Seismic Analysis of Structures
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Lecture - 01
Seismology

In this series of lectures on Seismic Analysis of Structures, we shall be covering 6 major topics namely: Seismology, Seismic Inputs, then the response analysis of structures for deterministic ground motion, the response analysis of structures for random ground motion using the spectral method of analysis, then the seismic response spectrum method of analysis and finally the inelastic response of structures for earthquake.

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We shall use the book by T. K. Datta on Seismic Analysis of Structures published by John Wiley. The PPT’s and the lecture materials all are prepared from that book. The last 2 links shows the records the Errata list of the book, so they are available from this Web links. The first 3 on the top web links they have the slides for this lecture series and one can download those slides free of charge because they are uploaded in a public domain.

Now, before I start the seismic analysis of structures specially the first topic that is the Seismology. Let me give you a very brief introduction about earthquake. Earthquake is a sudden and transient disturbance or motion on the surface of the earth produced due to geological disturbance within the earth itself.

The earth has suffered 100s of millions of earthquake in its formative stage before the human race came into existence. In the olden days people used to think earthquake as a curse of God, like other natural disasters. It is only in the 17th century or other the mid of 17th century that the earthquake was viewed as a geological process. Since, then systematic data and observations were recorded and utilizing those observations in the data, people try to understand about the earthquake phenomena occurring in the earth as a geological process.

Those data also help in providing the methods for the rational design an analysis of structures against earthquake. Those data also revealed some interesting features about earthquake that it is probabilistic nature. The future earthquakes are all random in the sense that the occurrence of earthquake is not precisely known. Therefore, the probabilistic modeling of earthquake and the probabilistic analysis of structures for the probabilistic ground motion became important.

Both the Seismologist and Earthquake Engineers they are interested in the recorded data, but for different purposes. The seismologist used the data for understanding the earthquake as a geological process, and try to look into the different causes aspects and other associated phenomena that lead to a better understanding of the earthquake process as such; whereas, the earthquake engineers use the data for constructing a seismic inputs for a structures and for analyzing and designing the structures. So the data which are recorded are they utilized by both seismologist and the earthquake engineers for their own professional purposes.

The data that is recorded they are systematically analyzed and many kinds of inputs for the analysis of structures were constructed from this particular data. Now before I get into the seismology that is the first part of first topic of the lecture.

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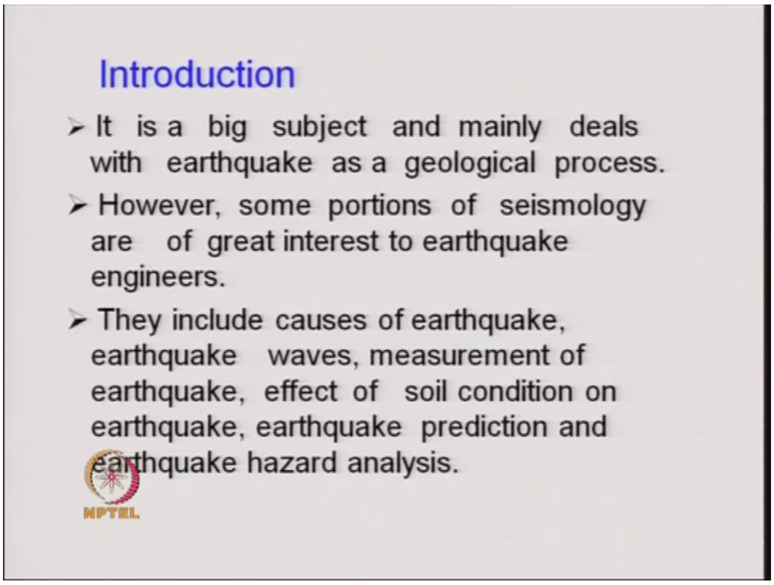

Let me tell you that the seismology itself is a very big subject and rather can form a series of lectures on the seismology itself. But there are certain portions of the seismology that are of great interest to earthquake engineers as well as to the seismologist as I told you before. They include the following that is a causes of earthquake, earthquake waves, measurement of earthquake, effect of soil condition on earthquake, then earthquake prediction and earthquake hazard analysis. So, these are the few topics on seismology that will be discussing in the first few lectures of these series.

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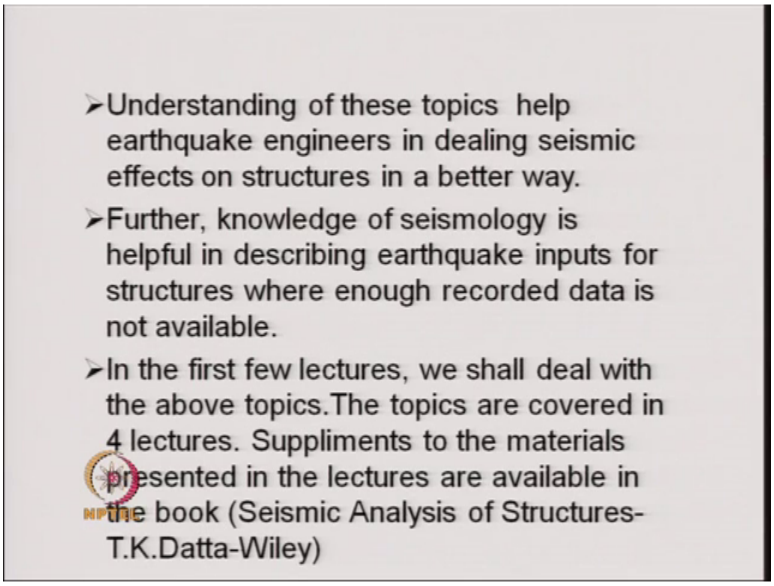

Understanding of these topics help in earthquake design and analysis of this structure in a better way further, the knowledge of seismology is helpful in describing earthquake inputs for structures where enough recorded data is not available. This is extremely important because there are many places where the earthquakes do occur and there is not a systematic recording data on the past earthquake. In those areas one can and construct artificially some earthquake inputs from the knowledge of seismology that earthquake engineers derived out of the data recorded on the earthquake.

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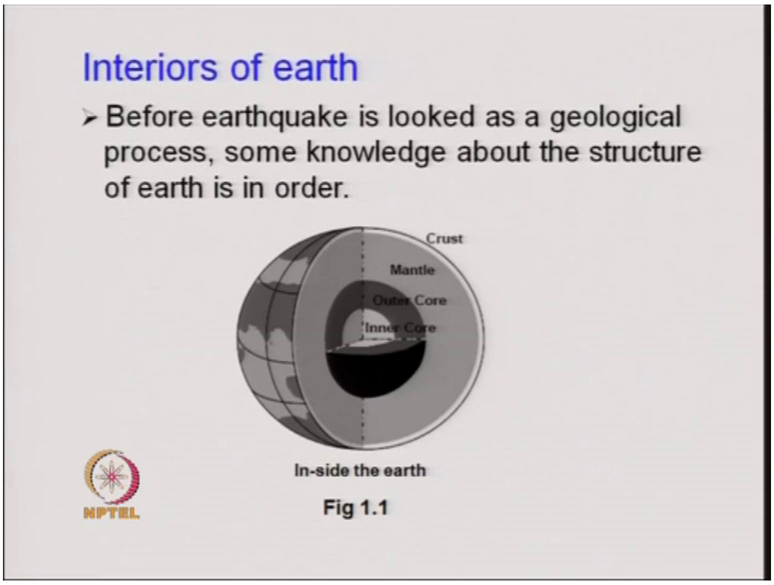

The seismology that we shall be discussing here requires some knowledge of the Interior of the earth. So, before we look into the earthquake as a geological process. Let us have a look into the interior of the earth.

The Figure 1.1 shows that the earth is made up of several layers; the top layer is called the Crust. It is a solid plate like substance slightly curved so that it can cover the entire outer surface of the earth, immediately below the crust is the Mantle. Mantle is a made up of molten material and therefore there is a distinct discontinuity between the mantle and the crust. The mantle is supported on the outer core and the inner core forming the core of the earth each one of these layers that is the inner core, outer core, mantle and the crust. They have a successively less density that means, the crust although it is a solid object it is having a less density compared to the mantle. Similarly mantle has a less density compared to outer code and so on.

Each layer has some distinct features and these distinct features in fact are the causes for many of the geological processes that takes place within the earth. First let us take the Crust.

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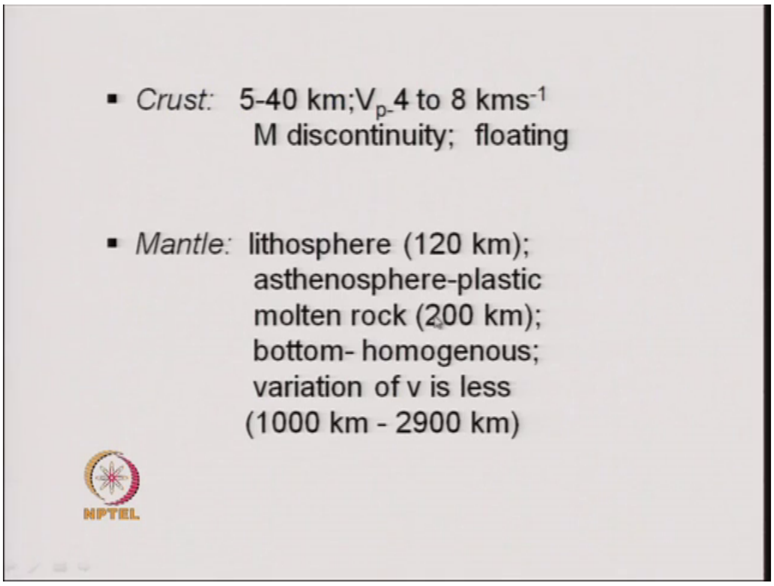

The Crust is a solid object or solid material that I told before it is thickness varies from 5 to 40 kilometer. The least thickness is found near the sea bottom whereas, the maximum thickness is observed in the region of the mountains. The seismic wave velocity through the crust is around 4 to 8 kilometer per second. As I told you before that exist a distinct discontinuity between the crust and the molten mantle and this discontinuity is called the M discontinuity after the name of the scientist Mohorovicic who first discovered this discontinuity by observing a sudden change of the seismic wave velocity as the seismic waves propagates from the crust to the mantle. The crust as such floats on the mantle with a by taking a portion of the mantle along with it.

Next we look into the property of the Mantle. The Mantle consists of again 3 distinct portions the top portion is called the lithosphere which is about 120 kilometer deep this lithosphere is integrally connected to the crust so that the crust along with the Mantle moves over the rest of the mantle immediately below the lithosphere is the asthenosphere. This asthenosphere is a plastic molten rock is having a thickness about 200 Kilometer.

The rest of the part of the mantle which is the bottom part of the mantle is fairly homogeneous and therefore there is a less variation of the seismic wave velocity within this zone. The thickness of the mantle is about 1000 kilometer to 2900 kilometer. Next is the Core.

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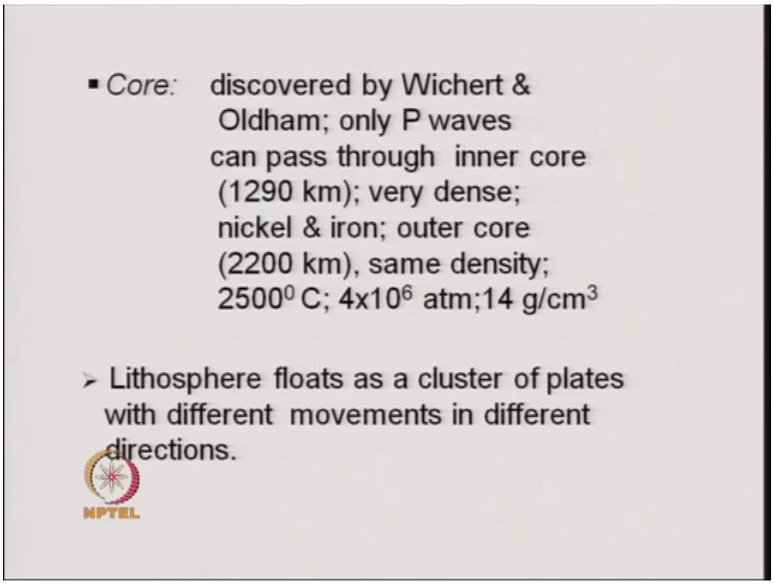

It was discovered by Wichert and Oldham it is so dense that only p waves can pass through the inner core which is about 1290 kilometer thick, it is very dense and very rare materials like nickel and iron. They are existing or they are found in the inner core. The immediately outside the inner core is the outer core which has a thickness about twenty 2200 kilometer. It has more or less the same density as that of the inner core. The temperature within the core is about 2500 degree centigrade pressure is about 4 into 10 to the power 6 atmospheric pressure and the density with of the core is about fourteen gram per centimeter cube.

As I told you the Lithosphere along with the crust float as a cluster of plates with a different movements in the different directions, this cluster of plates is known as the tectonic plates and the movement of these tectonic plates constitutes what is known as the plate tectonics are responsible for the earthquake that is caused due to the geological disturbances.

So, let us look into the plate tectonics which means the movement of the plate giving rise to different kind of interesting phenomena.

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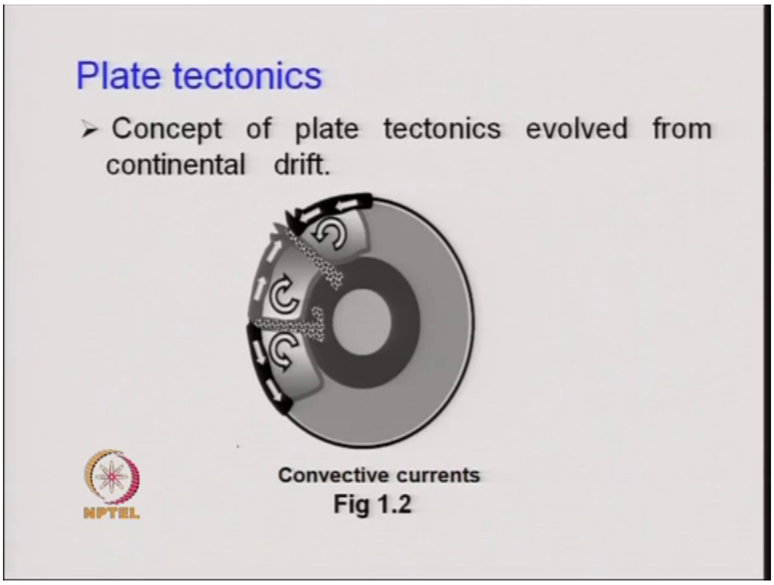

Convective currents
Fig 1.2

The Concept of plate tectonics emerged from the continental drift. In order to understand the continental drift let us have a look at figure 1.2. We can see that in this figure the in the mantle part there is a convective current and this convective current is produced due to the energy that is coming from the radio activity of the earth itself. These are the portions or the part of the mantle which moves upward and it flows through the gap between the 2 plates. The reason for the presence of these gaps between the cluster of plates is that these convective currents are not uniform all through and also there exist a difference in the temperature and pressure all along on the periphery of the mantle.

As a result of that, the solid portion of the outer surface of the earth known as the crust is not a 1 single unit covering the entire surface of the earth and there exists a gap between 2 segments or in other words these crust like plate that is consisting of a number of plates and between 2 plates there is a gap so through these gap the mantle flows outward because of the convective current. This phenomena give rise to the movement of the plates in different directions with the different velocity and this is known as the plate tectonics.

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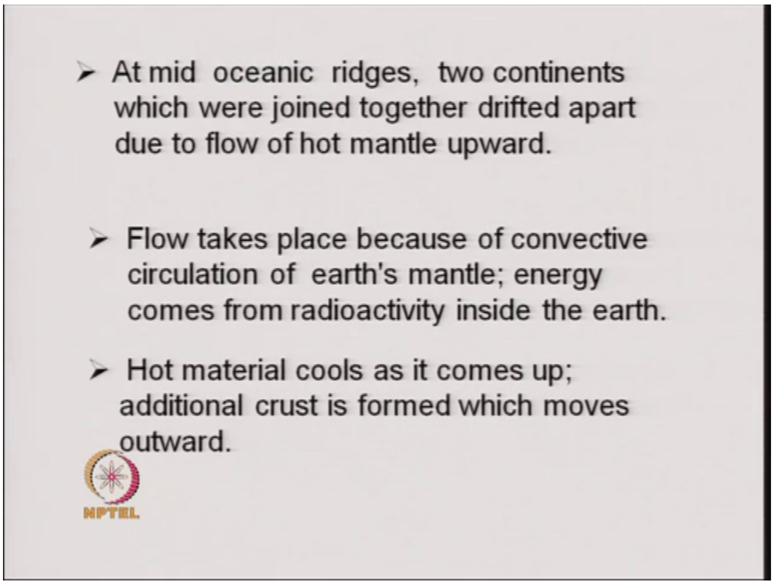

Now, at the mid ocean ridges where 2 continents were joined together in the past at some point in the geological time there the drift started between the 2 plates because of the upward flow of the hot mantle. As a result of that the plates, 2 plates drifted apart and give rise to the formation of the continents that we see today. And therefore the plate tectonics is the concept of plate tectonics came from the what you call continental drift.

The flow takes place because of the convective circulation of the earth's mantle that I showed before and also I mentioned that this convective current is present because of the energy that it derives from the radioactivity inside the earth. Now, as the hot materials comes to the surface through the gap it cools down and forms a additional crust and these additional crust tries to make it is own place.

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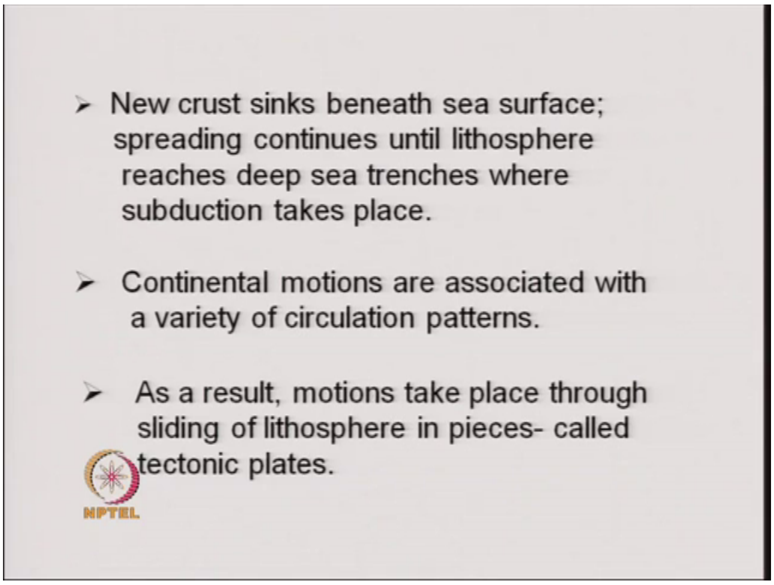

The New crust that is formed sinks beneath the sea surface; spreading continues and when the lithosphere part of the tectonic plate reaches deep sea trenches, then a subduction process takes place that is the crust which is already existing is experiencing a kind of crust because of the new crust that is formed. And because of this crust 1 plate which is already existing goes below the other plate and this process is known as the subduction process. We will discuss about the subduction process in more detail little later.

So, the material of the existing plates which gets into the molten material of the mantle that starts what melting down and as a result of that the old crust or the existing crust they gradually melt down and the new crust is formed at the gaps and thus there is a mass balance between the crust which is the newly formed and the crust that melts down due to the subduction process.

The continental motions are associated with a variety of circular circulation patterns and because of this variety of circulation patterns only we have the movement of the plates that is continually taking place. The movement of the plates essentially takes place through sliding of lithospheres and as I told you before this sliding takes place in pieces and these give rise to the movement of the tectonic plates known as the plate tectonics.

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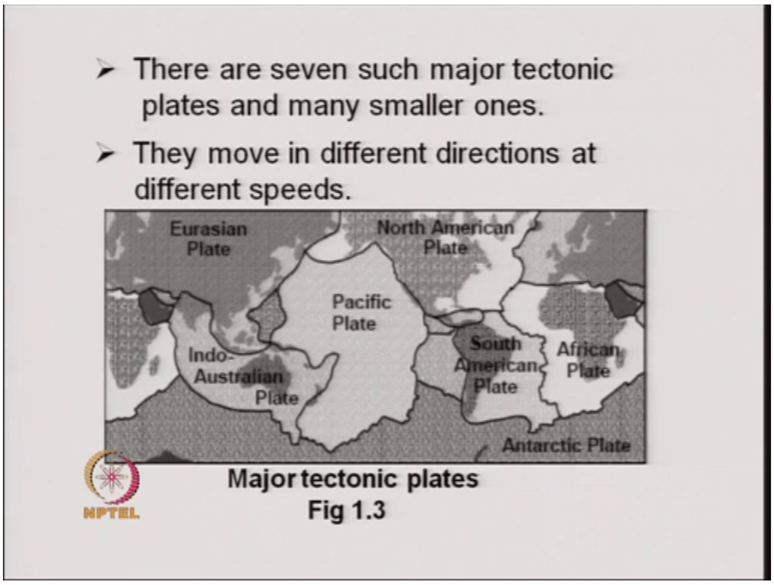

There are 7 such major tectonic plates and many smaller ones. They move in different directions at different speeds that I told you before. And here in this figure we can see those 7 plates. This is the Eurasian Plate, this is the North American Plate, this is the Pacific Plate, this is Indo Australian Plate, then this is South American Plate, this is African Plate and this is the Antarctic Plate. Between 2 plates we can see that the fault lines or the gap between the 2 plates that is continuously present or in fact, these fault lines or the gaps divide between the 2 plates. And these fault lines and gaps are very important in the sense that in this fault or the boundaries of the plate some tectonic activities take place resulting in the earthquake process that will be a describing little later.

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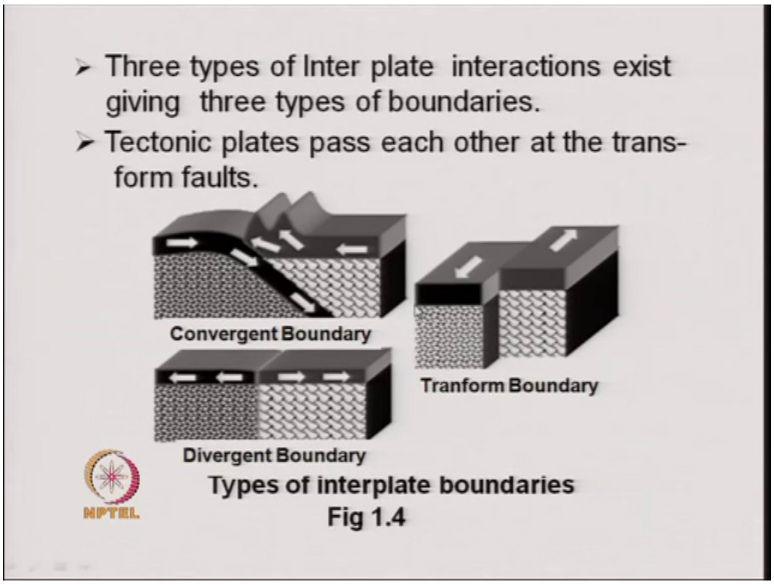

Three types of Inter plate boundaries that are existing; these boundaries are existing because of the different kinds of interactions between the plates that take place.

The first one is the convergent boundary, where 1 plate goes below the other plate which I describe a little before and this process is known as the subduction process. The plate which goes into the molten mantle that melts away and mergers with the mantle thus, there is a mass balance between the new plate created and the existing plates melting away.

Because of the subduction process that is 1 plate going below the other. There is a upward crust created on to the adjacent plate and these upward crust makes the end of the other plate going up this is responsible for the creation of the mountain. The Himalayan Mountain that we see today was about a few a feet height only at some point in the geological past. And right now the these Himalayan mountain has come to it is own size because of these subduction process that is continuously taking place.

This is called the transform boundary at the transform boundary 2 plates pass each other and this fault is called transform fault. And we can see that in the transform fault the 2 plates move parallel to each other perpendicular to the perpendicular to the surface of the paper. This is the divergent boundary means at this boundary or the fault line 2 plates move apart creating a wider gap and this process basically is responsible or was responsible for the creation of the ocean.

The movement of the plates outward that leads to some kinds of stresses and strains produced within the plate itself and that cause there is in turn some earthquake in the inside region of the plate which again we will describe little more in details.

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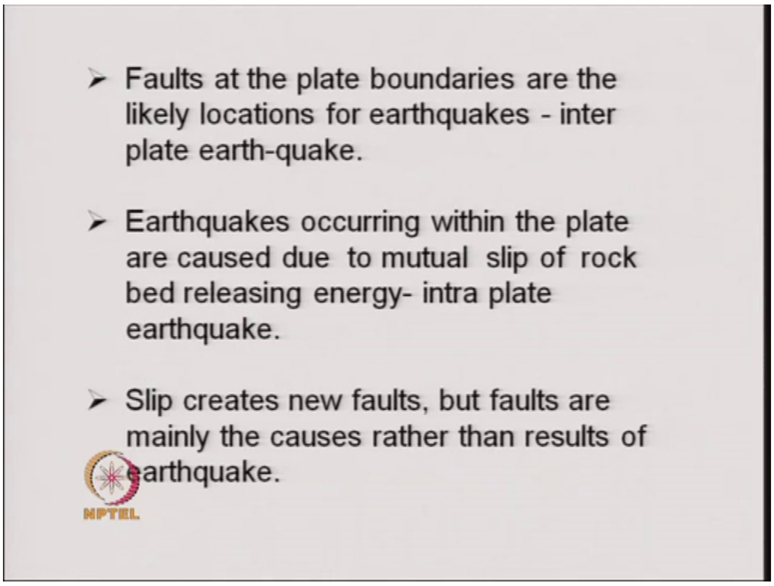

Faults at the plate boundaries are the likely locations for earthquakes and these earthquakes are called the inter plate earthquake. The earthquakes also do occur within the plate because of the stresses and strain that are developed due to the movement of the plate that I told you just before. And when the stresses reach some limiting value within the plate then there is a slip of rock bed releasing energy there and this kind of earthquake is known as the inter plate earth-quake.

The slip that takes place within the plate where the earthquake takes place that creates new faults, but it is generally said that the faults are mainly the causes of the earthquake rather than results of earthquake or in other words the most of the major earthquakes and the frequent earthquakes they do take place near the fault, the earthquakes that do occur within the plate itself creating a new fault that process is rather rare or less.

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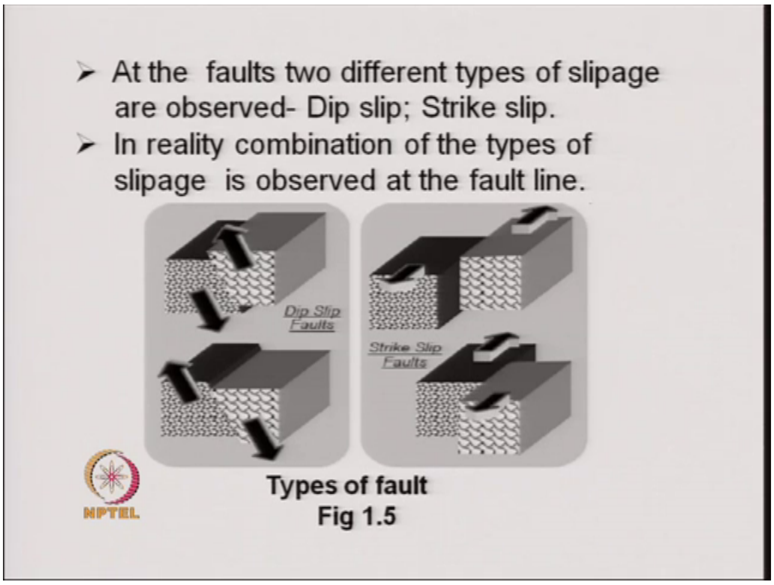

At the fault 2 different types of slipages are observed one is called the dip slip; the other is called the a strike slip. The dip slip is shown in this figure we can see that in the case of the dip slip the 2 plates move on an incline plane like this or like this. Where as in the case of the strike slip 2 plates move parallel to each other in this particular fashion or forming what is known as the transform boundary. In reality a combination of the different types of the slipage is observed at the fault line.

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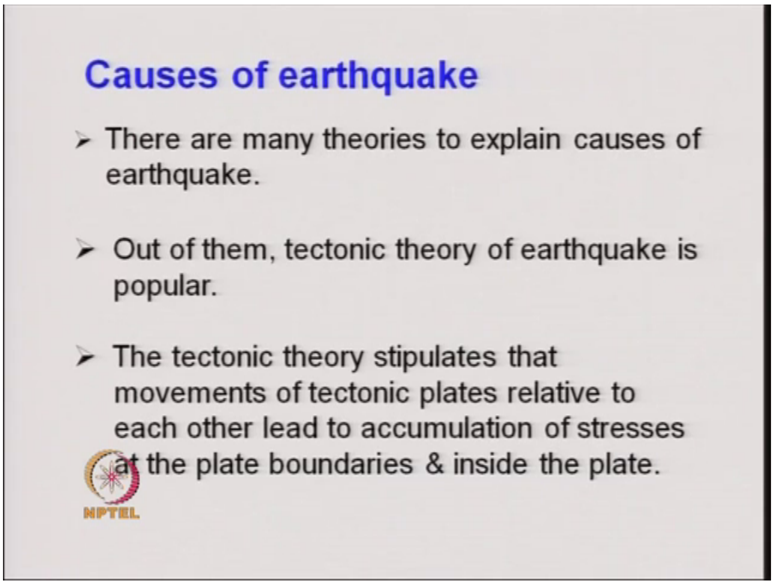

Now with this background of the plate tectonics, let us look into the causes of earthquake. There are many theories to explain the causes of earthquake out of them the tectonic theory of earthquake is most popular. The tectonic theory stipulates that movements of tectonic plates relative to each other lead to accumulation of stresses at the plate boundaries and also sometimes inside the plate.

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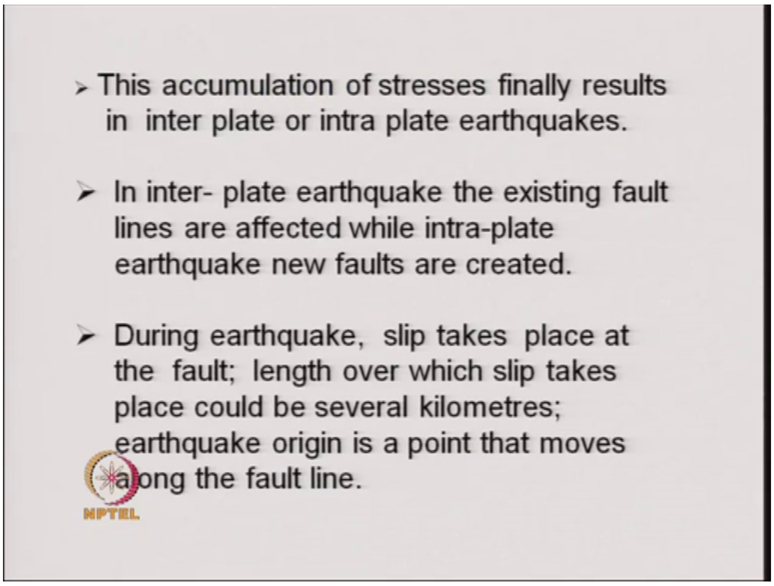

This accumulation of stresses whether at the plate boundaries or within the plate finally results in inter plate or intra plate earthquakes. In inter- plate earthquake the existing fault lines are affected while in the inter-plate earthquake new faults are created within the plate.

During earthquake, slip takes place at the fault; the length over which these slip takes place could be several kilometers and the earthquake origin that travels all along this line and therefore the earthquake origin is a point that moves along the fault line.

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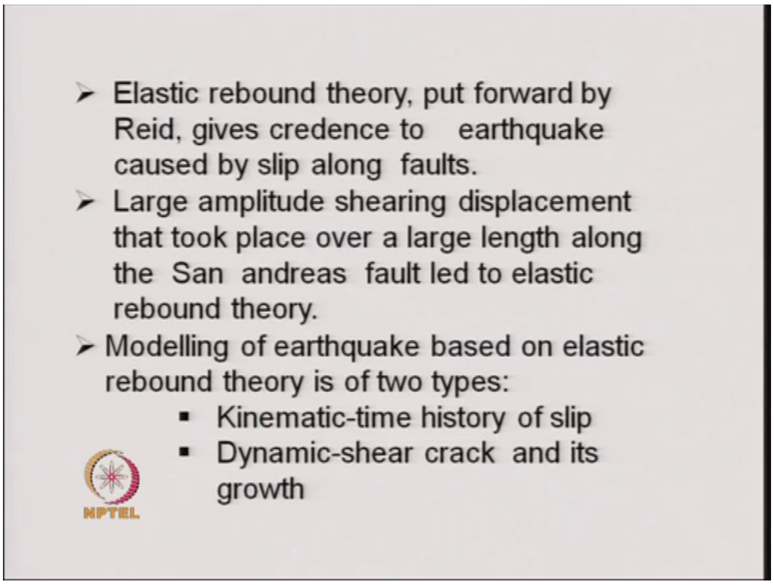

The elastic rebound theory proposed by Reid, gives credence to earthquake caused by slip along fault lines. The large amplitude shearing displacement that took place over a large length along San andreas fault led to the elastic rebound theory proposed by Reid. In order to understand the elastic rebound theory. Let us look at this figure.

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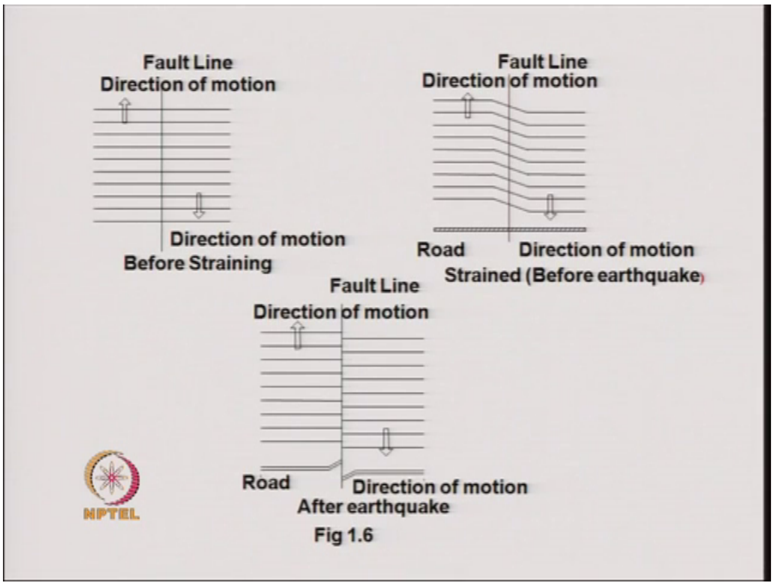

The figure shows the left hand figure or left side figure shows a number of parallel fences and these fences are on the surface of the ground. Below the fences at the crust level there exist a fault line which is perpendicular to the direction of the fences. Now before the earthquake takes place the 2 plates on either side of this fault line they move parallel to each other like those in a transform fault. And because of this movement of the 2 plates parallel to each other the strains are created at the gap or at the fault line over here.

The strained layers are depicted over here because of the movement and the resulting straining of the layers. The poles which are existing on the fences they are drifted apart in the direction of the motion and the layers are now taking a shape like this; this is just before the earthquake. When the strains which are accumulated along these fault line they reach a limiting value of the strain then the crushing of the material takes place over the length of the fault line. And as a result of that there is a release of energy and the earthquake takes place and as soon as this release of energy takes place then these layers bounces back to it is original position or in other words they again become parallel, but creating a permanent drift between the 2 layers or between the 2 poles in the direction of the fault line. So, this is a typical picture of the fences that was observed after the earthquake.

Now the modeling of earthquake based on elastic rebound theory is of 2 types:- one is the kinematic time history of slip in which the slip is continuously monitored over time and we have a time history of the slip that relative movement that takes place between the 2 plates the other was other is the dynamic shear crack and it is growth. So the cracks that takes place and how it grows is monitored overtime based on that we can model also the rebound theory.

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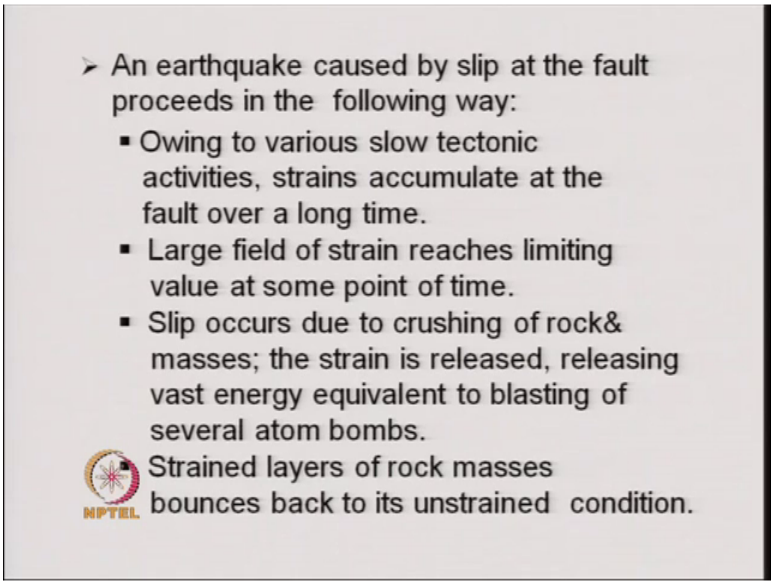

An earthquake caused by slip at the fault proceeds in the following way or in other words we can summarize how the earthquake is caused due to the slip.

Owing to various slow tectonic activities strains accumulate at the fault over a long time. Large field of strain reaches limiting value at some point of time. Then slip occurs due to crushing of rock and masses; the strain is released, releasing vast energy equivalent to blasting of several atom bombs. So, the energy that is released is very very large. And the strain layers of rock masses bounces back to it is unstrained condition and this is known as the elastic rebound theory.

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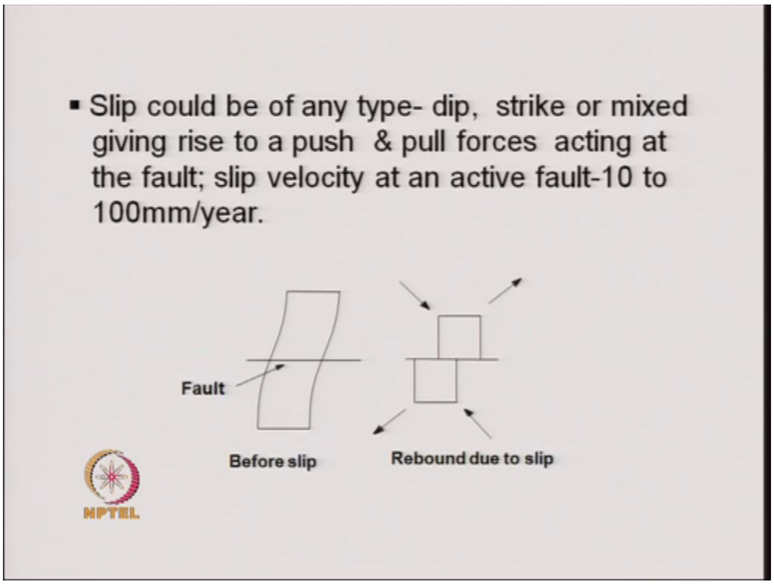

Now the slip could be of any type that we have described before that is dip strike or mixed giving rise to a push and pull forces as shown in this figure. This is the before the earthquake. So, the layers are strained over here 2 layers are strained and after the earthquake takes place the strain layers they bounces back to it is parallel position creating a permanent drift. And this movement of the 2 plates as a elastic body creates the push and pull forces. These push and pull forces they in fact make the energy to propagate in all directions that we will see in the next slide. The slip velocity at an active fault is about 10 to 100 millimeter per year.

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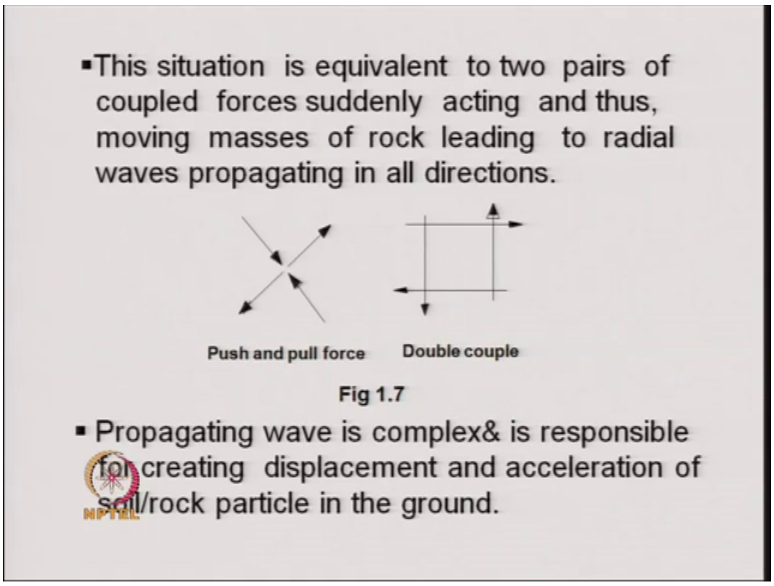

The push and pull forces can be conceived of as a double couple like this and these kind of double couple of forces that is generated at the place where the earthquake takes place. As a result of that we have the forces occurring in this direction as well as perpendicular to this direction and in this direction basically the wave start propagating. So, therefore the waves are produced due to the earthquake. They propagate in all directions from the point it is generated and these waves passed through the crust as well as the soil layer over line the crust.

Propagation of the wave is a very very complex process and is responsible for creating displacement and acceleration of the materials of the media. And this displacement and acceleration of the particles of the medium that basically we measure on the top of the ground and that gives us what is known as the earthquake record.

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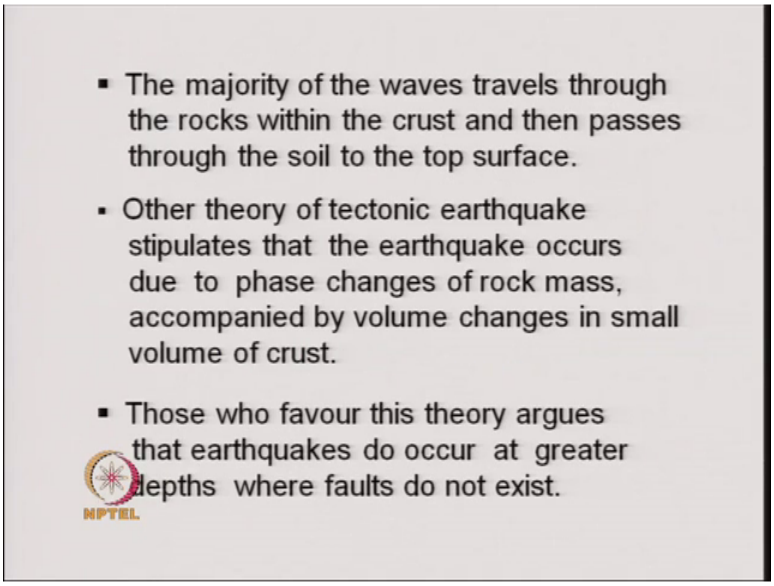

The majority of the waves travels through the rocks within the crust and then passes through the soil to the top surface. In this process of the generation of the waves can be explained from a simple example. If we consider a pool of water in that if we throw a stone then immediately there is a input of energy into the water mass and because of this energy input the ripples are created and the energy that is inputted travels by creating this ripples in the water medium known as the was water waves and it passes energy from one point to the other.

In the process also it temporarily or locally moves the medium particles up and down, but does not carry the materials along with it or the particles of the materials along with it. The other theory of tectonic earthquake stipulates that earthquake occurs due to phase changes of rock mass not because of the slipage or the slip that takes place at the fault line. And these a phase change of rock mass is accompanied by a volume changes in a small volume of crust and this in turn creates what is known as the tectonic earthquake.

The volume change which is associated with the changes of the phase of the rock mass is again is created due to convective current that is continuously taking place in the mantle. Those who favor this theory they are that the earthquakes do occur at greater depths where faults do not exist. And therefore the theory based on the slipage of the rocks at the fault line they no more becomes valid.

Now, let us come to the seismic waves that are created due to the release of energy at the point where earthquake takes place.

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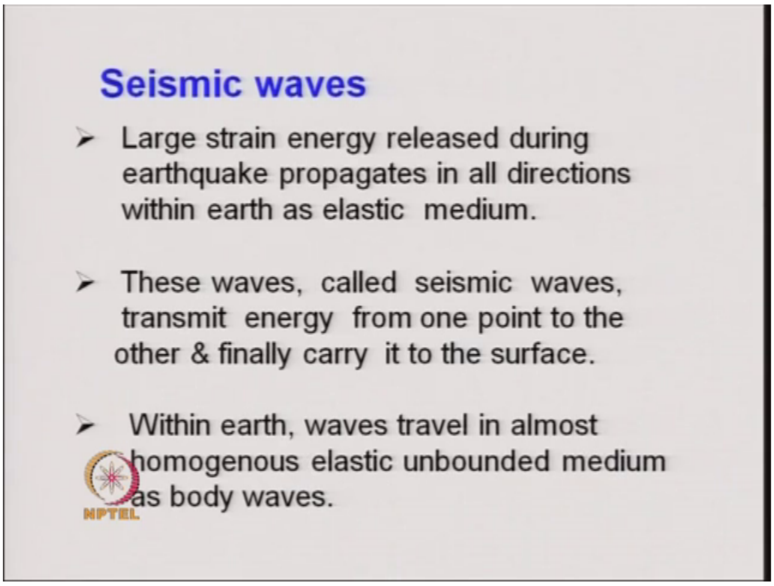

The largest strain energy which is released during earthquake propagates in all directions because of the push and pull forces that we described before. The seismic waves move within an elastic medium this elastic medium is the medium which is primarily consists of the solid rocks or the crust a plus the over line soil on that. These waves, called seismic waves, transmit energy from one point to the other and finally a carry it to the surface and how the seismic waves transmit energy from one point to the other that was discussed in before by giving an example of a pool of water.

Within the earth, the waves travel in almost a homogeneous elastic unbounded medium because within the earth itself the when the earthquake waves move, it moves within a very large volume. And therefore we can say that the elastic waves are moving within an unbounded a medium and these earthquake waves which are moving within the earth itself is called the body wave.

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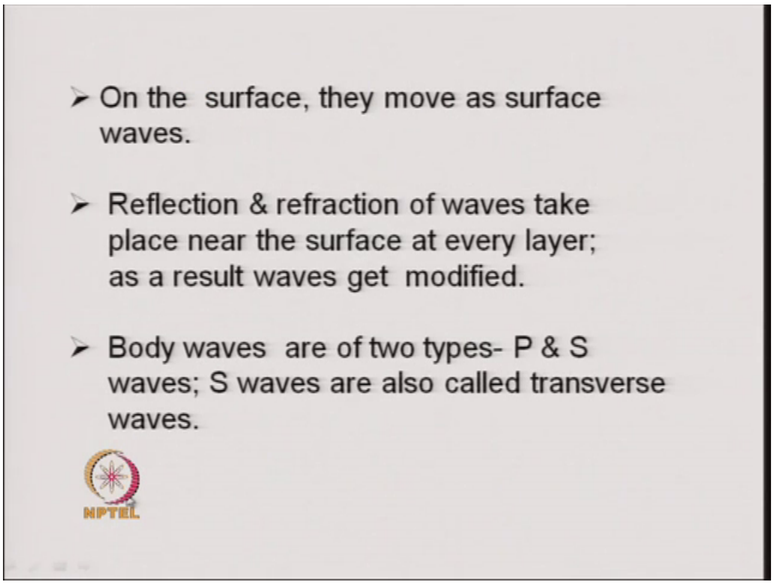

When these waves arrive on the surface they move as surface waves. The reflection and refraction of the waves do take place near the surface at every layer; because we have seen that the interior of the earth is a consisting not only of a few large layers called crust, mantle and so on.

But in the crust itself we have several layers and the layers which are adjacent to the surface of the ground. They are the reflection and refraction of the waves do take place and as a result of that the nature of the waves and they get modified or get changed. The body waves are of 2 types: P and S waves; S waves are also called the transverse waves.

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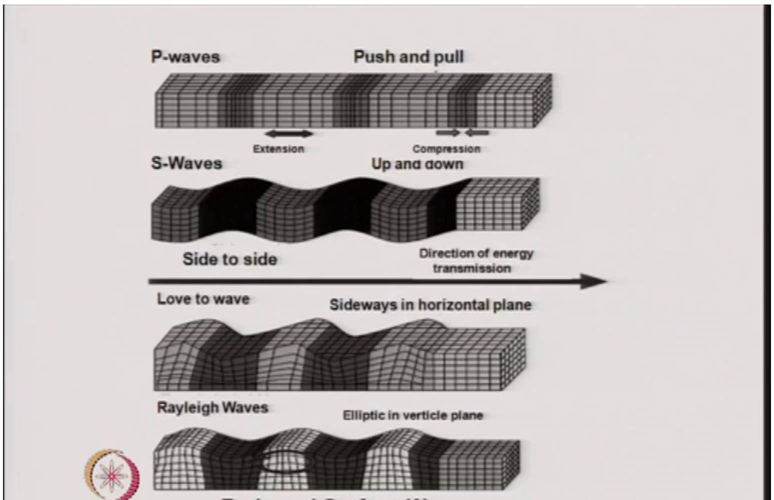

Body and Surface Waves
Fig 1.8

The P-waves are shown over here. In the P wave the particles of the medium move in the same direction of the seismic wave, whereas in the S wave the particles move perpendicular to the direction of the wave propagation. The other 2 are called Love and Rayleigh waves. They are different categories of the surface waves.

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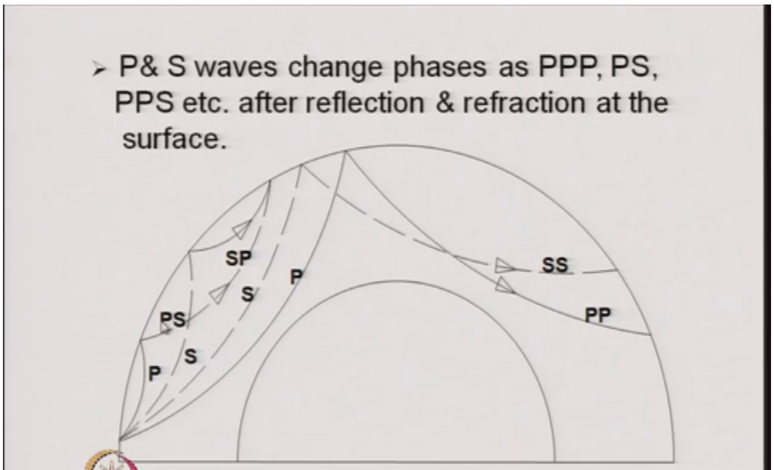

Reflection at the earth surface
Fig 1.9

But before I discuss that let me show you with the help of this figure the kind of reflection and refraction that takes places near the surface. For example, here the P wave after reflection becomes S waves. So then it is called S P wave. Similarly there is a PS wave, there is SS wave, there is a PP wave; PP wave signifies that after the reflection the wave remains again the P wave.

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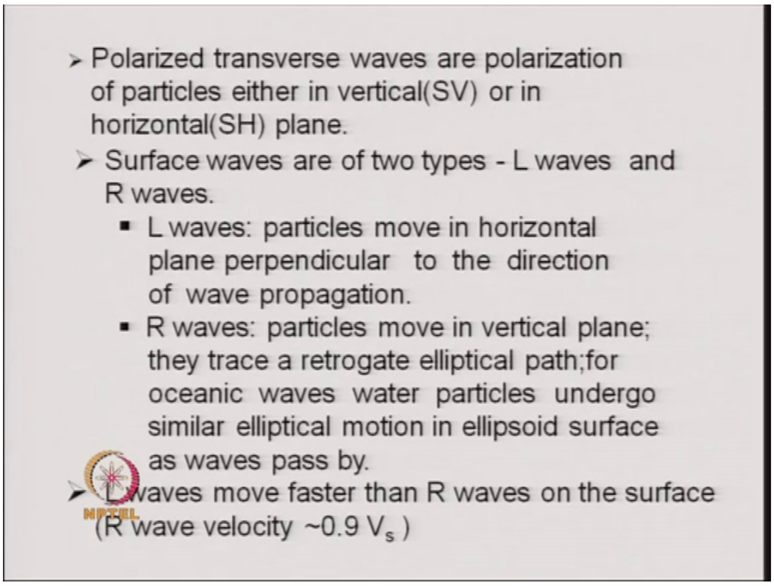

The surface waves which are propagating on the surface of the earth they are in fact at the polarized transverse waves either in the vertical plane or in the horizontal plane. The surface waves are of 2 types the L waves call Love waves or the R waves call the Rayleigh waves.

The L waves here the particle move in horizontal plane perpendicular to the direction of wave propagation. And in the R wave the particles move in an elliptical path which is shown in this figure. This is the Love wave, in the love wave the particles move in the horizontal plane whereas, in the Rayleigh wave the particles move in a retrograde elliptical path.

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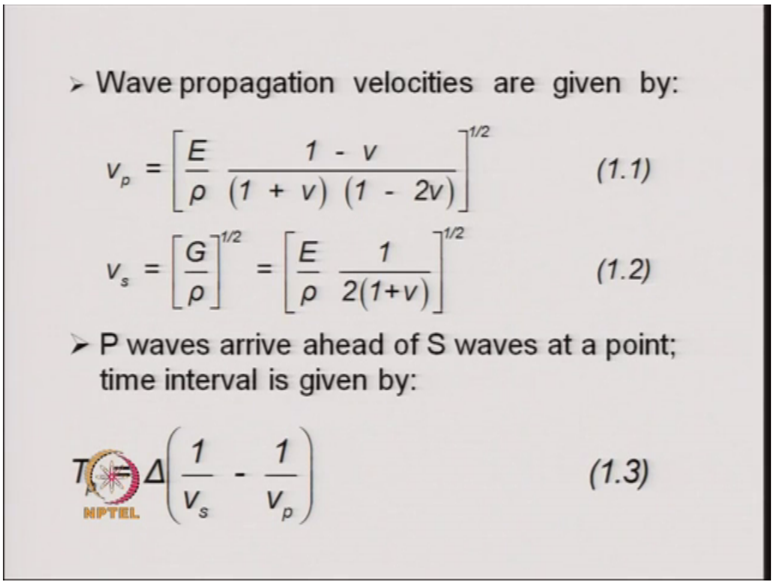

The wave propagation velocities are given by these 2 equation; equation 1.1 and 1.2. The first equation gives the velocity of the P waves. The second equation gives the velocity of the S waves, the e is the modulus of elasticity, g is the modulus of shear modulus of rigidity, rho is the mass density and nu is the mash ratio. The P waves arrive ahead of S waves at a point and the time interval between them is given by equation 1.3. If delta is the distance between the 2 points, then this is the time gap between the primary wave and the S waves.

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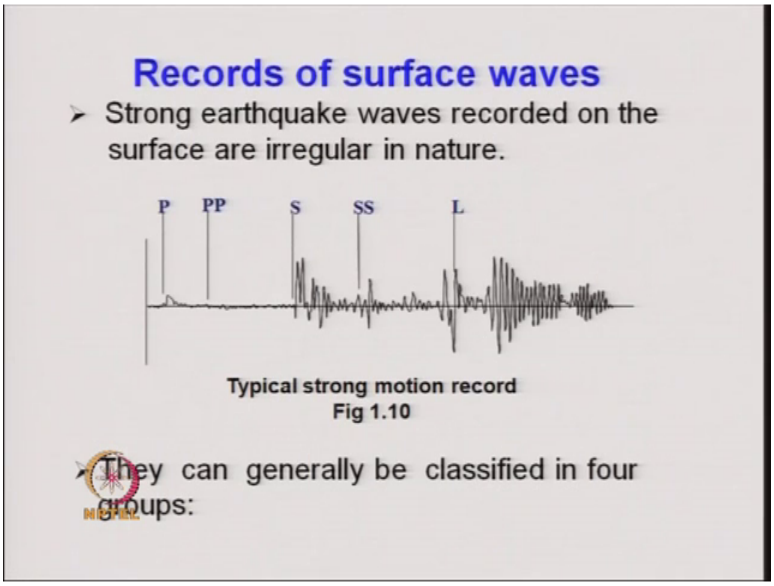

Now, as the waves come on to the surface then one can measure the earthquake records by measuring the ground displacement and accelerations. And this figure shows a typical recorded ground acceleration. Left hand side is the point of interest or the side itself and we can see that the P waves arrive first followed by PP, then followed by S waves, then followed by SS waves and at the end we get the surface waves. Now these waves can be classified into 4 categories.

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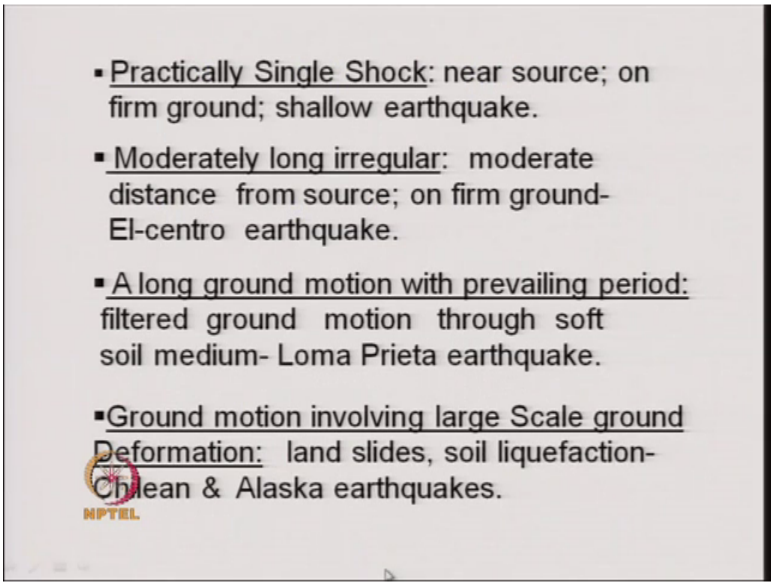

First one is practically a single shock; it occurs near the source that is if we take a record near the source we will get this kind of trace. It is observed in the firm ground and for shallow earthquake. Then we have got moderately long irregular trace of earthquake. This is observed for places which are at moderate distance from the source; also recorded on firm ground and example is that of El- centro earthquake.

A long ground motion with prevailing period this is typically happens when there is a soft soil and the ground motions gets filtered through the soft soil, the example as the Loma Prieta earthquake. And finally the ground motion which involving the large scale ground deformation that is a disastrous earthquakes, where landslides, soil liquefaction etcetera do takes place. The examples are Chilean and Alaska earthquake.

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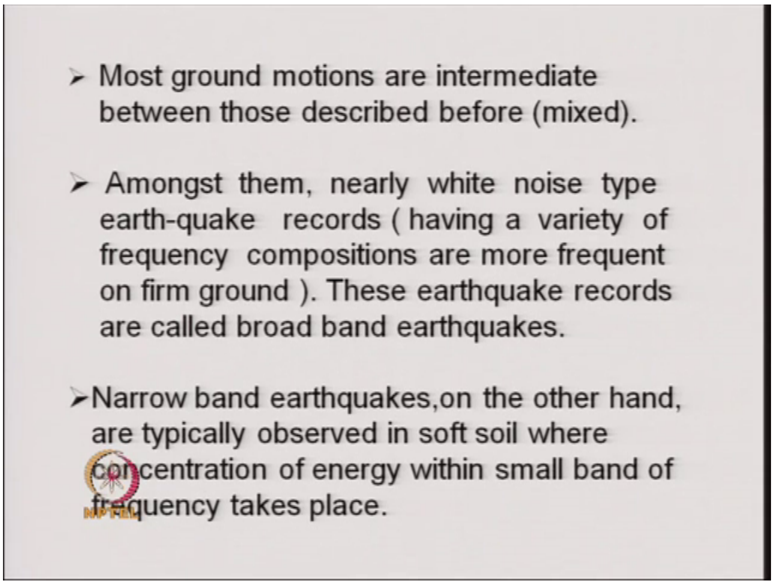

The most ground motions are intermediate between those described before or mixed type. Amongst them a nearly white noise type of earth-quake record having a variety of frequency compositions are more frequent on firm ground. These earthquake records are called broad band earthquakes.

Narrow band earthquakes are the ones, which are typically observed in the soft soil where concentration of energy is limited within the small band of frequency that is how it is called a narrow band earthquake.

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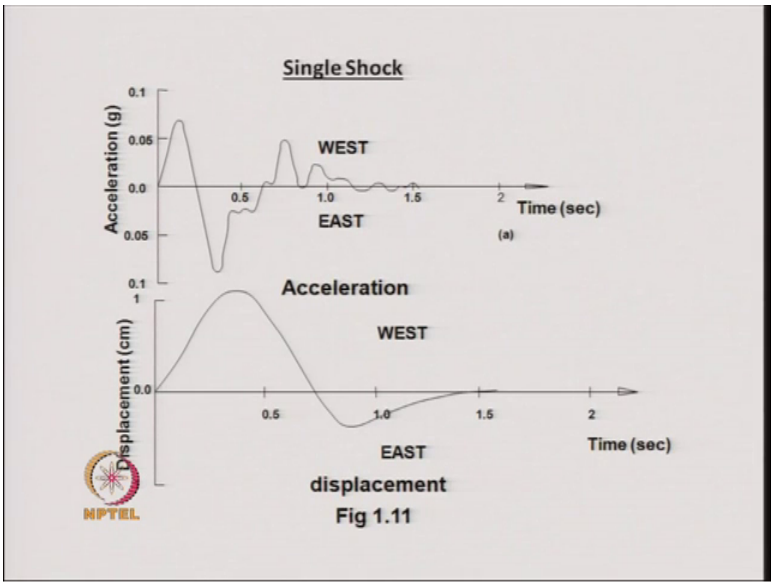

This figure shows the single shock kind of record and one can see that after the first shock itself the ground records they almost die down.

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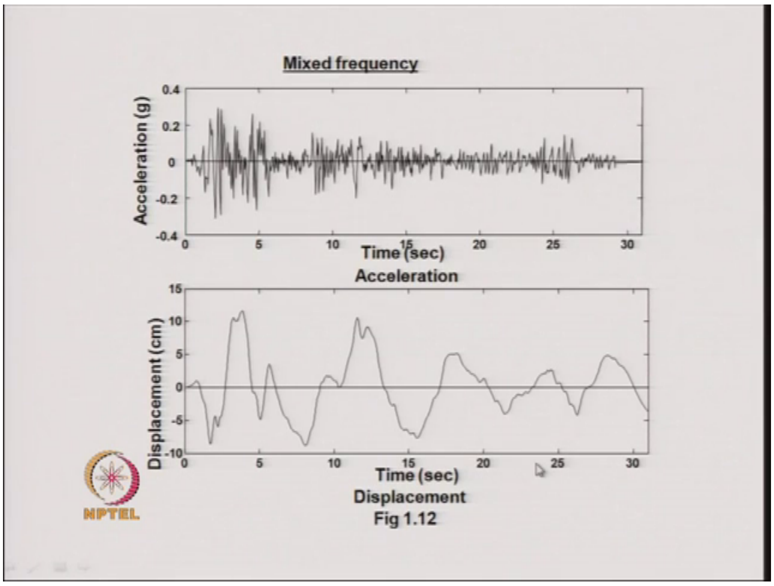

This is the mixed kind of ground record which are frequently observed in most of the earthquakes on firm ground. This has a mixed frequency and has broad band characteristics that is the energy of the earthquake is distributed over a large range of frequency.

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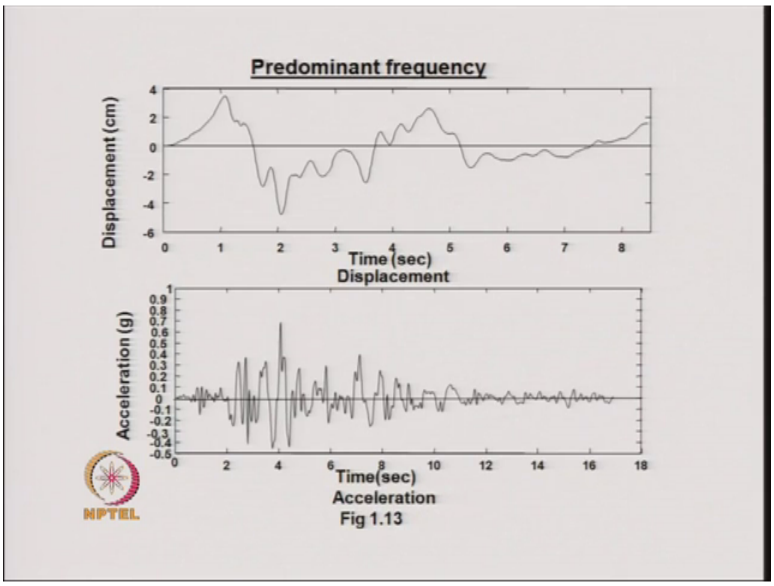

And this is the ground record or taken for or the soft soil condition. There, there is a predominant frequency as I told you and around that frequency the most of the energy is concentrated, so this is the predominant frequency one can see. We have different kinds of the earthquake traces or the 4 categories of the earthquake traces that I had described before.

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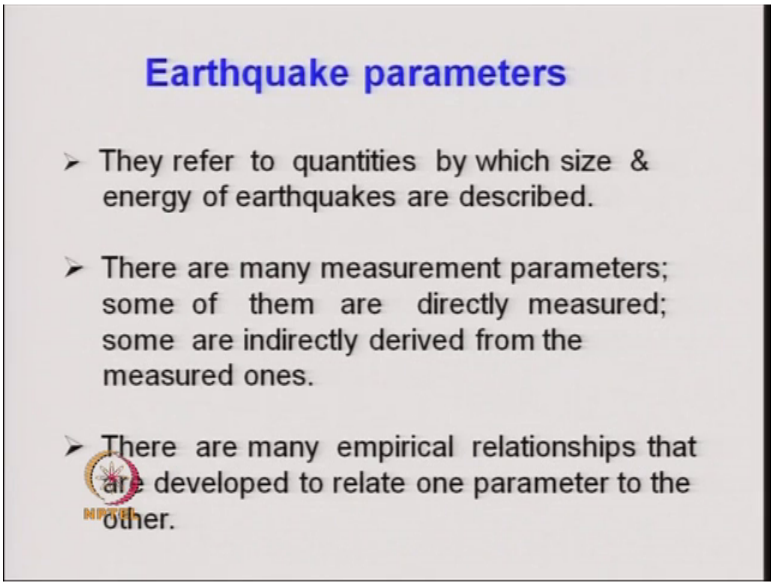

So, with this earthquake records we make many kinds of earthquake inputs and that will be describing in the subsequent lectures.