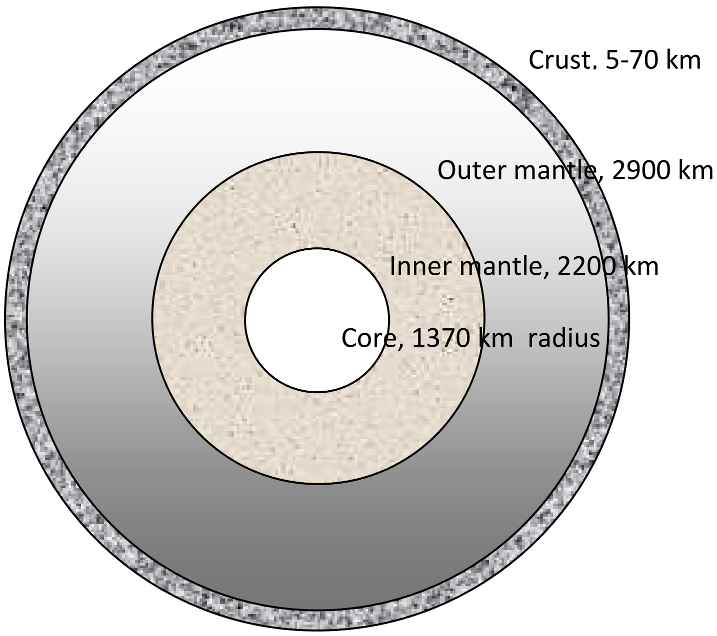


Figure 1.1 Cross-section of interior of earth.

Crust: or the lithosphere, is the outer part of the earth is where the life exist. The average thickness of crust beneath continents is about 40km where as it decreases to as much as 5km beneath oceans. The oceanic crust is constituted by basaltic rocks and continental part by granitic rocks overlying the basaltic rocks. Compared to the layers below, this layer has high rigidity and anisotropy.

Mantle: is a 2900 km thick layer. The mantle consists of 1) Upper Mantle reaching a depth of about 400 km made of olivine and pyroxene and 2) Lower Mantle made of more homogeneous mass of magnesium and iron oxide and quartz. No earthquakes are recorded in the lower mantle. The specific gravity of mantle is about 5. The mantle has an average temperature of about 2200degree Celsius and the material is in a viscous semi molten state. The mantle act like fluid in response to slowly acting stresses and creeps under slow loads. But it behaves like as solid in presence of rapidly acting stresses, e.g. that caused by earthquake waves.

Core: has a radius of 3470 km and consists of an inner core of radius 1370 km and an outer core (1370 km < R < 3470 km). The core is composed of molten iron, probably mixed with small quantities of other elements such as nickel and sulphur or silicon. The inner solid core is very dense nickel-iron material and is subjected to very high pressures. The maximum temperature in the core is estimated to be about 3000 degree Celsius. The specific gravity of outer core is about 9-12 where as that of inner core is 15.

1.3. Continental Drift and Plate Tectonics

1.3.1. Continental drift theory

German scientist Alfred Wegener, in 1915, proposed the hypothesis that the continents had once formed a single landmass before breaking apart and drifting to their present locations. His observations were based on the similarity of coastlines and geology between south America, Africa and Indian peninsula, Australia and Antarctica, Figure 1.2. He proposed that a large continent termed Pangae existed in earth around 200 million years ago and was surrounded by an ocean called Panthalassa. It was postulated that this super continent broke into several pieces that formed the present continents. These pieces have subsequently drifted into their current position. Although, he presented much evidence for continental drift, he was unable to provide a convincing explanation for the physical processes which might have caused this drift. He suggested that the continents had been pulled apart by the centrifugal pseudo force of the Earth's rotation or by a small component of astronomical precession. But the calculations showed that these forces were not sufficient cause continental drift.

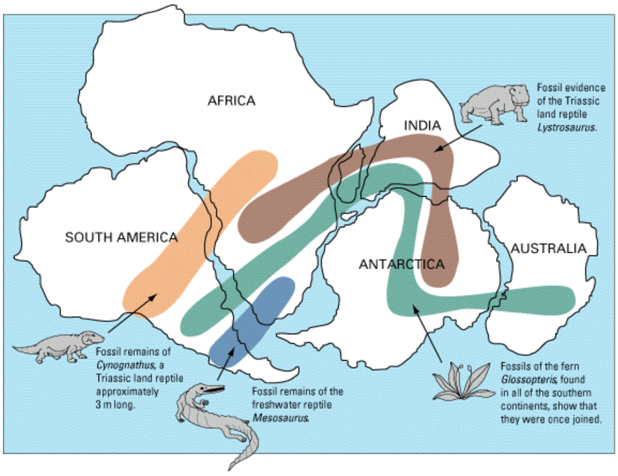


Figure 1.2 Similarity between the coastlines continents and distribution of fossils of ancient biota [Source: http://facstaff.gpc.edu/~pgore /Earth&Space/images/Fig4.gif].

1.3.2. Plate tectonics

The theory of plate tectonics, presented in early 1960s, explains that the lithosphere is broken into seven large (and several smaller) segments called plates as shown in Figure 1.3.

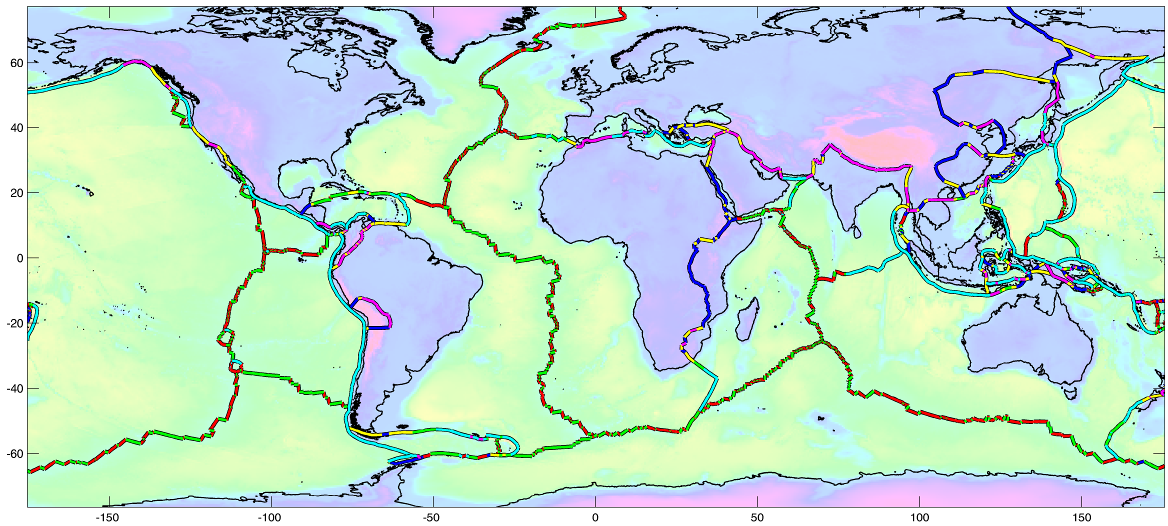


Figure 1.3 Tectonic plate map of the world.

The upper most part of the earth is considered to be divided into two layers with different deformation properties. The upper rigid layer, called the lithosphere, is about 100 km thick below the continents, and about 50 km under the oceans, and consists of Crust and rigid upper-mantle rocks. The lower layer, called the asthenosphere, extends down to about 700 km depth. The rigid lithospheric shell is broken into several irregularly shaped major plates and a large number of minor or secondary plates. The lithospheric plates are not stationary, on the contrary, they float in a complex pattern, with a velocity of some 2-10 cm/year on the soft rocks of the underlying asthenosphere like rafts on a lake.

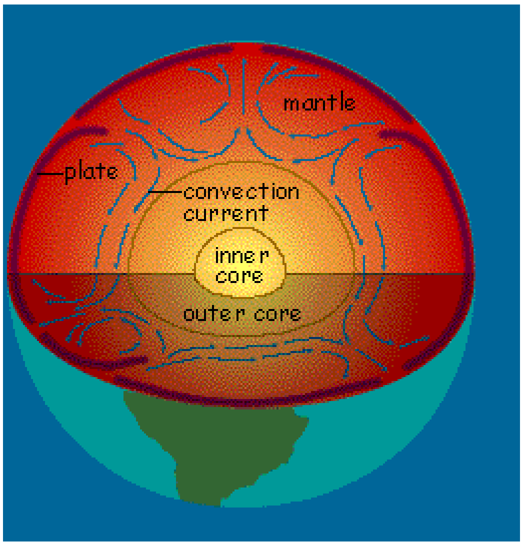


Figure 1.4 The state of convection currents below the earth's surface and their effect on plate movement (From http://www.pbs.org/gbh/aso/ tryit/ tectonics/intro.html].

This theory requires a source that can generate tremendous force is acting on the plates. The widely accepted explanation is based on the force offered by convection currents created by thermo-mechanical behavior of the earth's subsurface. The variation of mantle density with temperature produces an unstable equilibrium. The colder and denser upper layer sinks under the action of gravity to the warmer bottom layer which is less dense. The lesser dense material rises upwards and the colder material as it sinks gets heated up and becomes less dense (refer Figure 1.4). These convection currents create shear stresses at the bottom of the plates which drags them along the surface of earth.

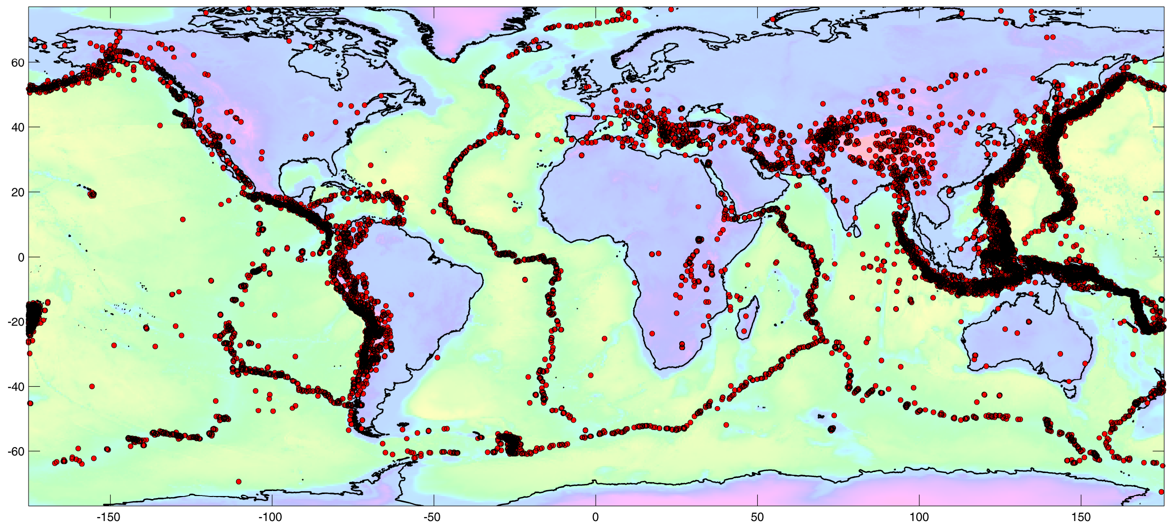


Figure 1.5 Map of distribution of earthquake epicentres around the world.

The continental sized plates are African, American, Antarctic, Indo-Australian, Eurasian and pacific plate. Apart from this, several smaller plates like Andaman, Philippine plate also exist. As plate glides over the asthenosphere, the continents and oceans move with it. Because the plates move in different directions, they knock against their neighbors at boundaries. The great forces thus generated at plate boundary build mountain ranges, cause volcanic eruptions and earthquakes. Most of the Earth's major geological activity occurs at plate boundaries, the zones where plates meet and interact. Figure 1.5 depicts the distribution of earthquake epicentres around the world.

The earthquake that occurs at a plate boundary is known as inter-plate earthquake. Not all earthquakes occur at plate boundaries. Though, interior portion of a plate is usually tectonically quiet, earthquakes also occur far from plate boundaries. These earthquakes are known as intra-plate earthquakes. The recurrence time for an intra-plate earthquake is much longer than that of inter-plate earthquakes

1.4. Movement of Plate Boundaries

Owing to the difference in movement between the plates that are in motion, three types of plate boundaries are found to exist along their edges:

1) *Spreading ridges*

Spreading ridges or divergent boundaries are areas along the edges of plates move apart from each other, Figure 1.6. This is the location where the less dense molten rock from the mantle rises upwards and becomes part of crust after cooling. Highest rate of spreading or expansion between plates is found to occur near Pacific Ocean ridges and the lowest rate of spreading occurs along mid-Atlantic ridges. Generally, spreading ridges are located beneath the oceans. A few areas where the spreading occurs along the continental mass are East African rift valley and Iceland.

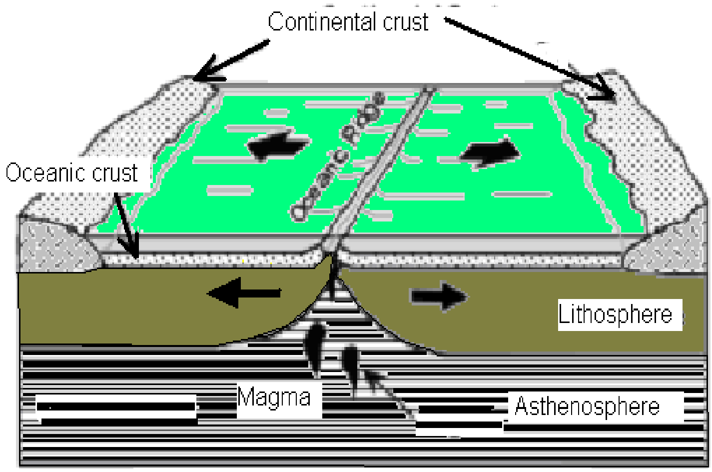


Figure 1.6 A cross-section of the divergent plate boundary.

2) *Convergent boundaries*

The convergent boundaries are formed where the two plates move toward each other. In this process, one plate could slip below the other one or both could collide with each other.

a. Subduction boundaries

These boundaries are created when either oceanic lithosphere subducts beneath oceanic lithosphere (ocean-ocean convergence), or when oceanic lithosphere subducts beneath continental lithosphere (ocean-continent convergence), Figure 1.7. The junction where the two plates meet, a trench known as *oceanic trench* is formed.

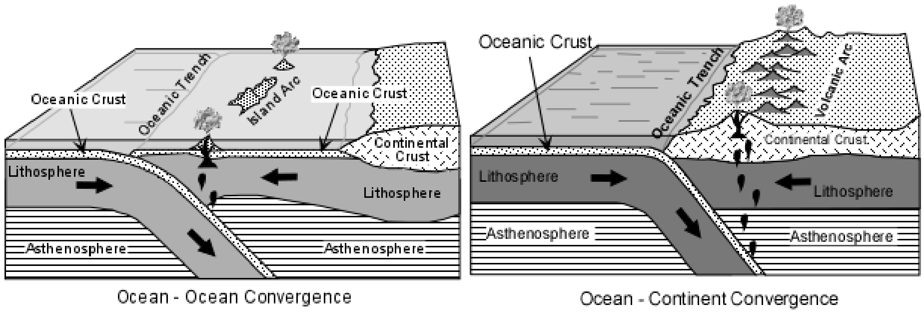


Figure 1.7 Creation of subduction boundaries [From: http://www.tulane.edu/~sanelson/geol204/struct&materials.htm].

When two plates of oceanic lithosphere run into one another, the subducting plate is pushed to depths where it causes melting to occur. When a plate made of oceanic lithosphere runs into a plate with continental lithosphere, the plate with oceanic lithosphere subducts because it has a higher density than continental lithosphere. The subducted plate melts as it encounters higher temperature regime inside earth melts and produces magma. This magma rises to the surface to produce chains of volcanos and islands known as island arcs. One of the areas around Indian peninsula where subduction process is in progress is near Andaman-Sumatra region, where the Indo-Australian plate is subducting below the Andaman and Sunda plates, Figure 1.8.

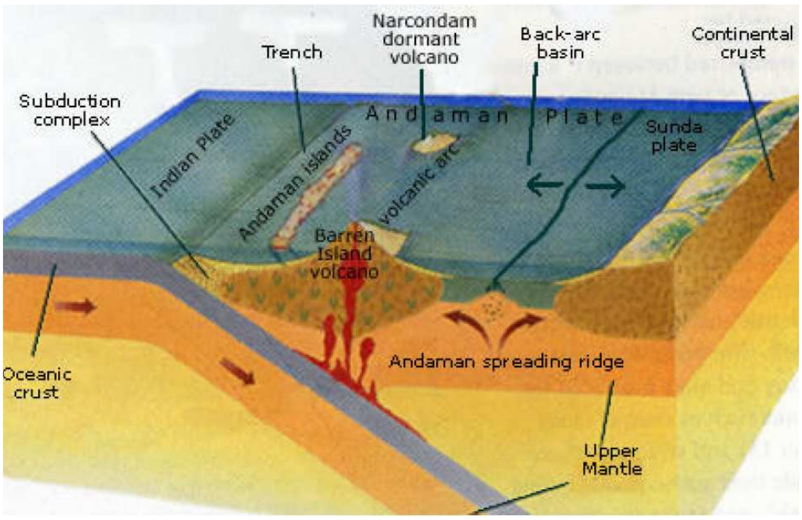


Figure 1.8 Subduction process along Andaman-Sumatra arc, [From Geological Survey of India, http://www.portal.gsi.gov.in/gsiDoc/pub/cs_sumatra.pdf].

b. Collision Boundaries

When two plates with continental lithosphere collide, subduction ceases and a mountain range is formed by squeezing together and uplifting the continental crust on both plates, Figure 1.9. The Himalayan Mountains between India and China were formed in this way.

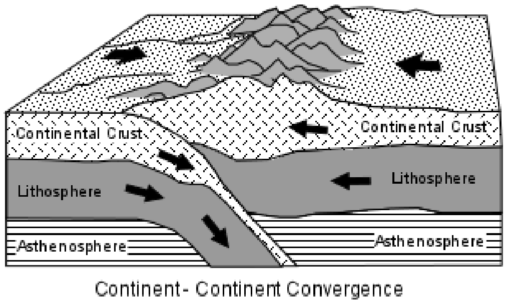


Figure 1.9 Creation of collision boundaries [From http://www.tulane.edu/~sanelson /geol204/struct&materials.htm].

3) Transform boundaries

Transform boundaries occur along the plate margins where two plate moves past each other without destroying or creating new crust, Figure 1.10.

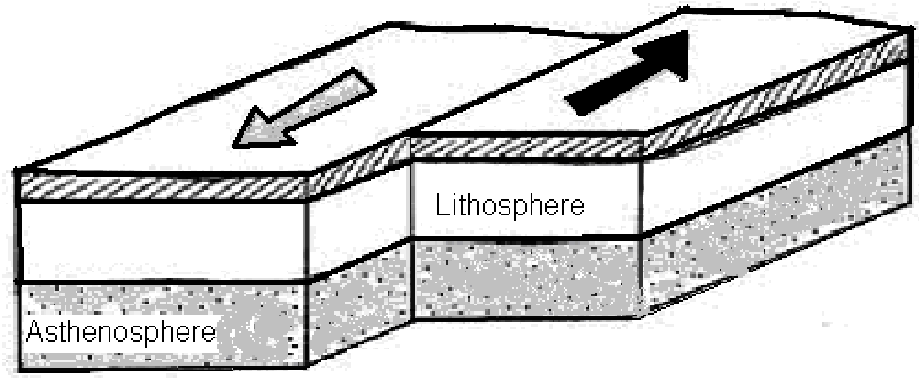


Figure 1.10 A typical profile of a transform plate boundary.

1.5. Faults

The term fault is used to describe a discontinuity within rock mass, along which movement had happened in the past. Plate boundary is also a type of fault. Lineaments are mappable linear surface features and may reflect subsurface phenomena. A lineament could be a fault, a joint or any other linear geological phenomena. Most faults produce repeated displacements over geologic time. Movement along a fault may be gradual or sometimes sudden thus, generating an earthquake.

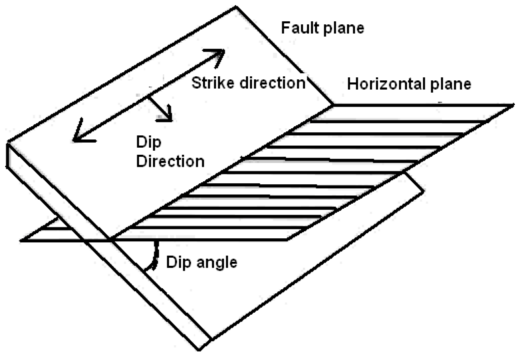


Figure 1.11 Various terminolgies assocaited with the rupture plane of a fault.

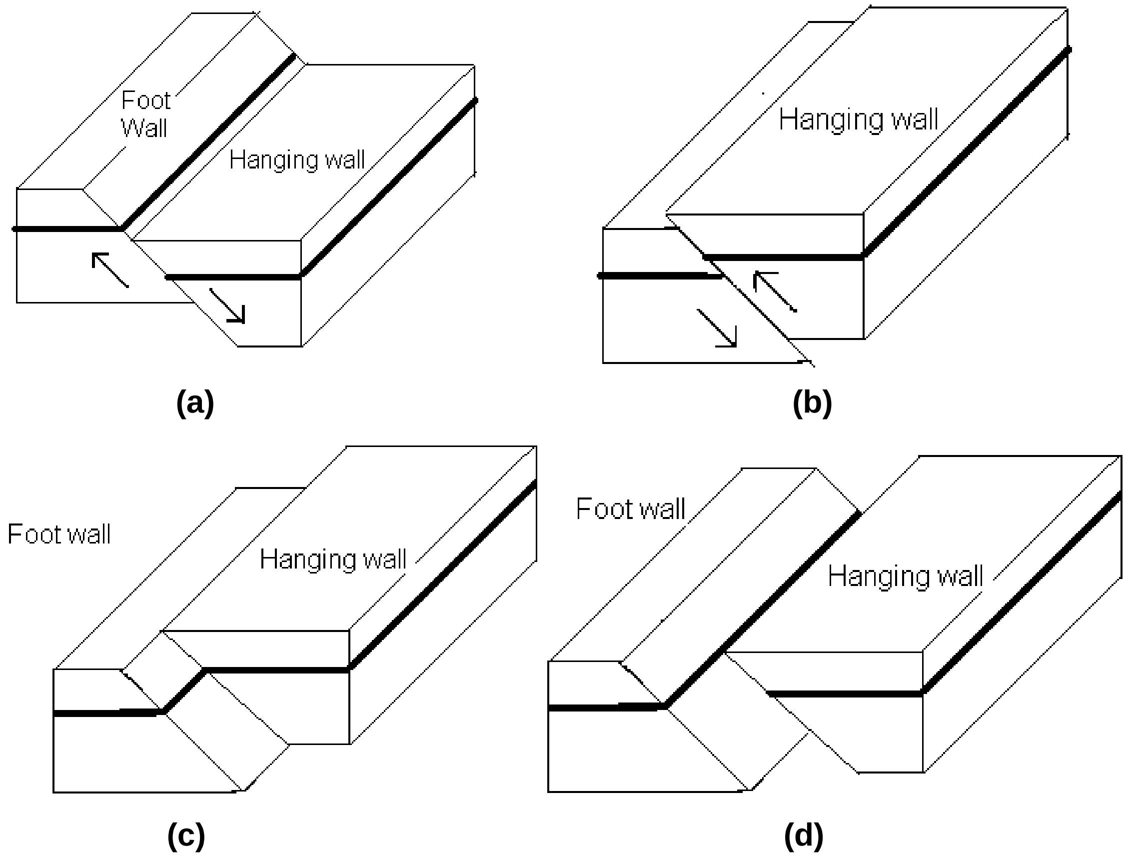


Figure 1.12 Types of faults (Arrow shows direction of relative displacement)
(a) Normal fault; (b) Reverse fault; (c) Strike-slip fault; (d) Oblique fault.

There are two important parameters associated with describing faults, namely, dip and strike, Figure 1.11. The strike is the direction of a horizontal line on the surface of the fault. The dip, measured in a vertical plane at right angles to the strike of the fault, is the angle of fault plane with horizontal. The hanging wall of a fault refers to the upper rock surface along which displacement has occurred, whereas the foot wall is the term given to that below. The vertical shift along a fault plane is called the throw, and the horizontal displacement is termed as heave.

Faults are classified in to dip-slip faults, strike-slip faults and oblique-slip faults based on the direction of slippage along the fault plane, Figure 1.12. In a dip-slip fault, the slippage occurred along the dip of the fault, Figure – 1.12(a) and (b). In case of a strike-slip fault, the movement has taken place along the strike, Figure 1.12(c). The movement occurs diagonally across the fault plane in case of an oblique slip fault, Figure 1.12(d). Based on relative movement of the hanging and foot walls faults are classified into normal, reverse and wrench faults. In a normal fault, the hanging wall has been displaced downward relative to the footwall, Figure 1.12(a). In a reverse fault, the hanging wall has been displaced upward relative to the footwall, Figure 1.12 (b). In a wrench fault, the foot or the hanging wall do not move up or down in relation to one another, Figure 1.12 (c). Thrust faults, which are a subdivision of reverse faults, tend to cause severe earthquakes.

Faults are nucleating surfaces for seismic activity. The stresses accumulated due to plate movement produces strain mostly along the boundary of the plates. This accumulated strain causes rupture of rocks along the fault plane.

1.6. Elastic Rebound theory

As the plate try to move relative to each other, strain energy gets built up along the boundaries. When the stress buildup reaches the ultimate strength of rock, rock fractures and releases the accumulated strain energy, Figure 1.13. The nature of failure dictates the effect of the fracture. If the material is very ductile and weak, hardly any strain energy could be stored in the plates due to their movement. But if the material is strong and brittle, the stress built up and subsequent sudden rupture releases the energy stored in the form of stress waves and heat. The propagation of these elastic stress waves causes the vibratory motion associated with earthquakes.

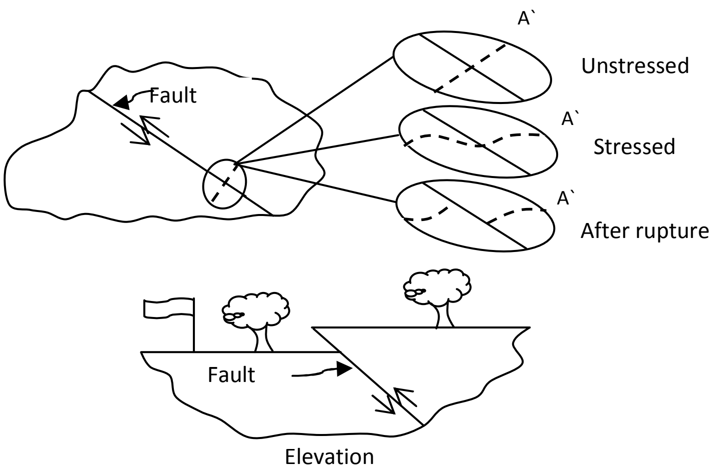


Figure 1.13 Elastic rebound across a fault.

The region on the fault, where rupture initiates is known as the focus or hypocenter of an earthquake. Epicenter is the location on the earth surface vertically above the focus. Distance from epicenter to any place of interest is called the epicentral distance. The depth of the focus from the epicenter is the focal depth. Earthquakes are sometime classified into shallow focus, intermediate focus and deep focus earthquakes based on its focal depth. Most of the damaging earthquakes are shallow focus earthquakes.

1.7. Earthquakes

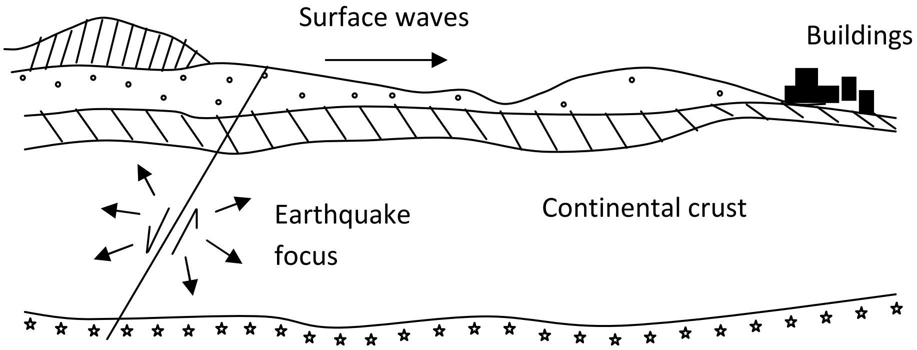


Figure 1.14 General depiction of an earthquake rupture scenario.

Earthquake is the vibration of earth's surface caused by waves coming from a source of disturbance inside the earth (refer Figure 1.14). Most earthquakes of engineering significance are of tectonic origin and is caused by slip along geological faults.

The typical characteristics of earthquake depends on

1. Stress drop during the slip
2. Total fault displacement
3. Size of slipped area
4. Roughness of the slipping process
5. Fault shape(Normal fault, Reverse fault, Strike slip fault)
6. Proximity of the slipped area to the ground surface
7. Soil condition

As the waves radiate from the fault, they undergo geometric spreading and attenuation due to loss of energy in the rocks. Since the interior of the earth consists of heterogeneous formations, the waves undergo multiple reflections, retraction, dispersion and attenuation as they travel. The seismic waves arriving at a site on the surface of the earth are a result of complex superposition giving rise to irregular motion

1.8. Earthquake Waves

Earthquake vibrations originate from the point of initiation of rupture and propagates in all directions. These vibrations travel through the rocks in the form of elastic waves. Mainly there are three types of waves associated with propagation of an elastic stress wave generated by an earthquake. These are primary (P) waves, secondary (S) waves and surface waves. In addition, there are sub varieties among them. The important characteristics of these three kinds of waves are as follows:

1.8.1. Primary (P) Waves

These are known as primary waves, push-pull waves, longitudinal waves, compressional waves, etc. These waves propagate by longitudinal or compressive action, which mean that the ground is alternately compressed and dilated in the direction of propagation, Figure 1.15. P waves are the fastest among the seismic waves and travel as fast as 8 to 13 km per second. Therefore, when an earthquake occurs, these are the first waves to reach any seismic station and hence the first to be recorded. The P waves resemble sound waves because these too are compressional or longitudinal waves in nature. Hence, the particles vibrate to and fro in the direction of propagation (i.e. longitudinal particle motion). These waves are capable of traveling through solids, liquids and gases.

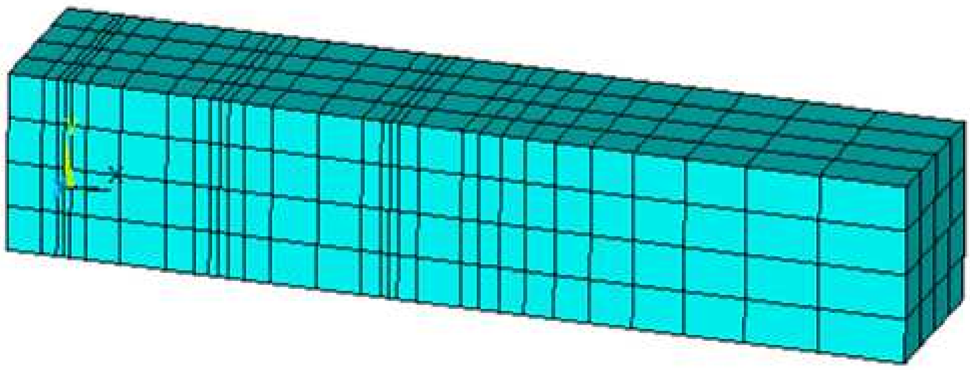


Figure 1.15 Nature of propagation of P waves.

The P-waves propagates radial to the source of the energy release and the velocity is expressed by

$$V_p = \sqrt{\frac{E}{\rho}\frac{(1-\nu)}{(1+\nu)(1-2\nu)}} \qquad (1.1)$$

where *E* is the Young's modulus; ν is the Poisson's ratio (0.25); and ρ is the density.

1.8.2. Secondary (S) Waves

These are also called shear waves, secondary waves, transverse waves, etc. Compared to P waves, these are relatively slow. These are transverse or shear waves, which mean that the ground is displaced perpendicularly to the direction of propagation, Figure 1.16. In nature, these are like light waves, i.e., the waves move perpendicular to the direction of propagation. Hence, transverse particle motion is characteristic of these waves. These waves are capable of traveling only through solids. If the particle motion is parallel to prominent planes in the medium they are called SH waves. On the other hand, if the particle motion is vertical, they are called SV waves. The shear wave velocity is given by

$$V_s = \sqrt{\frac{E}{2\rho(1+\nu)}} = \sqrt{\frac{G}{\rho}} \tag{1.2}$$

where $G = \dfrac{E}{2(1+\nu)}$ is the shear modulus.

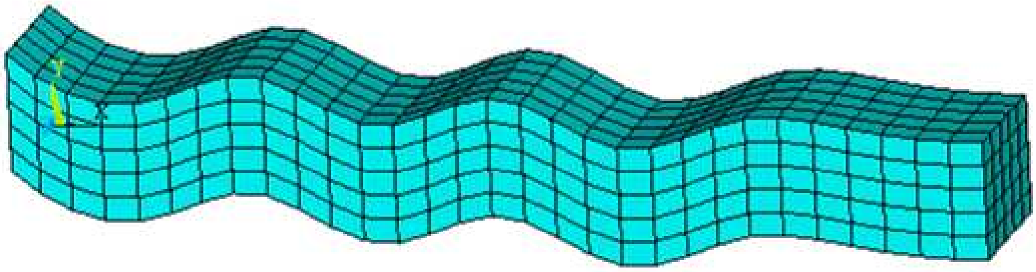


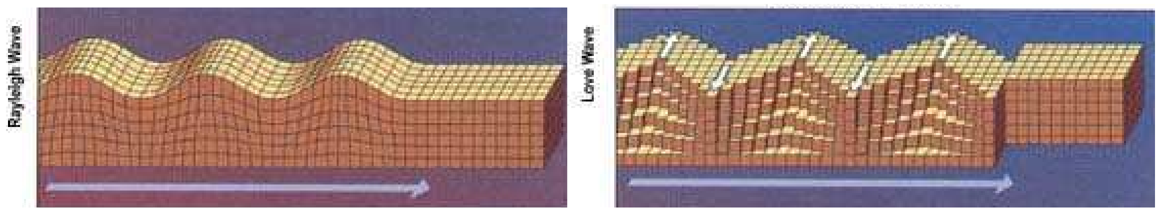
Figure 1.16 Nature of propagation of S waves.

They travel at the rate of 5 to 7 km per second. For this reason these waves are always recorded after P waves in a seismic station.

1.8.3. Surface Waves

When the vibratory wave energy is propogating near the surface of the earth rather than deep in the interior, two other types of waves known a Rayleigh and Love waves can be identified. These are called surface waves because their journey is confined to the surface layers of the earth only. Surface waves travel through the earth crust and does not propagate into the interior of earth unlike P or S waves.

Surface waves are the slowest among the seismic waves. Therefore, these are the last to be recorded in the seismic station at the time of occurrence of the earthquake. They travel at the rate of 4 to 5 km per second. Complex and elliptical particle motion is characteristic of these waves. These waves are capable of travelling through solids and liquids. They are complex in nature and are said to be of two kinds, namely, Raleigh waves and Love waves.



(a) **(b)**

Figure 1.17 Nature of propagation of (a) Rayleigh waves and (b) Love Waves (from http://earthquake.usgs.gov)

The Rayleigh surface waves are tension-compression waves similar to the P-waves expect that their amplitude diminishes with distance below the surface of the ground. Similarly, the Love waves are the counterpart of the "S" body waves; they are shear waves that diminishes rapidly with distance below surface, Figure 1.17.

The damage and destruction associated with earthquakes can be mainly attributed to surface waves. This damage potential and the strength of the surface waves reduce with increase in depth of earthquakes.

1.9. Earthquake Terminology

The motion of plates results in stress buildup along plate boundaries as well as in interior domain of the plate. Depending on the state of buildup of stress and amount of resistance offered by the fault strata, rupture is initiated as stress exceeds the capacity of the strata. Generally, the rupture causing earthquakes initiates from a point, termed as hypocenter or focus, which subsequently spreads over to a large area. Depending on the characteristics of strata where rupture occurs, the shape of the ruptured area could be highly irregular and the amount of interface slip along the ruptured surface could also vary. Several terms associated with earthquake rupture/propagation are discussed given below:

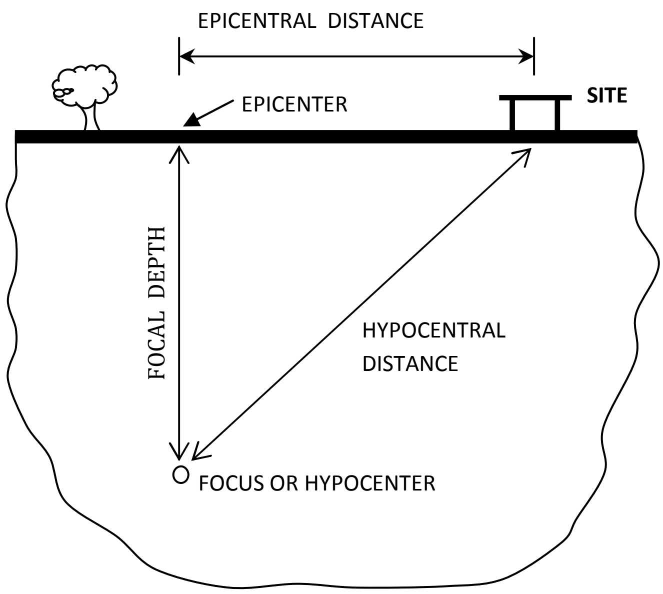


Figure 1.18 Various distance measurements associated with earthquake.

The place of origin of the earthquake in the interior of the earth is known as *focus* or origin or centre or *hypocenter* (refer Fig. 1.18). The place on the earth's surface, which lies exactly above the centre of the earthquake, is known as the 'epicenter'. For obvious reasons, the destruction caused by the earthquake at this place will always be maximum and with an increasing distance from this point, the intensity of destruction also decreases. The point on earth's surface diametrically opposite to the epicenter is called the anti-center. An imaginary line which joins the points at which the earthquake waves have arrived at the earth's surface at the same time is called a 'co-seismal'. In homogeneous grounds with plain surfaces, the iso-seismals and co-seismals coincide. Of course, in many cases due to surface and subsurface irregularities, such coincidence may not occur.

1.10. Recording Earthquakes [Murty, 2005]

The vibratory motion produced during an earthquake could be measured in terms of displacement, velocity or acceleration. A seismologist is interested in even small amplitude ground motions (in terms of displacement) that provides insight into the wave propagation characteristics and enables him to estimate the associated earthquake parameters.

As accelerations are the causative phenomena for forces that damage structures (Force = mass x acceleration), engineers are more concerned with the earthquake causing structural damage, hence are interested in acceleration measurement.

The instruments measure the ground displacements and are called seismographs. The record obtained from a seismograph is called a seismogram.

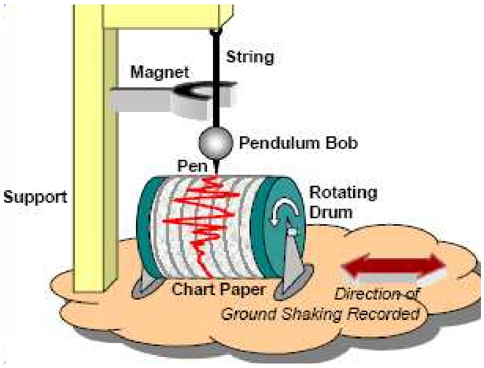


Figure 1.19 Schematic of a seismograph [Source: IIT-K BMTPC Eq Tips – 02].

The seismograph has three components – the sensor, the recorder and the timer. The principle on which it works is simple and is explicitly reflected in the early seismograph – a pen attached at the tip of an oscillating simple pendulum (a mass hung by a string from a support) marks on a chart paper that is held on a drum rotating at a constant speed. A magnet around the string provides required damping to control the amplitude of oscillations. The pendulum mass, string, magnet and support together constitute the sensor; the drum, pen and chart paper constitutes the recorder; and the motor that rotates the drum at constant speed forms the timer, Figure 1.19. By varying the characteristics of equipment one could record displacement, velocity or acceleration during an earthquake

The devises that measure the ground accelerations are called accelerometer. The accelerometers register the accelerations of the soil and the record obtained is called an accelerogram. Further discussions on accelerograms and its engineering applications are covered in section 2.

1.11. Determination of Hypocenter or Earthquake Focus

Seismologists use the elapsed time between the arrival of a P-waves and S-waves at a given site to assist them in estimating the distance from the site to the center of energy release. The distance of focus from the observation station is determined by the relative arrival times of the P and S waves. The distance from hypocenter to observation point is given by

$$S = \frac{T}{\left(\frac{1}{V_s} - \frac{1}{V_p}\right)} \tag{1.3}$$

where, T=difference in time of arrival of P and S waves at an observation point; S= distance from hypocenter to observation point; and V_p and V_s are the velocity of P and S waves, respectively.

The time T can be taken as the time of duration of the initial tremor to it built-up while V_p and V_s are geological properties for a given locations. Thus, the distance from the hypocenter to the observation point is approximately proportional to the time of duration of the initial tremor; the coefficient of proportionality is about 8 km/sec. When S has been determined for each of three observation points the hypocenter is located as the point of intersection of these spheres.

1.12. Size of Earthquakes

The size of earthquake could be related to the damage caused or parameters like magnitude. These two useful definitions of the size of earthquakes are sometimes confused.

1.12.1. Intensity of Earthquakes

The intensity of an earthquake refers to the degree of destruction caused by it. In other words, intensity of an earthquake is a measure of severity of the shaking of ground and its attendant damage. This, of course, is empirical to some extent because the extent of destruction or damage that takes place to a construction at a given place depends on many factors. Some of these factors are: (i) distance from the epicenter, (ii) compactness of the underlying ground, (iii) type of construction (iv) magnitude of the earthquake (v) duration of the earthquake and (vi) depth of the focus. Intensity is the oldest measure of earthquake.

The seismic intensity scale consists of a series of certain key responses such as people awakening, movement of furniture, damage to chimneys, and finally - total destruction. Numerous intensity scales have been developed over the last several hundred years to evaluate the effects of earthquakes, the most popular is the Modified Mercalli Intensity (MMI) Scale. This scale, composed of 12 increasing levels of intensity that range from imperceptible shaking to catastrophic destruction, is designated by Roman numerals. It does not have a mathematical basis; instead it is an arbitrary ranking based on observed effects. The lower numbers of the intensity scale generally deal with the manner in which the earthquake is felt by people. The higher numbers of the scale are based on observed structural damage. An abbreviated version of the MMI scale is given in Table 1.1 as per IS-1893:1984.

Another intensity scale is Mendvedev-Spoonheuer-Karnik scale (MSK 64). This scale is more comprehensive and describes the intensity of earthquake more precisely. Indian seismic zones were categorized on the basis of MSK 64 scale.

Some of the other intensity scales used are Rossi-Forel (RF) scale, Japanese Meteorological Agency (JMA) intensity scale, etc. Figure 1.20 gives a comparison of the various seismic intensity scales used worldwide.

An imaginary line joining the points of same intensity of the earthquake is called an 'iso-seismal'. In plan, the different iso-seismals will appear more or less as concentric circles over a plain, homogeneous ground if the focus of the earthquake is a point. On the other hand, if the focus happens to be a linear tract, the iso-seismals will occur elongated. Naturally, the areas or zones enclosed by any two successive iso-seismals would have suffered the same extent of destruction.

Over the years, researchers have tried to develop more quantitative ways for estimating earthquake intensity. One of such relationships correlating earthquake intensity to peak ground velocity is given by

$$\text{MMI} = \frac{\log_{10} 14V_g}{\log_{10} 2} \qquad (1.4)$$

where V_g is the peak ground velocity in cm/sec.

Another such relation reported by Wald et.al, (1999) based on Californian earthquake database is

$$\text{MMI} = 3.47 \log(V_g) + 2.35 \qquad (1.5)$$

In addition to peak ground velocity, empirical relationships correlating peak ground acceleration to MMI has also been reported. For e.g.,

$$\text{MMI} = 3.66 \log (\text{Peak Ground Acceleration in cm/sec/sec}) – 1.66 \qquad (1.6)$$

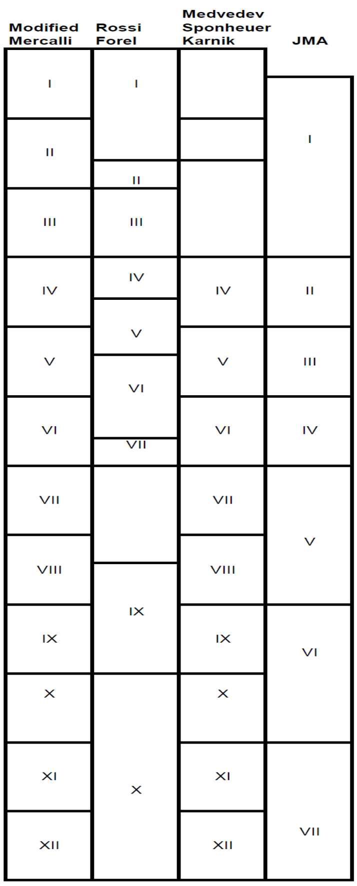


Figure 1.20 A comparison of various seismic intensity scales used worldwide.

Table 1.1 Modified Mercalli Intensity Scale (IS-1893:1984).

MMI Intensity	Remarks
I	Not felt except by a very few under specially favourable circumstances
II	Felt only by a few persons at rest, specially on upper floors of buildings; and delicately suspended objects may swing.
III	Felt quite noticeably indoors, specially on upper floors of buildings but many people do not recognise it as an earthquake; standing motor cars may rock slightly; and vibrations may be felt like the passing of a truck.
IV	During the day felt indoors by many, outdoors by a few, at night some awakened; dishes, windows, doors disturbed; walls make creaking sound, sensation like heavy truck striking the building; and standing motor cars rock noticeably.
V	Felt by nearly everyone; many awakened; some dishes, windows, etc, broken; a few instances of cracked plaster; unstable objects overturned; disturbance of trees, poles and other tall objects noticed sometimes; and pendulum clocks may stop.
VI	Felt by all, many frightened and run outdoors; some heavy furniture moved; a few instances of fallen plaster or damaged chimneys; and damage slight.
VII	Everybody runs outdoors, damage negligible in buildings of good design and construction; slight to moderate in well built ordinary structures; and some chimneys broken, noticed by persons driving motor cars.
VIII	Damage slight in specially designed structures; considerable in ordinary but substantial buildings with partial collapse; very heavy in poorly built structures; panel walls thrown out of framed structures; falling of a chimney, factory stacks, columns, monuments, and walls; heavy furniture overturned, sand and mud eject in small amounts; changes in well water; and disturbs persons driving motor cars
IX	Damage considerable in specially designed structures; well designed framed structures thrown out of plumb; very heavy in substantial buildings with partial collapse; building shifted off foundations; ground cracked conspicuously; and underground pipes broken.
X	Some well built wooden structures destroyed; most masonry and framed structures with foundations destroyed; ground badly cracked; rails bent; landslides considerable from river banks and steep slopes; shifted sand and mud; and water splashed over banks.
XI	Few, if any, masonry structures remain standing; bridges destroyed; broad fissures in ground, underground pipelines completely out of service; earth slumps and landslips in soft ground; and rails bent greatly.
XII	Total damage; waves seen on ground surfaces; lines of sight and levels distorted; and objects thrown upward into the air.

1.12.2. Magnitude of Earthquake

The magnitude of an earthquake is related to the amount of energy released by the geological rupture causing it, and is therefore a measure of the absolute size of the earthquake, without reference to distance from the epicenter. While earthquake intensity is depicted in Roman numerals and is always a whole number, magnitude is depicted in Arabic numerals and need not be a whole number. Similar to intensity scales, over the years, a number of approaches for measurement of magnitude of an earthquake have come into existence.

1.12.3. Richter Magnitude, ML

A workable definition of magnitude was first proposed by C.F. Richter. He based on the data from Californian earthquakes, defined the earthquake magnitude as the logarithm to the base 10 of the largest displacement of a standard seismograph (called Wood-Anderson Seismograph with properties T=0.8 sec; m=2800; and damping nearly critical ≈ 0.8) situated 100 km from the focus.

$$\mathrm{M}=\log_{10}A \qquad (1.7)$$

where A denotes the amplitude in micron (10^{-6}m) recorded by the instrument located at an epicentral distance of 100 km; and M is the magnitude of the earthquake.

When the distance from the epicenter at which an observation is obtained other than 100 km, a correction is introduced to the equation as follows:

$$\mathrm{M}=\mathrm{M}_{\Delta}-1.73\log_{10}\left(\frac{100}{\Delta}\right) \qquad (1.8)$$

where M is the magnitude of the earthquake; Δ=distance from epicenter (km), M_{Δ}= magnitude of the earthquake calculated for earthquake using the values measured at a distance Δ from the epicenter. The graphical form of this procedure is given in Figure 1.21.

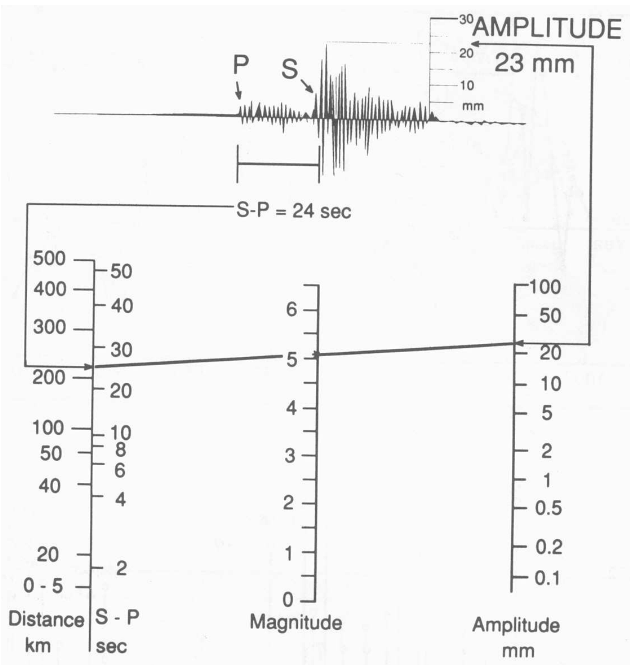


Figure 1.21 A graphical form of the estimation of Gutenberg – Richer magnitude [From Lay and Wallace, 1995].

Because of the logarithmic nature of the definition a difference of 1.0 in the magnitude represents a difference of 10 in the seismograph amplitude. Magnitude observations by different recording stations usually differ quite widely, often by as much as one magnitude, which is later corrected taking into account the recordings from a large number of instruments.

1.12.4. Moment magnitude

Over the years, scientists observed that different magnitude scales had saturation points and the magnitudes estimated by different approaches did not point to a unique value of earthquake size The Richter magnitude saturates at about 6.8, and the surface wave magnitude at about 7.8. In addition, these magnitude estimates did not have a linear relation with the energy released due to earthquake rupture. To address these short falls, Hanks and Kanamori, in 1979 proposed a magnitude scale, termed as 'moment magnitude', based on the seismic moment due to earthquake rupture. The moment magnitude is given by

$$M_w = \frac{2}{3}\left(\log_{10} M_0 - 9.1\right) \tag{1.9}$$

where M_w is the moment magnitude, M_0 is the seismic moment in N-m.

In addition to the magnitude scales as discussed, Surface wave magnitude, M_s, based on the amplitude of Rayleigh waves having a period of about 20 seconds, body wave magnitude, M_b based on the amplitude of first few P wave cycles are also being used.

A comparison of various magnitude scales are given in Figure 1.22. It can be noted from Figure that the moment magnitude does not saturate.

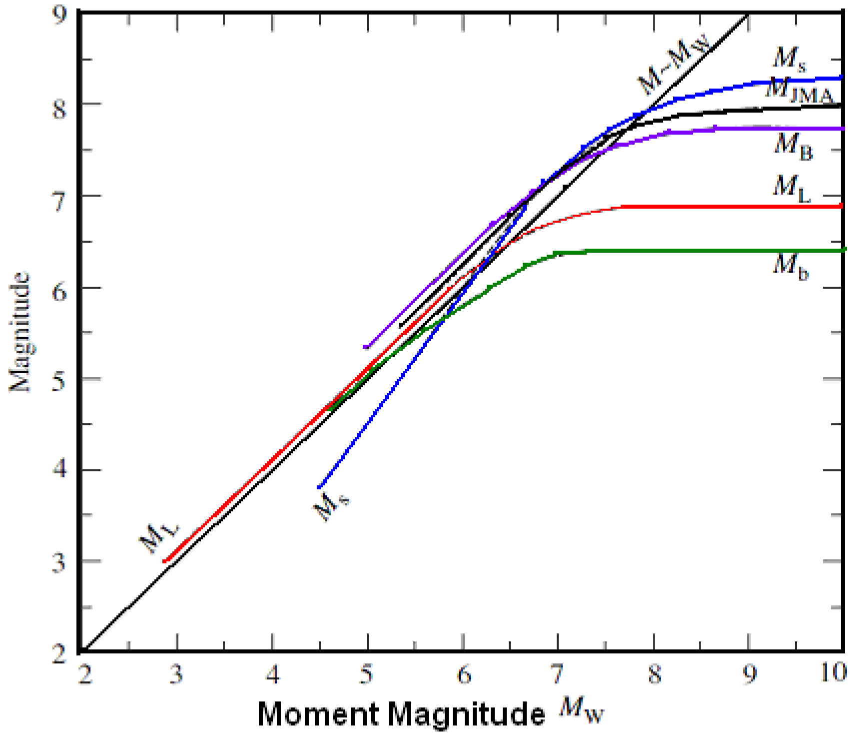


Figure 1.22 A comparison of different magnitude scales.

Example 1.1

Calculate the moment magnitude of an earthquake with the rupture area dimensions of length 35km, width 15km and slip 1meter. Assume modulus of rigidity, mu = 3.5 x 10^{10} N/m^2

Solution: Given

Length of ruptured area of fault : 35 km

Width of ruptured area of fault : 15km

Average slip : 1 m

Seismic moment = mu x Length x Widthx Slip

= 3.5 x 10^{10} x (35 x 1000) x (15 x 1000) x 1

= 1.84 x 10^{19} N-m

Earthquake magnitude, M_w = (2/3) x [log(1.84 x 10^{19}) – 9.1]

= 6.8

1.13. Energy of an Earthquake

An approximate relationship between surface wave magnitude, M_s, and the energy released by an earthquake, E, is given by

$$\log_{10} E = 4.8 + 1.5 M_s \qquad (1.10)$$

where E is measured in joules. Thus the ratio of energies released by two earthquakes differing by 1 is magnitude is equal to 31.6. The ratio is 1000 for earthquakes differing by 2 in magnitude, Table 1.2. Comparisons have been made between natural forces and nuclear weapons. The energy released by a 1 megaton hydrogen bomb is roughly equivalent to a magnitude 7.4 earthquake. Figure 1.23 shows the variation of the energy released against the magnitude.

Table 1.2: Increase in Energy Release for Various Range of Increase in Value of Magnitude

Increase in Magnitude	Increase in Energy Release
0.2	2 Times
0.447	5 Times
0.67	10 Times
1	31.6 Times
2	1000 Times

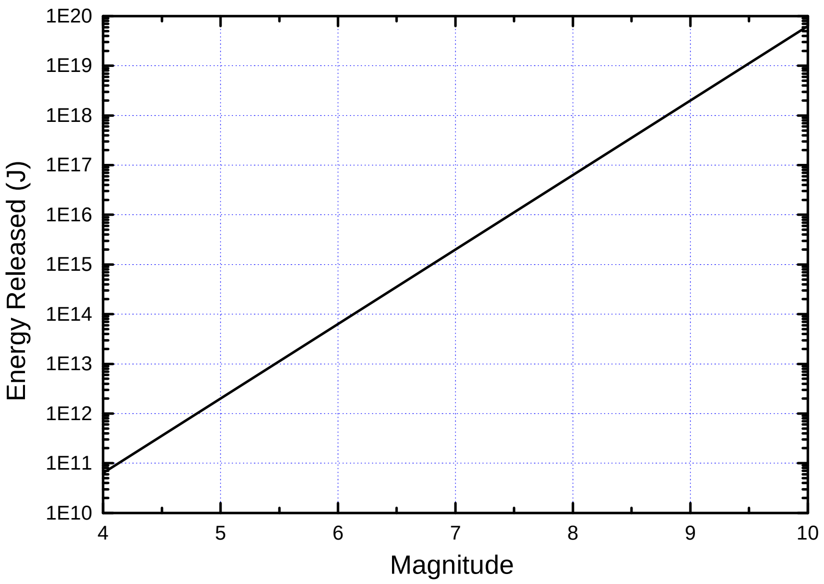


Figure 1.23: Energy magnitude relationships.

1.14. Comparison of Magnitude and Intensity

Comparisons between magnitude and intensity are fraught with difficulty. Firstly, intensity varies with distance from the epicentre. Secondly, a large earthquake may occur away from inhabited areas and therefore cause little apparent damage. Focal depth, ground conditions and quality of building construction can have a considerable effect on subjective assessments of damage. Magnitude-intensity relationships are not favoured for engineering purposes. However, intensity could be the only information available for large historical earthquakes and the inputs from intensity measurements would be necessary in estimating the maximum earthquake potential of the region.

In 1956, Richter proposed a simple relationship between magnitude and epicentral intensity given by

$$M_L = \frac{2}{3}(I_0) + 1 \tag{1.11}$$

The equation was derived by comparison of magnitude and epicentral intensity data of Californian earthquakes.

This relationship could vary from region to region. For e.g., Street and Turcotte in 1977 proposed a magnitude intensity relation specific to North-eastern North America, given by

$$m_{bLg} = 0.49(I_0) + 1.66 \tag{1.12}$$

However, it is found that correlations between intensity and magnitude are not particularly accurate for estimation of earthquake magnitude. In addition to epicentral intensity, researchers have attempted to associate other intensity related parameters like log of area with intensity greater than IV; log of felt area, fall off intensity, etc., with varying levels of success. Figure 1.24 shows a comparison of magnitudes estimated from intensity using different approaches as mentioned above.

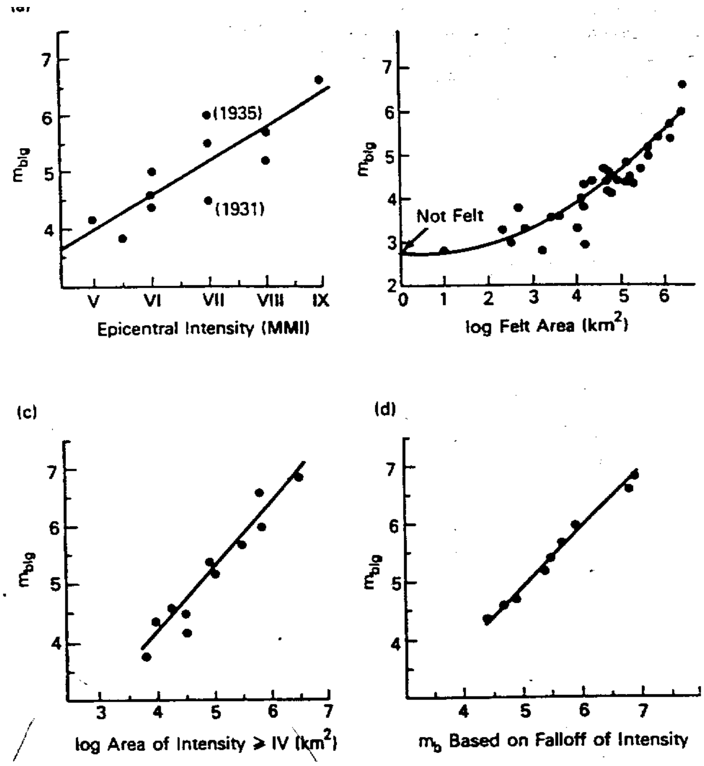


Figure 1.24 Correlation between earthquake magnitude and various intensity measures. [From Reiter L., 1989].

1.16 Tutorial Problems

1. Where do earthquakes happen?
2. Where do over 90% of earthquakes occur?
3. Why do earthquakes happen?
4. What are the formulae for P and S velocity?
5. What is an earthquake?
6. Indicate the approximate radius of the earth, inner core, and outer core.
7. How are Earthquake Magnitudes Measured?
8. What is a fault?
9. What are different types of faults?
10. What is the biggest earthquake recorded?
11. What is intensity?
12. The Mohorovicic discontinuity is the seismic boundary between

    (A) Crust and mantle.

    (B) Asthenosphere and lithosphere

    (C) Core and mantle

    (D) Mantle and lithosphere
13. Which type of seismic wave does not pass through a fluid?

    (A) Surface wave

    (B) Body wave

    (C) S-wave

    (D) P-wave
14. The size and shape of the earth's core can be measured by information from the

    (A) Earth's weight

    (B) S-wave shadow zone

    (C) nature of meteorites

(D) P-wave shadow zone

15. Part of the earth's core is believed to be liquid as indicated by information from the

    (A) Nature of meteorites

    (B) S-wave shadow

    (C) Earth's magnetic field.

    (D) P-wave shadow

16. The least dense rocks are found in

    (A) Continental crust.

    (B) Oceanic crust.

    (C) The mantle.

    (D) the core.

17. At a recording station a difference in time of arrival between P waves and S waves was observed to be 1.5 seconds. What is the approximate distance from the station at which the event occurred? Assume P wave velocity as 4 km/sec and S wave velocity as 2 km/sec.

18. During an earthquake the maximum amplitude recorded at a site by Wood-Anderson Seismograph is 20 cm. The maximum ground velocity recorded was 25 cm/sec. The site was found to be 75 km away from the epicenter. Determine the Magnitude and Intensity of the occurred earthquake.

19. The epicentral intensity of an earthquake that occurred in 1870 is estimated to be IX in MMI scale. Estimate the approximate magnitude of the earthquake.

20. Estimate the moment magnitude of an event with rupture length of 100km, rupture width of 45km and slip of average fault slip of 3m. Take modulus of rigidity, mu as 3.5×10^{10} N/m^2

1.17 Answers to Tutorial Problems

1. Earthquakes occur all the time all over the world, both along plate edges and along faults. Most earthquakes occur along the edge of the oceanic and continental plates. The earth's crust (the outer layer of the planet) is made up of several pieces, called plates. Earthquakes usually occur where two plates are running into each other or sliding past each other.

2. At plate boundaries

3. Earthquakes are usually caused when rock underground suddenly breaks along a fault. This sudden release of energy causes the seismic waves that make the ground shake.

4. The P-waves propagates radial to the source of the energy release and the velocity is expressed by

   $$V_p = \sqrt{\frac{E}{\rho}\frac{(1-\nu)}{(1+\nu)(1-2\nu)}}$$

   where E is the Young's modulus; ν is the Poisson's ratio (0.25); and ρ is the density.

   The shear wave velocity is given by

   $$V_s = \sqrt{\frac{E}{2\rho(1+\nu)}} = \sqrt{\frac{G}{\rho}}$$

   where $G = \dfrac{E}{2(1+\nu)}$ is the shear modulus

5. Earthquake is the vibration of earth's surface caused by waves coming from a source of disturbance inside the earth. Most earthquake of engineering significance is of tectonic origin and is caused by slip along geological faults.

6. The average thickness of crust beneath continents is about 40km where as it decreases to as much as 5km beneath oceans. Mantle is a 2900 km thick layer. The mantle consists of 1) Upper Mantle reaching a depth of about 400 km made of olivine and pyroxene and 2) Lower Mantle made of more homogeneous mass of magnesium and iron oxide and quartz. Core has a radius of 3470 km and consists of an inner core of radius 1370 km and an outer core (1370 km < R<3470 km).

7. The magnitude of most earthquakes is measured on the Richter scale, invented by Charles F. Richter in 1934. The Richter magnitude is calculated from the amplitude of the largest seismic wave recorded for the earthquake, no matter what type of wave was the strongest. The Richter magnitudes are based on a logarithmic scale (base 10).

8. A fault is a fracture or zone of fractures between two blocks of rock. Faults allow the blocks to move relative to each other. Faults may range in length from a few millimeters to thousands of kilometers.
9. During an earthquake, the rock on one side of the fault suddenly slips with respect to the other. The fault surface can be horizontal or vertical or some arbitrary angle in between. Earth scientists use the angle of the fault with respect to the surface (known as the dip) and the direction of slip along the fault to classify faults. Faults which move along the direction of the dip plane are dip-slip faults and described as either normal or reverse, depending on their motion. Faults which move horizontally are known as strike-slip faults and are classified as either right-lateral or left-lateral. Faults which show both dip-slip and strike-slip motion are known as oblique-slip faults
10. The largest earthquake to occur in the twentieth century is the 1960 Chilean earthquake, which occurred off the coast of South America. The magnitude of this earthquake has been estimated to be a 9.5. The earthquake created a deadly tsunami more than 10 m in height along the Chile coast, eliminating entire villages. Some hours later, the tsunami killed hundreds more in Japan, more than 13000 km from the earthquake source.
11. Of the two ways to measure earthquake size, magnitude is based on instrumental readings and intensity is based on qualitative effects of earthquakes.
12. Ans: A, Ugoslavian scientist Mohorovicic in 1909 discovered the boundary between the crust and the mantle. The boundary is a zone where seismic P-waves increase in velocity because of changes in the composition of the materials.
13. Ans: C, S-wave cannot because you can compress a fluid (P-wave) but you cannot shear a fluid (S-wave).
14. Ans: D, Seismic P-waves spread throughout the earth from a large earthquake. These waves are measured by seismic recording stations all around the world except between 103o and 142o of arc from the earthquake. This is the P-wave shadow zone,
15. Ans: B, The S-wave shadow zone is formed because S-waves cannot travel through the earth's core. This, and other seismic data indicate that the outer part is liquid, or at least it acts like a liquid.
16. Ans: A, continental crust.
17. Given

    V_p = 4000m/sec, V_s = 2000m/sec

    T = 1.5 sec

    Distance = 1.5 / { (1/2000) – (1/4000) }

    = 6000m = 6km.
18. Solution: Given Data

A=20 cm = 0.2 m = 0.2×10^6 micron

Δ=75km

V_g=25 cm/sec

The magnitude of the earthquake

$$M = \log_{10}(0.2\times10^6) - 1.73\log_{10}\left(\frac{100}{75}\right) = 5.1$$

The intensity of the earthquake

$$MMI = \frac{\log_{10}14\times25}{\log_{10}2} = 8.45 \text{ (say VIII)}$$

19. Solution: Given Data

Epicentral Intensity, I_0 = IX.

Equivalent earthquake magnitude = (2/3) I_0 +1

= (2/3) * 9 + 1 = 7

20. Solution: Given Data

Fault length = 35km = 35 x 1000 m

Fault width = 15km = 15 x 1000 m

Slip = 1m

Seismic moment = 3.5 x 10^{10} x 35 x 1000 x 15 x 1000 x 1 = 1.84 x 10^{19} N-m

Moment magnitude = (2/3)($\log_{10}$(1.84 x 10^{19}) – 9.1) = 6.8