Engineering Geology
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Lecture - 32
Earthquake Hazard Assessment

Today, we are going to talk about earthquake hazard assessment. We are going to emphasize actually those points which are related to the work of an engineering geologist.

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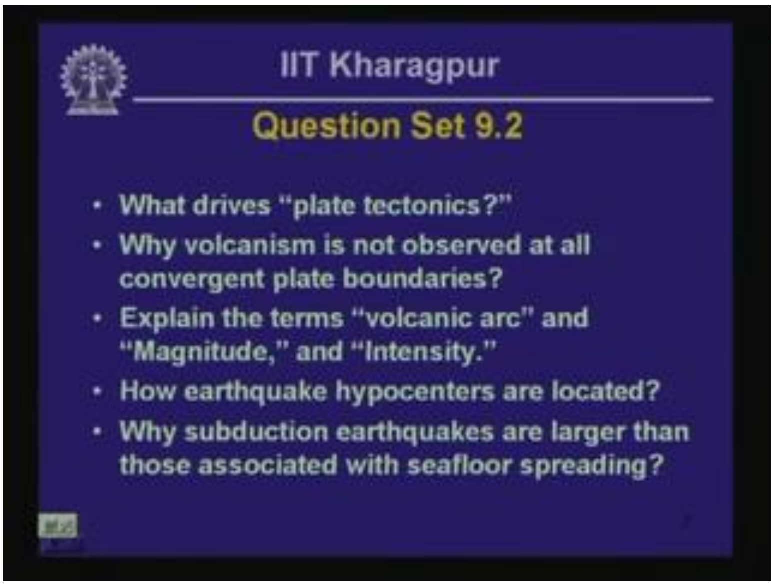

But before we get on with today's lesson the subject matter, we are going to look back at the question set that I gave at the end of the previous lesson. So, these are the questions. The first question that I asked was what drives plate tectonics. So, basically what you have learnt from the previous lesson is that the crust of the earth is composed of several different individual plates that are moving relative to each other. And these plates are essentially mobilized because of the circulation or because of the convective action because of the heat that is coming out from deep interior of the earth's within the underneath the surface of the earth

So, the convection is actually driving the relative movement of the plates with respect to or relative to each other. So, that is the answer of the first question. Now the second question that I asked was why volcanism is not observed at all convergent plate boundaries? And as you might have guessed, one of the examples of such convergent plate boundary is the Himalayan arc. Now you do not see at the present time any volcanism at this particular plate boundary and many other similar plate boundaries. That is because in order to have volcanism, you need to have a remarkable subduction and melting of the subducting plate is the essential cause which feeds into the magma or feeds into the magma plume that is going to come out of the volcanic eruptions.

Now if you do not have much of subduction going on, then the melting of subducting plate does not occur, and as a result, volcanism is absent from such plate boundaries. Typically, if you have got continent to continent collision more often than not, there is no volcanism associated with such convergence. One example is the Himalayas, and if you recall that continent to continent collision actually begins as the convergence between an oceanic plate and a continental plate. So, there is volcanism associated with that stage of the convergence, but by the time two continents they come in convergence, the volcanism becomes relit.

So, that is the answer that is the cause that is the reason why you do not observe volcanism at all convergent plate boundaries. Third question was explain the terms volcanic arc, magnitude and intensity. Volcanic arc is essentially associated with ocean to continent convergence or even ocean to ocean convergence. What happens there is let me draw a sketch or let me draw a section to make it clear.

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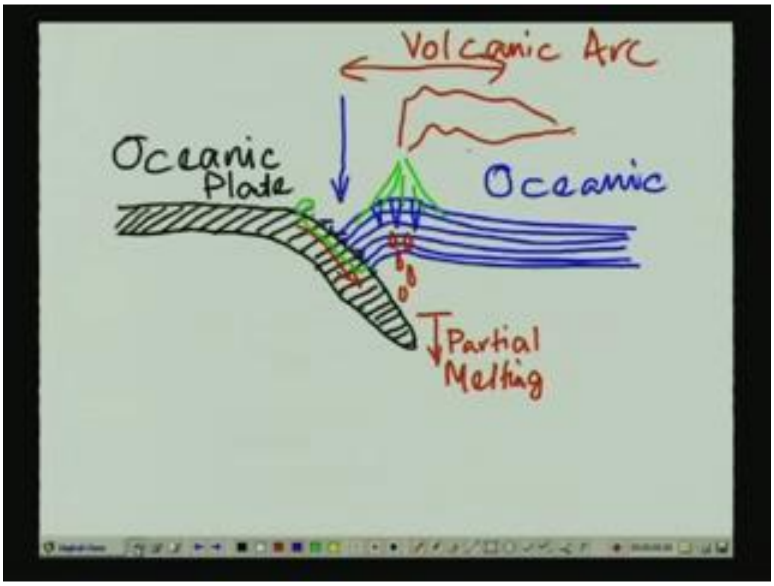

If you recall it is going to be a very simplistic sketch here. So, let us say the oceanic plate is subducting under a continental plate. So, in this case, what is going to happen at the beginning of the convergence may be the plates are going to be like this. In fact, typically, what happens actually the continental plate is much thicker than the oceanic plate. So, let me draw it as such. So, this is my continental plate, and let us say this is the oceanic plate. Now what happens during convergence? You can imagine that this particular plate is going down like this, and because of the friction that develops at the contact between the oceanic plate and the continental plate at that area there.

Because of that the continental plate, it gets bent; it gets bent, and it might actually take a shape like this. The deform shape of the continental plate may actually look like this. And this particular thing which is locked up because of friction with the oceanic plate that actually starts moving downward. And eventually, what you will end up with is a configuration like this. Eventually, what you will get is a situation like this; the continental plate which was in contact with the the locked up area rather that actually is going to move downward with the ongoing subduction. And what you are going to have is a fore arc trench. So, this one is a fore arc trench.

And at this area because of the flexure of the plate, the plate is going to get; cracks may develop within the plate. And the plume the oceanic plate that is subducting to this depth here, it will undergo partial melting. And magma is going to start rising and feed out into the surface may be through the cracks and through the discontinuities that develop because of the deformation within the continental plate in this particular sketch that I am drawing. And eventually, what might actually happen is an entire volcano may develop, and that particular volcano might actually be susceptible to periodic eruption.

So, this type of this area actually which is on either side of the volcanic activity, and the area which is arched upward because of the subduction activity as I have shown here. So, this particular strip of land is called a volcanic arc. Now volcanic arc is not only in this particular case I was giving the example of a convergence between an oceanic plate and a continental plate. But a very similar situation arises when the convergence is taking place between one oceanic plate and another oceanic plate. And what you are going to end up in such a situation is a chain of volcanic islands.

And Japan is actually an example of such a chain of islands that arose because of volcanism at the intra-plate converging boundary, okay. So, that is the explanation of the term of volcanic arc. Then I asked you to explain the terms magnitude and intensity. These are essentially the measures of the strength of an earthquake. Magnitude is actually a measure of the energy released during the earthquake. So, it does not depend on the distance where you measure the magnitude; it is irrespective of the distance. So, one particular earthquake has got one single magnitude, whether you are looking at the earthquake from the United States of America or India or wherever it is.

Intensity on the other hand that also actually is an alternative measure of the strength of an earthquake but here what it is actually; intensity is essentially actually is a systematic scale or qualitative scale that sums up the damage caused by an earthquake or the strength with which the earthquake was felt in different parts of the affected area. So, intensity of an earthquake will depend on the distance because as you would imagine the damage caused by an earthquake is going to be more significant near the epicenter of the earthquake. And it is going to gradually decay out as you move out laterally from the epicenter of the earthquake.

So, intensity is essentially a qualitative scale of the damage caused by an earthquake or how strongly the earthquake was felt, whereas magnitude is an instrumental scale; it is a scientific measure of the energy released during an earthquake, okay. The fourth question that I asked was how earthquake hypocenters are located. Now what I have indicated in the previous lesson was that the S-waves arrive at a particular site after the arrival of the P-waves. And from the time difference between the arrival of the S-waves and P-waves are S-P interval as it is called; you can find out what is the distance from the location of the instrument which is measuring the earthquake arrival typically accelerometers and the point where the waves started to travel outward.

Now for that, you also need an additional input about what is the velocity of propagation of S-wave and P-wave through the intervening rock mass, and generally, models are available over the most part of the earth’s crust. So, the velocities of S-waves and P-waves from those models can be used together with a S-P interval to find out what is the distance from the instrument location and the focus of an earthquake. Now if you have got three such measurements or if you have got records at three different locations from which you have found out what is the S-P intervals; from those three measurements, you can find out what is the location of the focus of that particular event.

So, that is the way actually hypocenter of an earthquake is located. The fifth and the last question that I gave you was why subduction earthquakes are larger than those associated with sea floor spreading. Now subduction earthquakes are basically thrust; it is caused by thrust faulting. The major mechanism that is involved in case of a subduction earthquake is thrust faulting, whereas sea floor spreading is essentially a tensile regime where you have got normal faulting.

And if you recall the discussion that we had some time back on rock strength, the strength of geologic material usually increases as the compression increases at a particular location. So, you would imagine that in case of thrust faulting where compression is the major principle stress; you are going to have a larger strength of rock mobilize before the failure takes place. And because the strength is larger, you are likely to trigger; once the failure occurs, the failure is or rather let me put it in another way. Because of the strength is higher in because the rock mass is in compression, it is going to be able to mobilize a larger magnitude of strength before failing.

So, once the failure is triggered, the failure is going to be more violent compared to a situation, where the rock is subjected to a tensile failure as is the case in the situation of sea floor spreading. So, from that logic, it becomes evident that the earthquakes are typically larger where you are having subduction scenario. On the other hand at the location of sea floor spreading or spreading boundary, the earthquakes are typically smaller, okay. So, that wraps up the question set.

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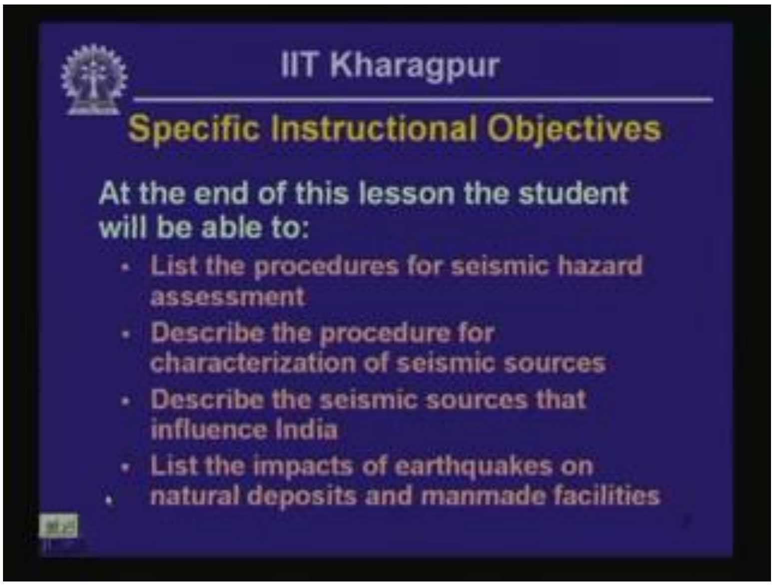

Now we are going to move on to today's subject matter. What we would like to achieve at the end of this lesson are the following. We would like to be able to list the procedures for seismic hazard assessment just the outline of those procedures; we are not going to get into mathematical details of those procedures. We would like to be able to describe the procedure for characterization of seismic sources, and this is where the engineering geologists have maximum involvement. Describe the seismic sources that influence India. And finally, list the impacts of an earthquake on natural deposits and manmade facilities.

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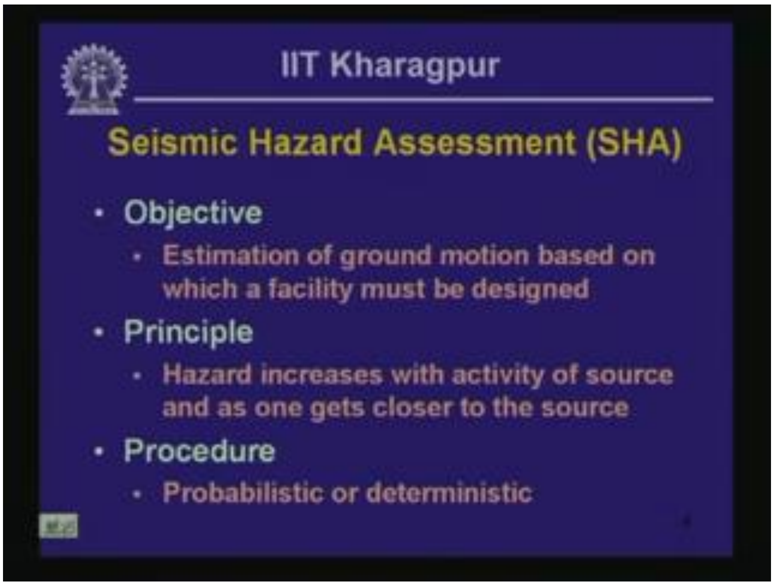

So, first of all we want to answer the question is that what is meant by seismic hazard assessment. What do we do when we are trying to assess the seismic hazard? The objective of seismic hazard assessment is essentially estimation of ground motion based on which a facility must be designed. So, that design basis is going to put if you do a facility design based on that design basis, then you would have expect that the risk associated with that design is going to be acceptable to the operator of that particular facility.

Now essential principle in seismic hazard assessment in a nut shell is the following. Hazard increases with activity of the source and as one gets nearer to the source. So, what is meant by that is that if you are nearer to a particular source which is likely to cause an earthquake, then hazard will increase, number one. And number two, if you are at equal distance from two sources; one is, say, you consider two sides which are at x kilometer distance from two different seismic sources. And if one of those two sources is more active than the other source, then the site that is near to that particular source is going to be more hazardous from the point of view of seismic hazard.

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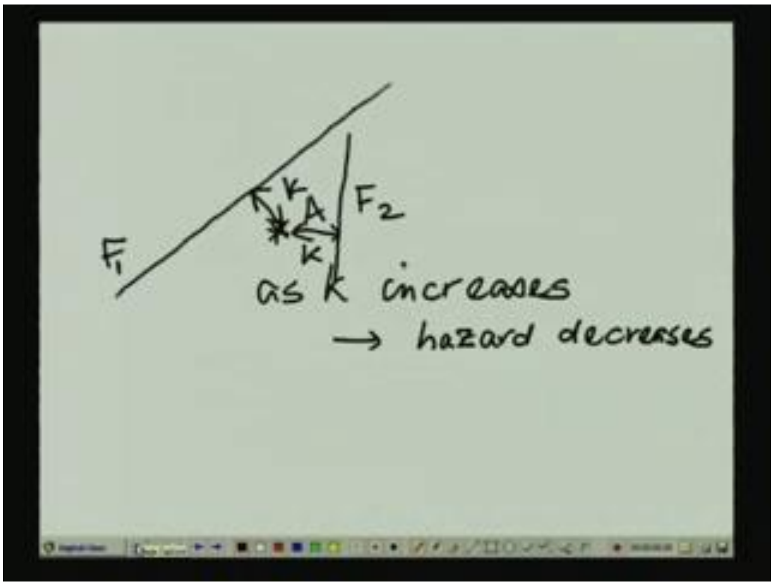

In other words, let us say we have got a fault, and we have got a site here site a, and this is the earthquake source f. So, this is the distance from the fault k kilometers. So, as k increases, hazard decreases; that is number one. Secondly, if you have got another fault that is affecting a, let us call this one the old one as f 1 and the new fault as f 2, and this one also is at distance k. Now the hazard on site a is going to be more influenced by f 1 if f 1 has got larger potential for triggering a larger magnitude earthquake, then the hazard because of f 1 at site a will be greater than the hazard because of f 2.

So, these are the two points that I wanted to make with the respect to the principle of seismic hazard assessment. And then finally, the procedure for seismic hazard assessment could be probabilistic or it could be deterministic. In other words, you could talk about an earthquake that has got a certain amount of probability of exceedance during the lifetime of a structure. And in order to find that in order to estimate that the procedure that you have to follow is the probabilistic seismic hazard assessment, or you could do the design based on the maximum concealable earthquake in that particular region.

And as is the case with very important and very sensitive facilities such as nuclear power plants; in that case, the maximum earthquake that is likely to affect that region that area that site is considered in the design. And the procedure that is followed for estimating that particular scenario earthquake as it is called is deterministic seismic hazard assessment, okay.

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Now what are the ingredients or what are the necessary inputs for undertaking a seismic hazard assessment? First of all, what you need to do in assessing seismic hazard is to identify and characterize the seismic sources that are likely to affect a particular site.

What are the key issues there? Number one is geometry or the foot print or the length and the location of the seismic source and the activity associated with that particular seismic source.

And you need to characterize each one of the sources that are going to affect a particular site. As I indicated a few minutes back, by activity what I mean is the likelihood of triggering of a larger magnitude earthquake within a given time ascribable to a given source is called the activity of that particular source. Second input involves assessment of ground motion attenuation with source to site distance. As I have mentioned earlier is that the intensity decreases with the increased epicentral distance, and basically, intensity is related although with some uncertainty with the peak ground acceleration horizontal and vertical accelerations.

So, you will imagine that peak horizontal ground acceleration is also going to decrease with everything else remaining the same as the epicentral distance increases, okay. That is not the only thing that you need to consider though; I want to stress at this point that you also need to consider whether the site for which you are estimating the seismic hazard is basically a soft soil site that is going to be. At that site the PGA is going to be relatively larger compared to a site that is located on an outcrop of hard rock.

So, there are many things involved, but still you can say on the whole is that as the distance increases from the location of the energy release, the intensity of shaking is going to decrease; although, local site effects such as what is the depth of bedrock or how soft is the soil that is underlying the site or whether the site itself is situated on bedrock or not; that is also going to be another vital factor in attenuation of ground motion.

So, crustal characteristics are a factor that actually affects attenuation of ground motion. So, it depends really whether you are in the eastern part of India or in the western part of India or in eastern united states or western united states or in southern Europe or where actually on the globe your site is located, the attenuation of the ground motion actually depends on the geographic location of the site. Third input is as I have indicated as I have alluded to earlier is the tolerable risk level.

Now basically, tolerable risk level is associated with the importance of the structure. If you are considering the seismic hazard of a site where a nuclear power plant is to be established, the risk tolerance for that particular facility is going to be much lower than at a site where a simple multistoried dwelling is going to be constructed. So, tolerable risk attenuation, ground motion attenuation relationship and the uncertainty of that particular attenuation relationship and source characteristics are the three major inputs of seismic hazard assessment, okay.

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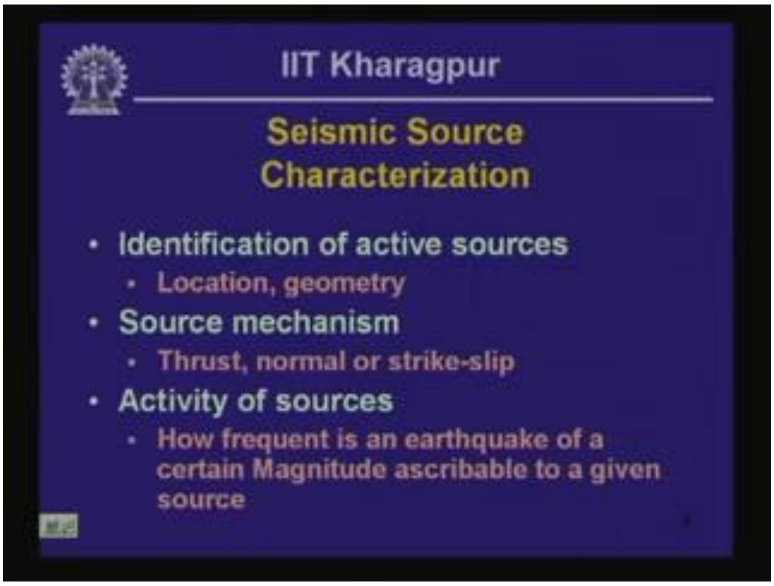

Now I also indicated earlier is that the major involvement of engineering geologists in seismic hazard assessment are in seismic source characterization. So, what are the tasks here? The tasks here include identification of active sources, location and geometry of the sources, source mechanism, whether you are looking at thrust faulting or normal faulting or strike-slip faulting. And thirdly what is the activity of the source; in other words how frequent is an earthquake of a certain magnitude ascribable to a given source is likely to be exceeded within a certain time frame. So, these are the factors that one needs to answer; these are the things that need to be estimated for seismic source characterization.

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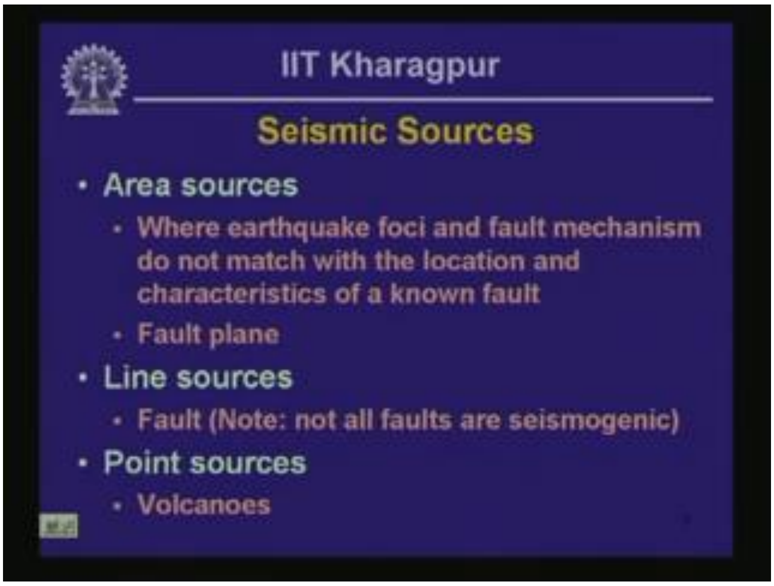

Now question arises then what are the seismic sources. And you know roughly what is the answer of this particular question. There could be area sources. Area typically covers the areas where earthquake foci and fault mechanism do not match typically with the location and characteristics of any known fault. This has also given the term as defuse or background seismicity. For instance, in many parts of peninsular India, we know earthquakes as large as magnitude 5.5 or 6 frequently occur, but in those areas, we do not know whether it is not known for certain what is the orientation and location of a fault activity of which is giving rise to those magnitude 5.5 to magnitude 6 earthquakes.

So, those areas typically are considered as area sources or the sources of defused seismicity. Then fault plane also could be viewed as area sources. Let us say you have got a fault, and the fault is a shallow dip fault, or it is dipping at a flat angle with horizontal. And the entire fault plane is likely to give give rise to a certain magnitude earthquake, then that particular fault plane the foot print of that particular fault plane may be considered as an area source.

There could be line sources; faults are typically considered as line sources. At this juncture, I need to actually make it clear that all faults are not going to give rise to earthquakes or all faults are not really active faults. What we are looking at here are only those sources which are active within the recent past geologically speaking; we are going to look at what kind of time frame we are looking at a little bit later. Then there could be point sources and one example of point sources is a volcano. So, these are the seismic sources.

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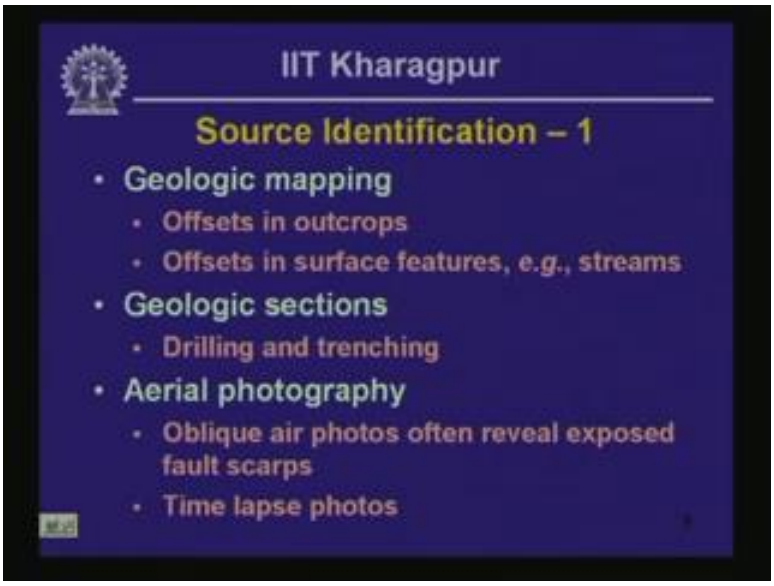

Now source identification, what are the procedures typically followed by engineering geologists for identifying sources are discussed here. First of all, geologic mapping is one of the important sources of information for identifying sources. What you can see here is offsets; what you can see is an offset in outcrops of two different types of rocks. Then you could also see offsets in surface features such as streams, and these features can tell a lot in terms of whether that particular feature on the hot surface is seismogenic or not.

For example, if an offset cuts through a rock of a certain geologic age, then we know for certain that that particular fault has been active within that time frame. Similarly, if you see a stream offset because a stream relatively speaking is a young geomorphologic feature. So, if you see stream offset, then you can be very sure; you can be reasonably sure that the fault movement that has caused the stream offset is likely a Holocene fault movement.

Geologic sections are another bunch of important considerations. So, in order to construct geologic sections, you could consider drilling or more common in case of seismic source identification is the activity called trenching. We will see how trenching is done and what kind of data you get out of trenching. Then thirdly, you could take help of aerial photography; typically, oblique aerial photo air photo often revealed exposed fault scarps.

And then there is also a practice of taking time lapse photographs or time lapse remote sensing images, and comparison of those time lapse remote sensing images show shuttle changes on the geometric characteristics of the features that are observable on the surface of the earth. For example, exposed fault scarp and from that you could actually establish or you could actually estimate what kind of movement is going on in, what kind of deformation is taking place in that particular area. And larger the deformation, the greater is the likelihood of failure of that particular fault.

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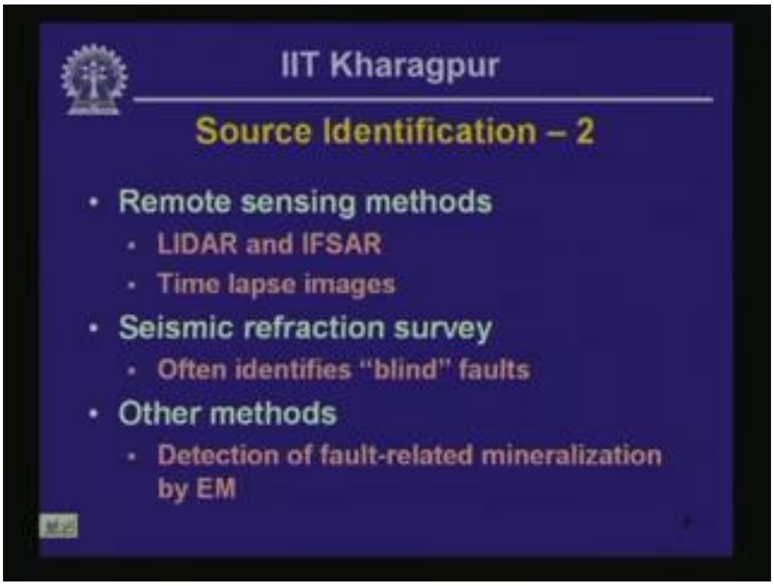

As I mentioned, remote sensing images here also the two procedures that are used very commonly are LIDAR and IFSAR. We have talked about it earlier on, and time lapse images are important here as I indicated a few seconds back. Seismic refractions survey is another important source of information for identifying blind seismogenic features such as blind faults. What is meant by blind fault is a fault that does not cut through the surface sediments or surface soils. And in other words, the scarp of that fault is not visible at the surface of the earth; that type of fault is called a blind fault.

Seismic refraction survey actually is one of the most important sub-surface investigation tools that are used to detect blind faults from velocity anomalies. Now there are several other methods for detecting faults such as electromagnetic method and gravitational method; typically, activity of faults gives rise to mineralization such as many iron ore deposits are on associated with fault related mineralization. So, those deposits are often detected by electromagnetic survey. So, electromagnetic survey can actually detect in some situations blind faults or even exposed faults, okay.

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So, now it appeared from what we discussed so far, faults an important seismogenic source. Now you need to consider only active faults as I indicated in the preceding discussion. So, faults are considered active if the fault has moved over the last 35000 years, typically. Then faults may become inactive actually after the stress regime in a given geographic location changes because of the changes in seismotectonic setting, but these faults remain as zones of weaknesses within the system. And they are susceptible to dislocation because of intra-plate perturbation in this stress regime because of the activities at the plate boundaries.

Let us take an example here. Let us say actually we talked about plate tectonics, and from the history of the earth, we can see that several areas of the earth over the recent past and distant past; they have undergone continent to continent collision or other type of convergence or divergence plate convergence and divergence in geologic past. And those convergence boundaries are typically called sutures. These convergent boundaries they remain within the plates, although, they may not be yet active anymore.

They are relic features, and these features remain within the plate has locations of weaknesses. And these weak locations can actually get dislocated because of stress change within the plate because of the large stress changes that are occurring near the plate boundaries.

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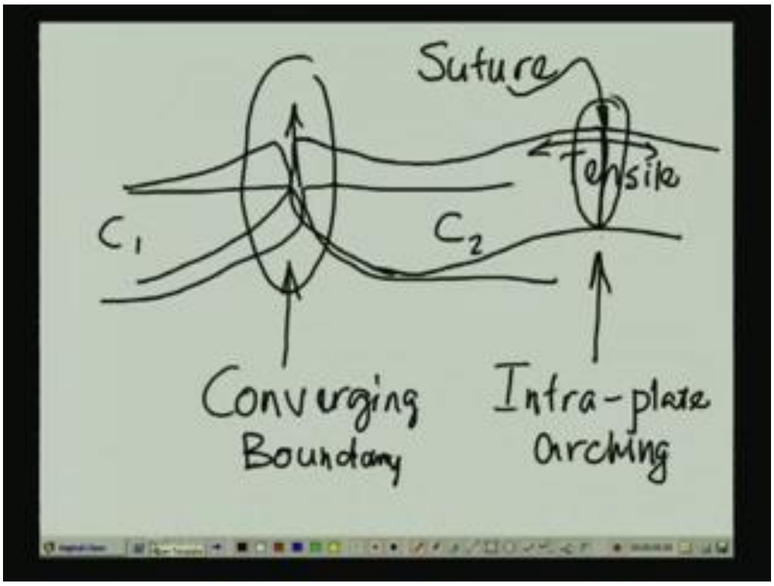

For instance, let us say a continent is colliding with another continent. So, this is a continental plate called c 1, another second continental plate as c 2. And this particular collision what is going to happen because of this is a mountain chain is likely to get lifted up, and the situation is going to be somewhat like this. And because of the compression in the plate boundary, a flexure is likely to develop or an arching is likely to develop within at some distance away from the location of the convergence. So, this is the converging boundary on this particular sketch or section.

So, away from the converging boundary, in many situations it is observed or inferred that an arching is going to develop. So, this is the location of an intra-plate arching, and because of arching, what is going to happen? The zone near the top is going to be under tensile regime, and since rock mass and soil mass, they are weak in tension, failure is likely to get triggered in this area.

Now if you have got a relic feature cutting through the crust at this particular location. Let us say at this particular location, you have got a suture from a continent to continent collision that took place several hundred million years ago. If such a feature exists within plate c 2, then that is going to make the likelihood of failure even greater, and as a result, that particular feature may be a source of intra-plate earthquakes arising from the failure through the weakness within the feature that is left from the convergence of two earlier plates that took place several hundred million years ago, okay.

So, that has actually been proposed as one of the important causes of intra-plate tectonics. And we will see later on that this particular aspect has got some implication on the seismicity that is observed in the peninsular India, okay.

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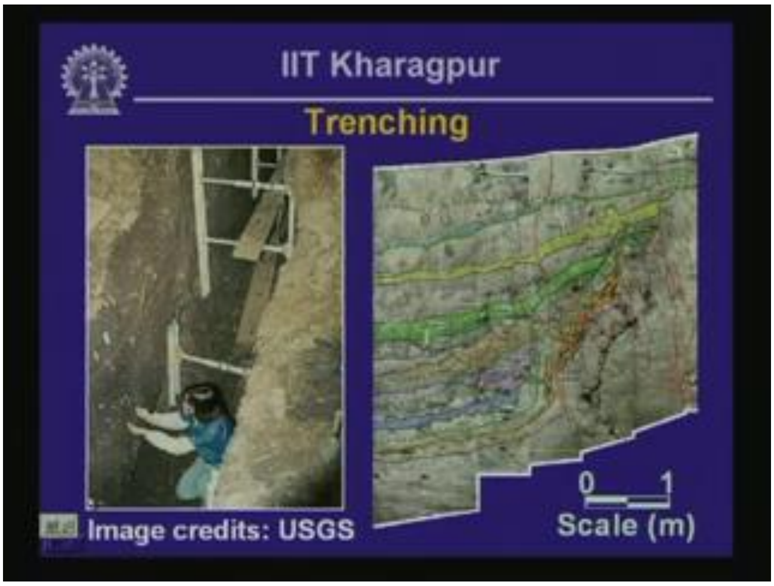

Now trenching, the activity of trenching fault trenching to expose the fault surface is a very important consideration in identifying what is the activity of a given fault. So, what is done here? You just actually dig a trench as shown on the photograph on the left and try to map the surface features on either walls of the trench. And what you get in the process is a drawing which is shown or a section which is shown on the right of this particular slide.

Now you can see here that area actually to the right of this particular section, you can see a lot of red lines, and these red lines are individual faults that are cutting through the trench. Now you can see the deformation of the different lithological units; these are color coded.

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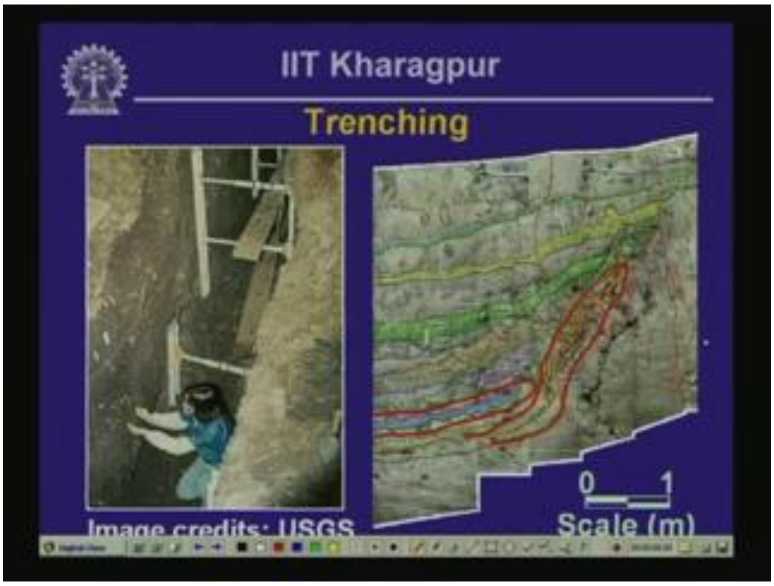

For instance, this one here is coded orange, then you have got another color coded lithological unit shaded blue and so on and so forth. Now the amount of deformation of these lithological units or the pattern of the deformation of these lithological units, you could estimate or you could infer the amount the extent of coseismic slip or the amount of the fault movement that has taken place as a result of a single earthquake. That is what is meant by the term coseismic slip, and from the coseismic slip, you could estimate what is the magnitude of associated with that particular earthquake.

And also from the dating of the lithological unit, you could time as to how many years back or how many million years back, this particular earthquake has taken place. So, trenching has become a very important tool in assessing the activity associated with the given fault. Now for instance, in a log like this if you see that a particular fault is not cutting through a rock unit which is older than, say, hundred million years or it cuts through only those lithological units that are older than hundred million years, then you could say that the fault has not been active since one hundred million years ago. So, that particular fault is not actually you do not need to consider that fault in assessing the seismic hazard of a given site located near that particular fault, okay.

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Source mechanism and activity of a given fault can also be inferred from fault trenching, because from fault trenching, you could assess what is the direction of coseismic slip. And as I indicated from the magnitude of the coseismic slip, you could imagine you could infer or the length of the coseismic slip you could infer what is the magnitude of the earthquake as well.

Now size of a potential earthquake for a given source is inferred, because larger earthquakes are going to correspond to larger coseismic offsets, and breaking of longer fault segments, where this is going to be clear from one of the examples that we are going to consider a little bit later.

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Now frequency of the earthquake can also be inferred as I indicated from the dates and sizes of coseismic slips inferred from fault trenching and frequency and size of earthquake ascribable to a given source with reasonable confidence. Either one of these two can tell us what is the frequency of an earthquake that is likely to occur because of the activity of a sudden individual source.

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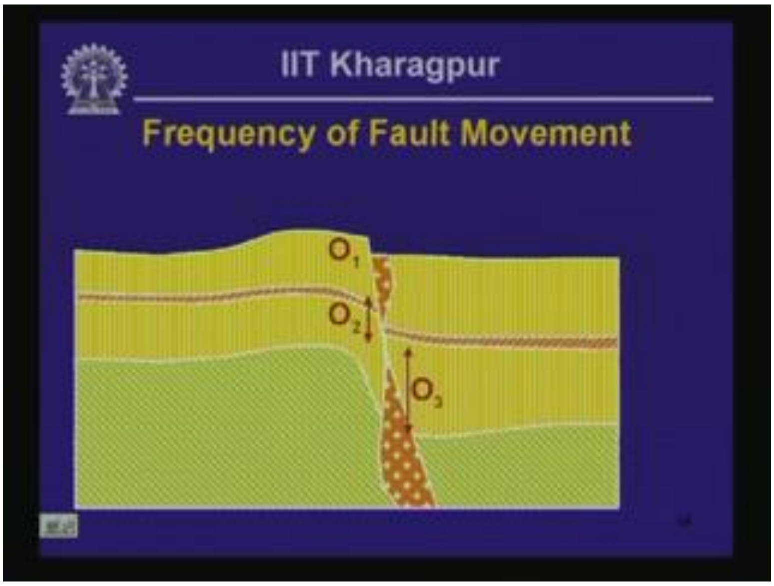

Now this particular cartoon actually is going to show us as to how to estimate the frequency or the activity of a given fault. Now here what we see is there are three offsets o 1, o 2 and o three across the fault, and the fault is very clear clearly visible in the trench wall. Let us say this is the feature that you have observed on a trench wall near the centre that the fault plane is visible near the centre of this particular section showing the features on the trench wall.

And what you can see is o 1 is clearly visible as an offset at the ground surface, then o 2 is the offset of the thin pink cross hatched layer near the top of this particular formation. And then you have got o 3, another earthquake that took place still further back in past and that is near the bottom. And here what you will see that the cross hatched greenish layer has undergone that particular offset. So, o 1 is an offset associated with an earthquake which is more recent; o 2 is an early earthquake, and o 3 is the earliest earthquake related offset that is visible on this particular trench.

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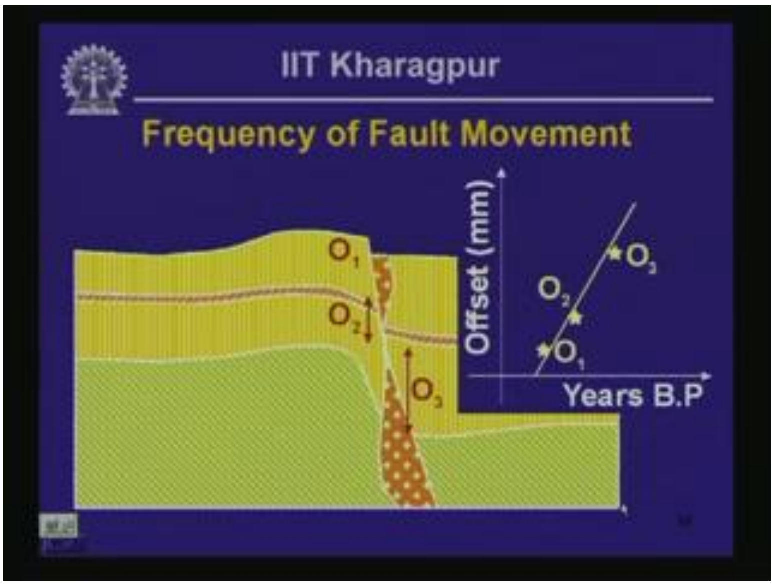

Now what you do then is to plot the distances o 1, o 2 and o three on one axis on the vertical axis and year of occurrence of these offsets from the dating of the material through which is affected by this particular offset. For instance, o 3 is affecting the bottom most layer of this particular sequence. So, the date of the top portion of the bottom most unit of this section will give us the approximate date of the offset o 3. So, if the offsets are plotted against the timing of the offsets, then we can find out what is the interval or what is the recurrence interval before which the fault is likely to get moving once again.

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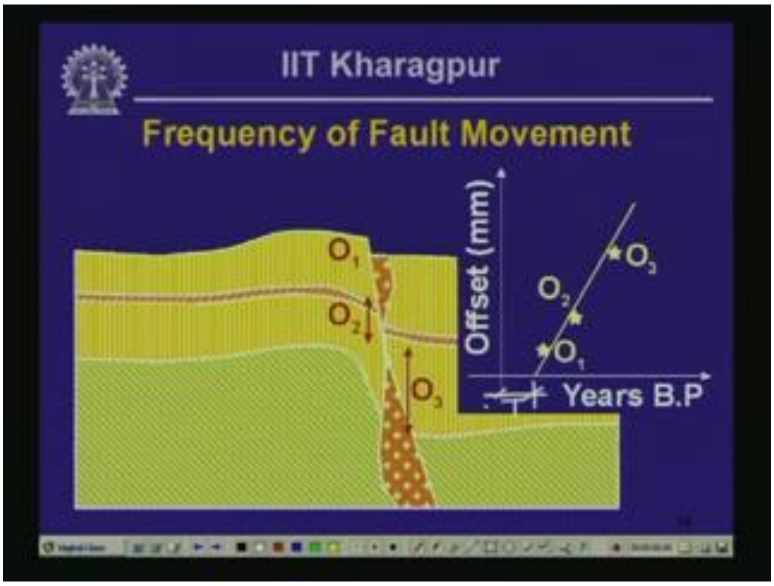

So, that interval in this particular case is this time distance; this time t is the recurrence interval of this particular fault. So, it is going to move once every t years, okay.

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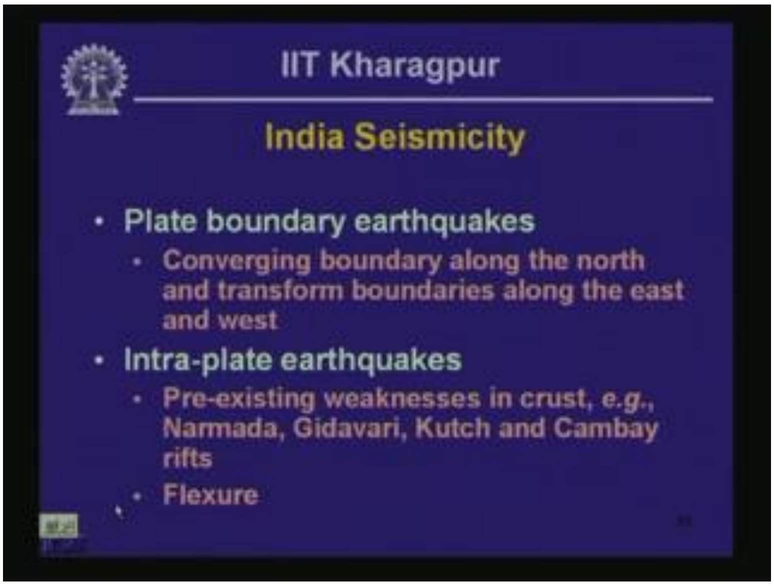

Indian seismicity we are going to consider now. The seismicity of India is controlled by plate boundary earthquakes which mainly take place at the converging boundary along the north and the transform boundaries along the eastern and western parts of India or north east and north west of India. And also intra-plate earthquakes which have been proposed actually by many researchers to have been triggered along pre-existing areas of weaknesses in the crust such as the rifts of Narmada, Godavari, Kutch and Cambay and flexure that is associated with the convergence of Indian plate and the Eurasian plate.

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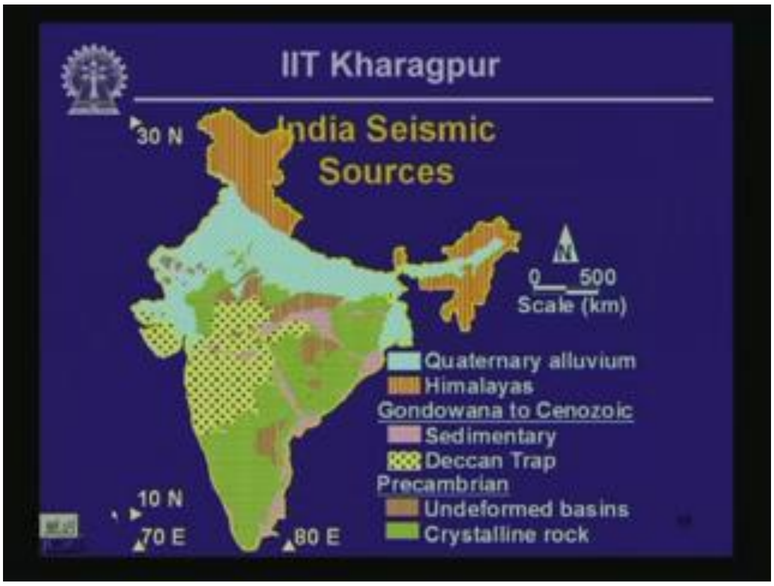

Okay, this is the geologic map of India. You have seen this map earlier on and this one here, you can see the northern part is the Himalayan belt, just to the south is the quaternary alluvium of the river Ganges. And then the southern part is largely underlain by older rocks of Gondowana to Precambrian age, Cenozoic to Precambrian age.

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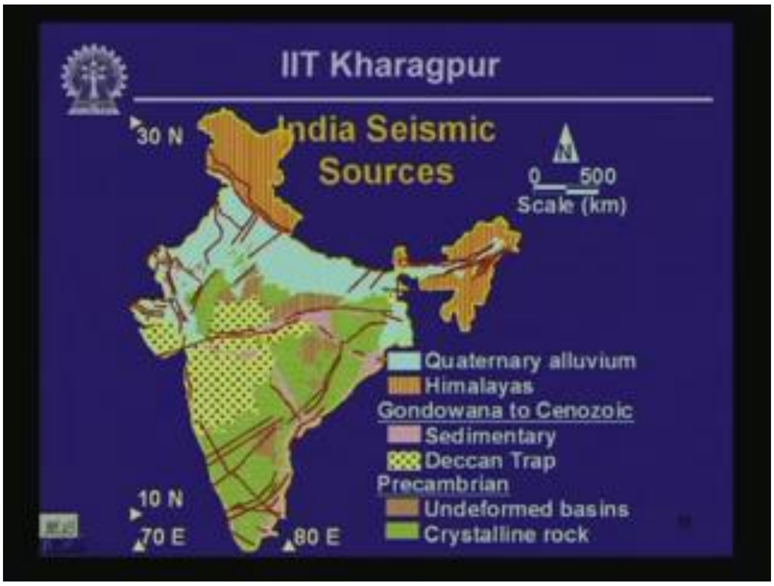

Several faults have been identified criss-crossing the country, and the faults are indicated on this particular map.

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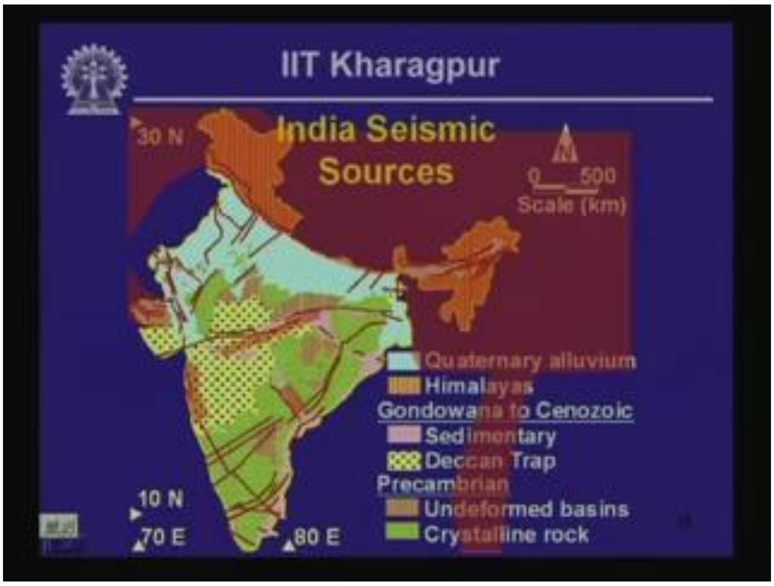

And the activity of these faults have been associated have been clubbed together in the form of seismic sources shown on the shaded map on this particular slide.

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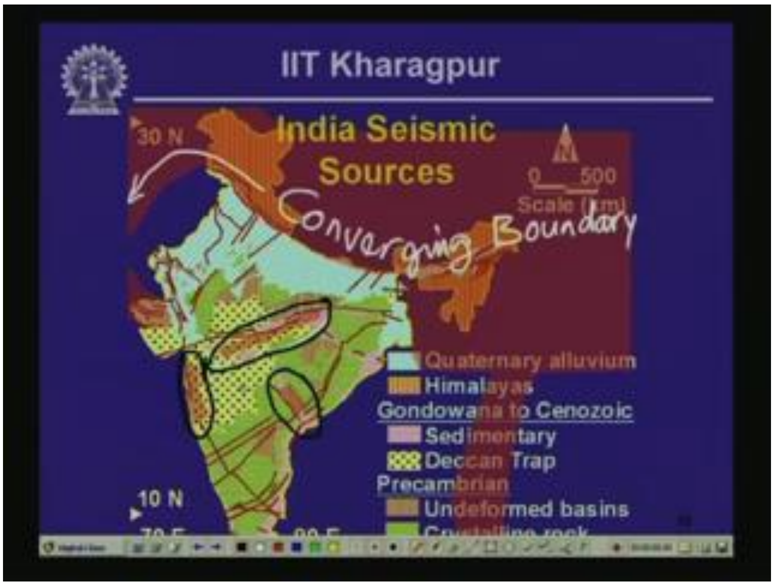

Now this is the Himalayan; this area out here this is the converging boundary largest earthquakes that affect India occur along this particular belt. And some intra-plate seismic sources have also been identified such as this is the Narmada lineament which is essentially the rift valley; that is a relic feature from the Precambrian, then area around the Koyna reservoir near the west coast of Maharashtra and Godavari rift valley just in Andhra Pradesh. So, these are three major seismogenic sources that affect peninsular India. So, these are some of the major seismic sources that affect our country.

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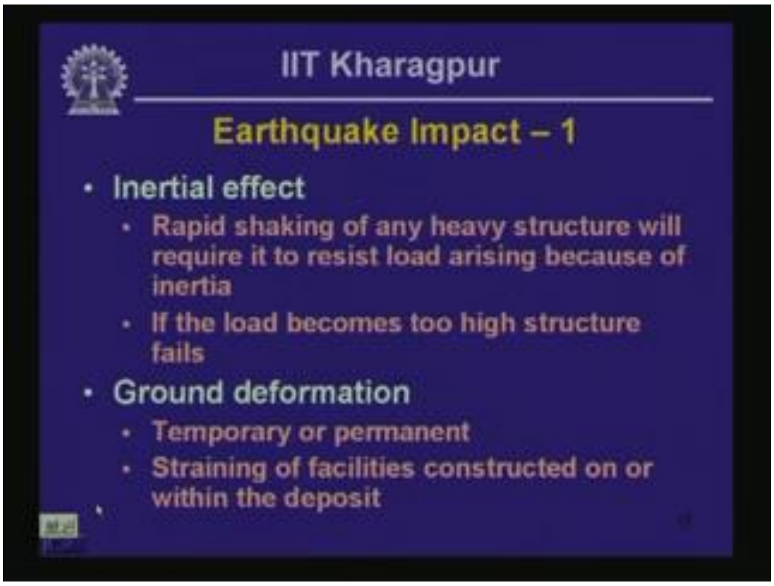

Earthquake impacts, what kind of effect that you are going to have of earthquakes on manmade facilities and natural deposits. Number one is the inertial effect rapid, shaking of any heavy structure will require it to resist load arising because of inertia. So, inertial effect is one of the important impacts of earthquake must be provided for in the design of a facility.

If the load becomes too high the inertial load, then the structure is likely to fail. Then ground deformation, it could be temporary or it could be permanent; that is going to cause straining of facilities constructed on or within the deposit such as railway line or in underground tunnel is going to get affected by movement of a fault that it might actually cross if the fault moves.

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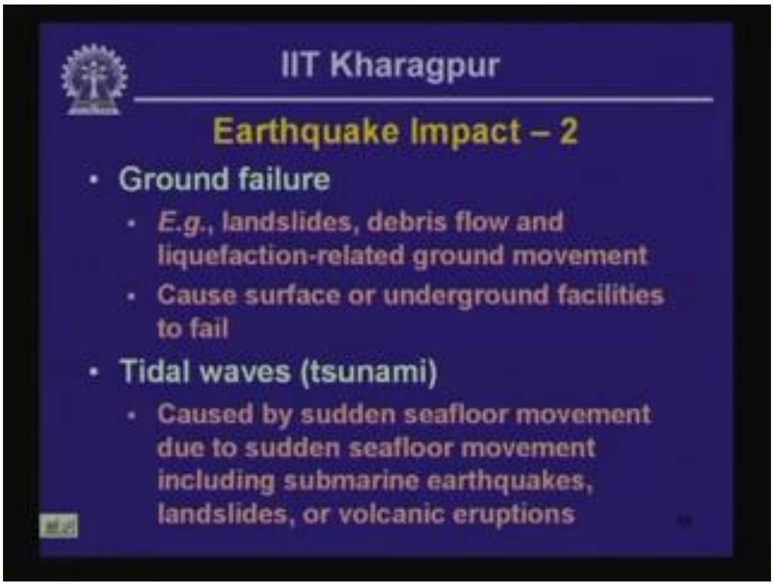

Ground failure can also be triggered by earthquakes such as landslides, debris flows, liquefaction-related ground movement. And another effect of earthquake is tidal waves or tsunami as it is called; that is caused by sudden sea seafloor movement. It could also be caused by underwater landslides or volcanic eruptions.

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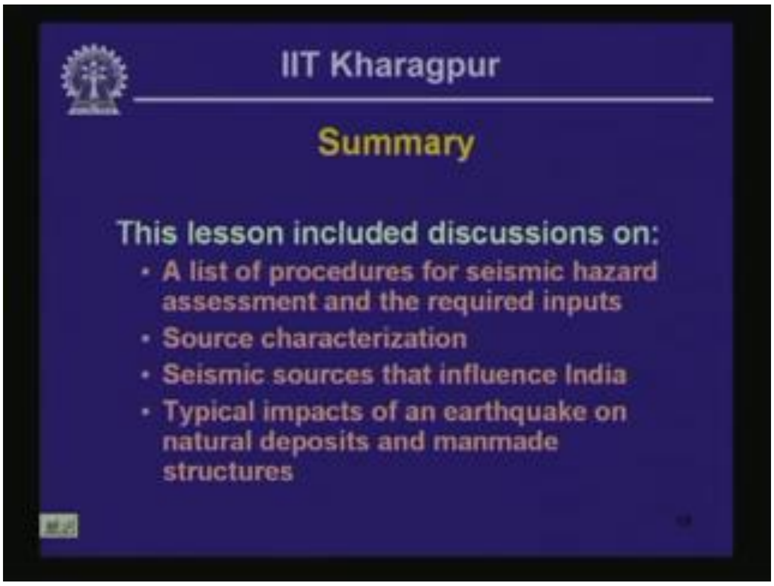

Now we have come to the end of this particular lesson. To summarize, what we discussed in this lesson; we looked at a list of procedures for seismic hazard assessment just looked at a list, we did not look at the procedural details of these methods. Then we looked at seismic source characterization. We looked at seismic sources that influence India, and typical impacts of an earthquake on natural deposits and manmade structures.

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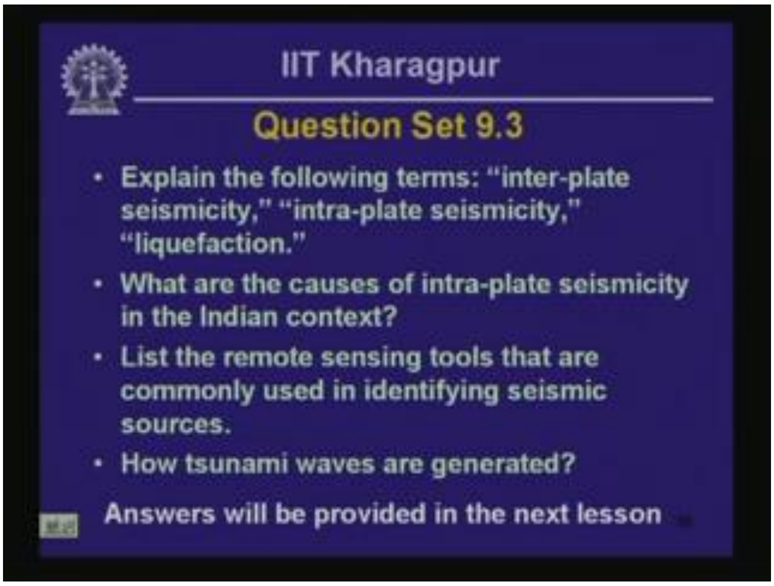

So, finally, to wrap up this particular lesson give you this question set. The first question that I asked is explain the following terms intra-plate seismicity and liquefaction. What are the causes of intra-plate seismicity in the Indian Context? List the remote sensing tools that are commonly used in identifying seismic sources and how tsunami waves are generated. Try to answer these questions at your leisure; I will give you my answers to these questions when we meet with the next lesson.

So, until then bye for now, thank you very much.