Engineering Geology
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Lecture - 22
In-situ State of Stress

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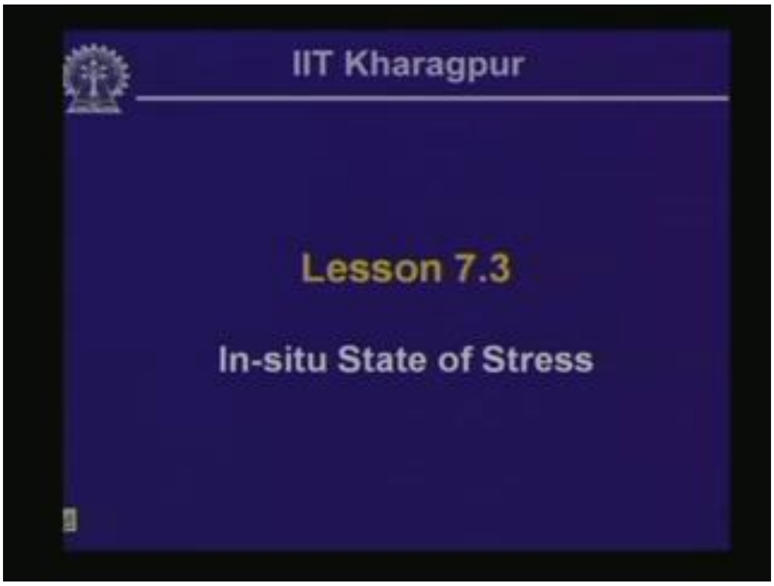

Hello everyone and welcome back. Today we are going to talk about in-situ state of stress, but before we carry on with today's lesson, we are going to look at the questions that I gave you as part of the previous lesson.

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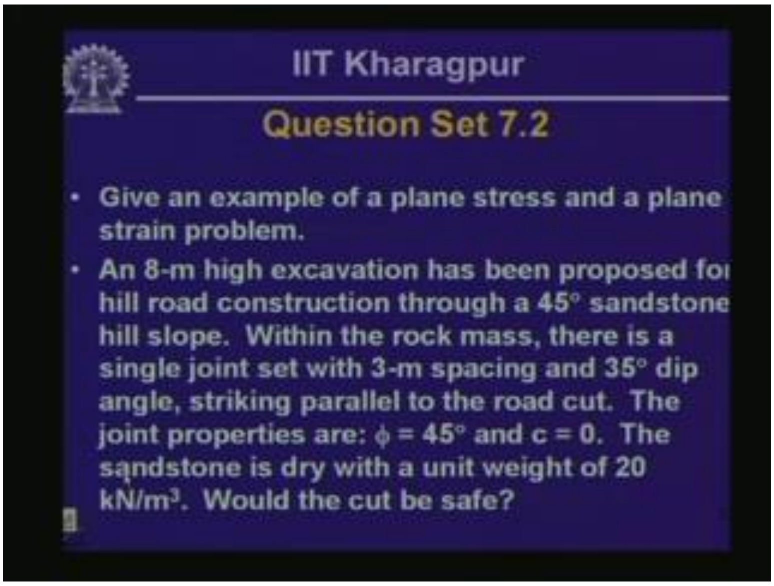

So, these are the questions. The first question that I asked was to give an example of a plane stress and a plane strain problem. Now, plane stress, if you recall in plane stress problem, what you have are essentially two principle stresses. In one plane and the out of plane, principle stress in that case is zero. So, we can consider an example from the prospective of engineering geology.

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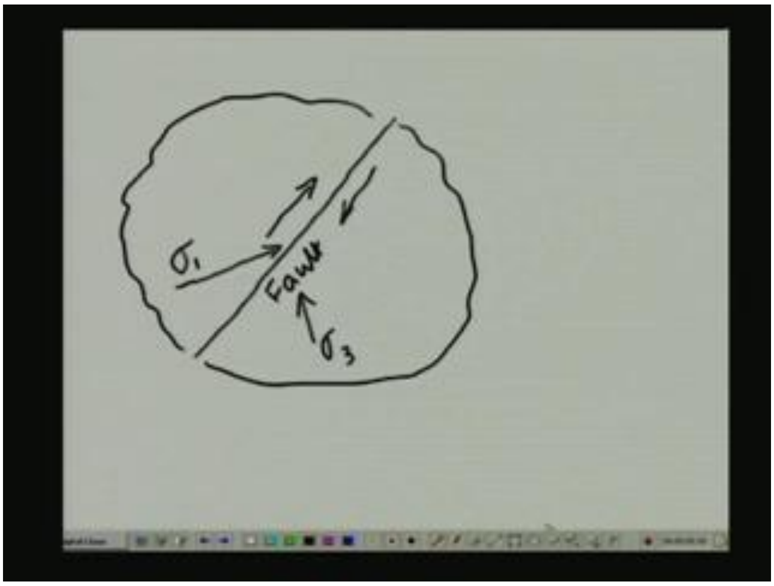

Let us say we have got a fault, we have got a tri-slip fault which is rupturing at ground surface. So, what is happening in that case is say the block that is to the top left of this fault, so this is our fault is moving up and the block that is on the bottom right, that is moving down and to the left. So, in this situation, this problem and mind you what we are looking at here is a plane view, birds eye side view looking downward and this fault is rupturing at ground surface.

So, in this case, the principle stress perpendicular in the vertical direction actually is going to be 0 because the rupture is taking place at surface, and the two principle stresses in this case are going to be aligned in this direction, and we are going to look at the configuration in greater detail later in this lesson. So, this problem is essentially a plane stress problem. Now, we are going to look at the problem. We are going to look at an example of plane strain problem.

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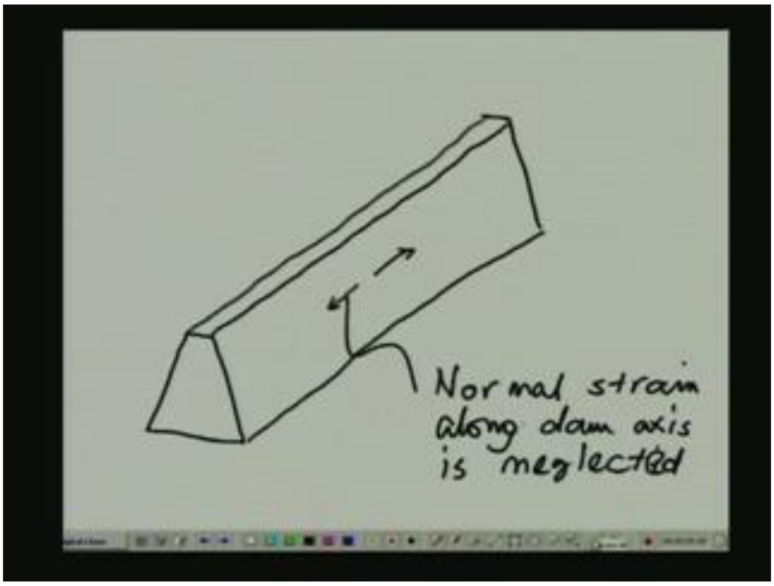

Now, let us say we have got a dam which is very long in comparison to its height, and in this particular case, the strain in the direction perpendicular to any of the cross-section or in the direction of the dam, axis can be neglected and as a result what we have got is I am talking about the normal strain. So, the normal strain in this direction, normal strain along dam axis can be neglected and this problem thus becomes a plane strain problem. The deformation associated with the dam body dealt with as a plane strain problem. So, those are two examples.

Now, getting back to question number 2. So, in this case, what I asked is that there is an 8 meter high excavation proposed on a hill slope, 45 degree hill sandstone, hill slope and the rock underlying this particular hill side, it has got a single joint set which is striking parallel to the road cut and it has got 3 meter spacing and 35 degree dip angle. The joint has got 45 degree friction angle, and cohesion intercept for the material within the joint is 0, the sandstone is dry with a unit weight of 20 kilo Newton per meter cube. The question was whether the joint is going to be safe. So, let us draw the configuration then.

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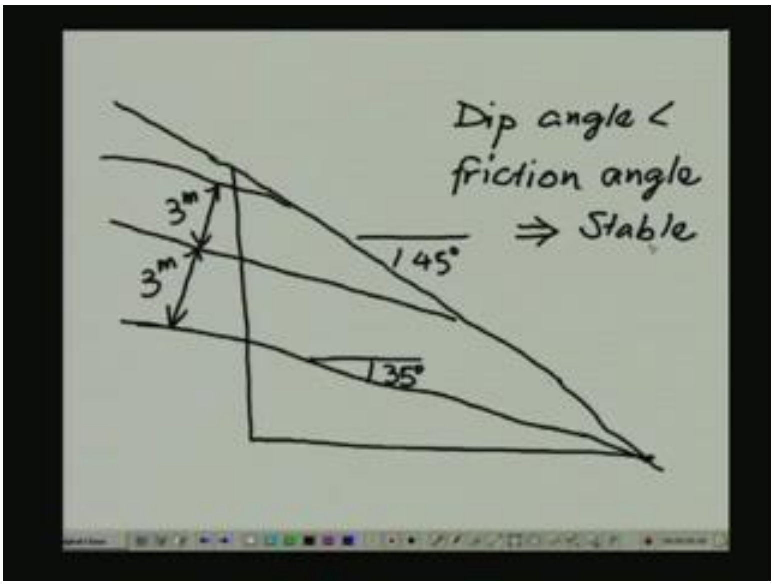

So, what we got here is actually let us draw it in a proper manner. So, what we got is a hill slope like this, and this angle here is 45 degree and actually the sandstone has got joints in it, and these joints are a little bit shallower-dipping, then the hill slope itself. So, the joints are like this and the spacing between the joints is 3 meters. All the joints are at 3 meter spacing and what we are up to. We are up to cutting this particular hill slope in this manner, and the question that I asked was whether this particular configuration is going to be safe or unsafe.

Now, what you need to look at really is whether the rate of the joints is going to be carried, whether the rate of the joint rate of the sandstone in between two joints is going to remain stable or not. Now, what we know here is that this angle is 35 degree, and since the dip angle in this case is lower, the dip angle of the slope is lower than the frictional strength dip angle is smaller than the frictional angle. From this we can easily conclude that this particular slope is going to remain stable, and actually let me complete this particular sketch here after the excavation is over, then the configuration post excavation configuration is going to be like this.

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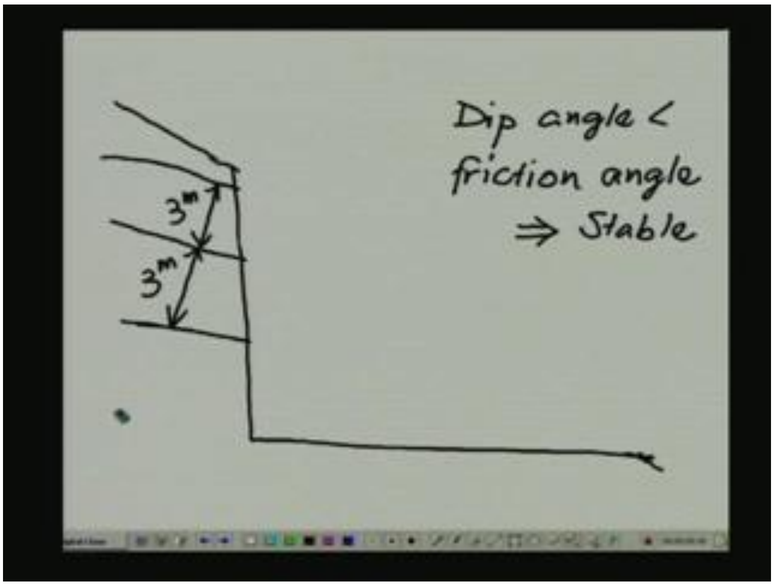

So, the better the joint sandstone of this type is going to remain stable. So, that is the conclusion that we have drawn from this particular simple example.

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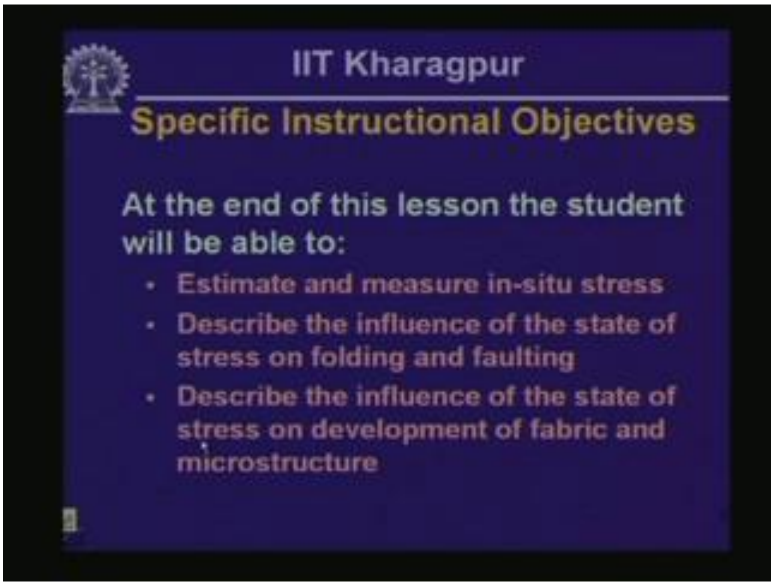

Now, we get on with today’s lesson. So, what are the objectives of today’s lesson are as follows. We would be able to estimate and measure in-situ stress. Then, we would like to describe the influence of the state of stress on the problems of structural geology, such as folding and faulting, and finally we should be able to describe the influence of the state of stress on development of fabric and microstructure of block of rock.

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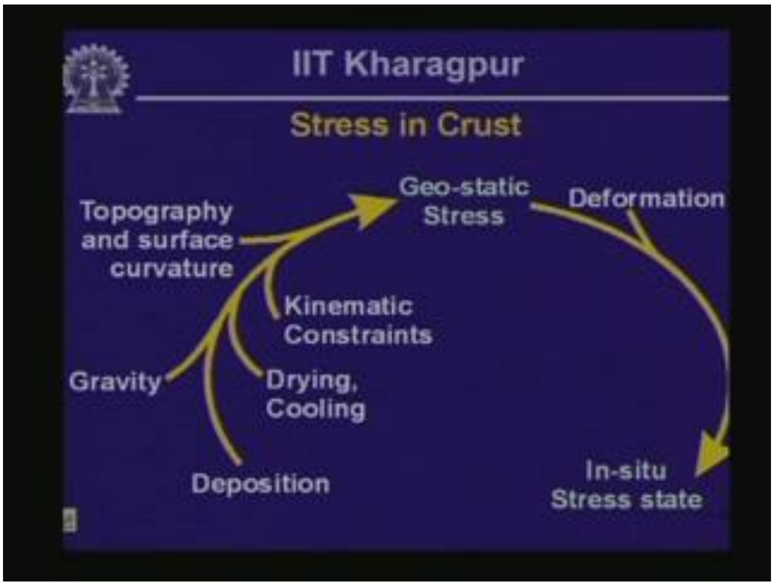

So, first question comes how the state of stress develops within a particular element at some depth within the crust of the earth. So, what are the factors that affect the state of stress are as follows. The depositional environment controls the state of stress. Gravity plays a major role and then, topography and surface curvature is another important aspect that controls the development of the state of stress within the earth's surface, and kinematic constraints whether we are allowing during the depositional process align any grain movement in a certain direction, or we are restraining the grains that are being deposited from moving in a certain direction. That particular aspect also affects the development of the state of stress.

Now, the state of stress that is going to develop in this manner is called geostatic stress because of the fact that the development is a result of quasi-static process, and no movement of masses of rock is involved in this particular process. So, let us consider all these aspects one by one.

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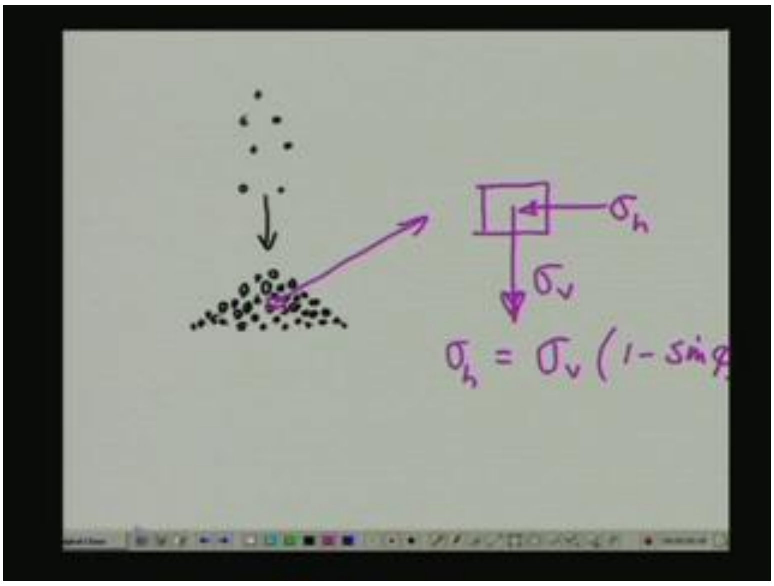

So, first of all, let us imagine that you are actually depositing grains of sand or gravel in the vertical direction, and they are going to actually take shape of the heap basically and the way within this particular heap, there is going to be a vertical stress and a horizontal stress. So, within this heap at some depth if we consider a small volume and if we bring it out, then this particular volume is going to have a vertical stress. We are going to call it sigma v and they are going to be a horizontal stress.

Now, the question is what are the values or relative values of sigma v and sigma h. We are going to consider this thing in greater detail later on, but what is sufficient at this stage is that sigma v is roughly equal to the weight of the soil that is above, or the rate of the soil or the rate of the particles that are above this particular element, and sigma h is controlled by the lateral restraint of the grain movement, and typically in this particular case, sigma h is going to be controlled by the friction angle and it is going to be given by sigma v times 1 minus sin pie typically.

Now, what is also important to notice at this stage is that because of the fact that here the main stress or main effect that the intergranular contract is trying to resist is the vertical weight or the action of gravity. So, what happens in such a depositional environment is that more grain contacts develop in the vertical direction than in the horizontal direction. As a result what happens is that such a type of soil generally behaves in a much stronger manner. If it is subjected to a deformation process in the vertical direction than in the horizontal direction, such a behavior is called anisotropic stress strain behavior.

Then, the second effect. So, we have already taken care of deposition and the effect of gravity. The second effect that is important here, we also talked about kinematic constraints. Now, another important aspect here is the effect of topography. So, for instance what I said before is that sigma v, the vertical stress is typically equal to the weight of the particles above a certain horizon, but that is not considering the topographic effect.

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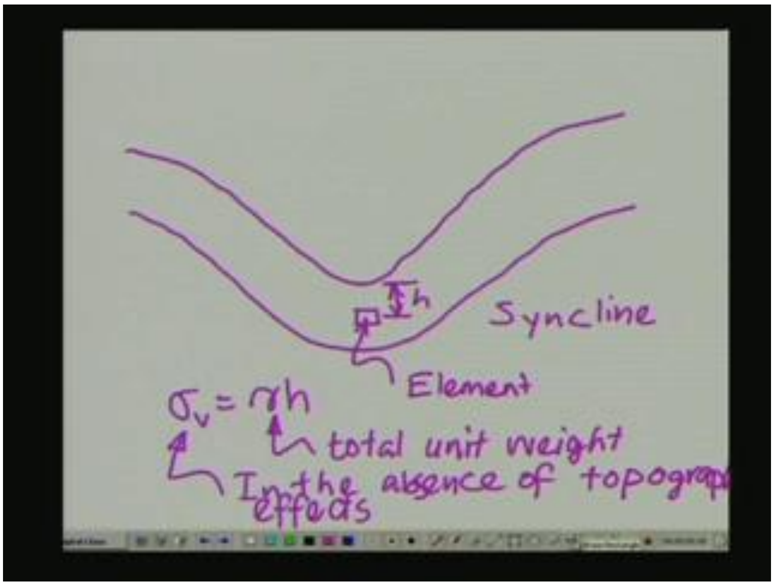

Now, let us say we have got a configuration, where there are layered rocks and what we have got here is a fold called syncline. You recall this thing from your previous notes. In this particular case, if we consider an element at some depth within the valley here, what we have is a height of h of the rock layer above this particular element. So, this is the element that we are considering. So, this case had the topographic effect being absent. We would have said that the vertical stress is equal to sigma v. Vertical stress of sigma v is equal to gamma times h, where gamma is the total unit rate of the rock layer.

For simplicity, I am considering here that this particular rock layer is dry, and there is no water in the vicinity. So, this is in the absence of topographic effect. Now, what happens because of topography is like this. What happens because of topography is as follows.

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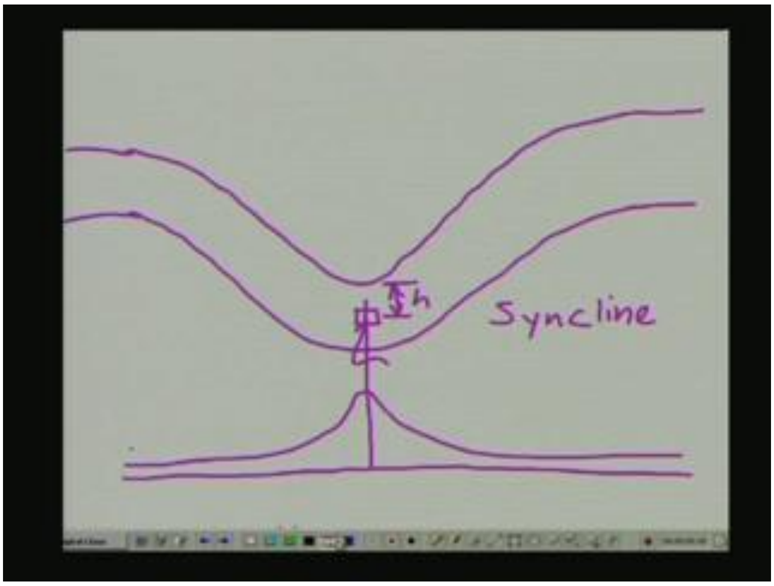

Because of topography, the stress, the vertical stress near the valley bottom is going to be much larger in comparison with the stresses which is near the shoulder of this particular fold, and this particular, this increase over the background value would actually be several times and that depends on how steep or how narrow this particular valley is. So, that is the effect of topography.

Now, these all factors give rise to a set of geostatic stress. What we have done so far is development what we have looked at. So, far is the development of the vertical stress and horizontal stress. Now, under the action of the geostatic stress or because of tectonic effects, because of movements between different block, relative movement between different parts of a rock, mass deformation could be there, there could be deformation of the volume of rock and this deformation process alters the geostatic stress, and what we end up with is what is called as in-situ state of stress. So, what are the factors? Then, to sum up that gives rise to a set of in-situ stress.

First of all is deposition and then, action of gravity, then drying or cooling. Because of drying or cooling, you can imagine that there could be cracks developing and as a result, the stress regime near the crack is going to be altered. Then, kinematic constraints we have looked at that in detail in the discussion before topographic effect and finally, deformation of the rock mass. All these aspects will give rise to in-situ state of stress.

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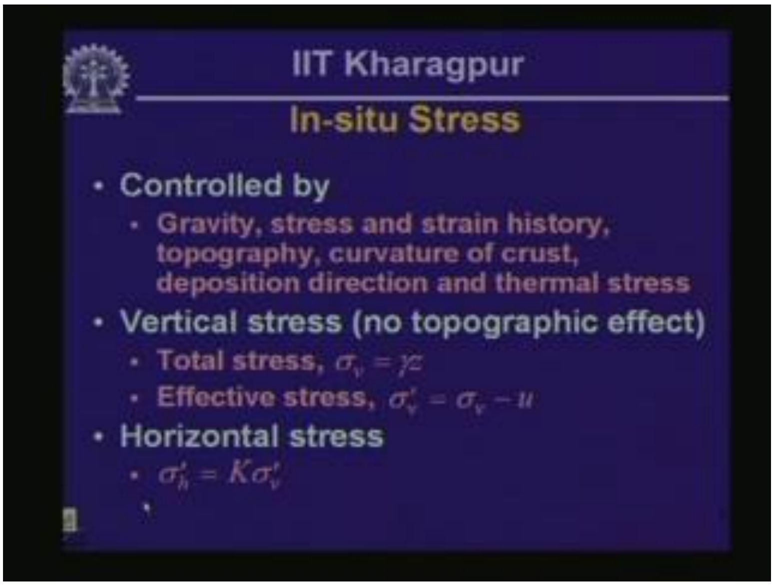

This is stated again here in the first bullet. So, in-situ state of stress is controlled by all those aspects that we have discussed in the previous slide. Now, in-situ state of stress consists primarily of the vertical total stress. This is vertical total stress, and we have looked at that also that is going to be given by gamma times z. Gamma is the total unit rate of the soil or rock which is above the element that is being considered, and z is the depth of an element below the surface. Then, we can also introduce another term which is the effective stress, and as we know effective stress is simply equal to the total stress minus the water pressure that is acting on the element.

What we are neglecting here is the topographic effect, and what we are also neglecting when we are using this definition of effective stress is that there is no movement of ground water. Then, the other component of the in-situ state of stress is the horizontal stress, and here the horizontal stress is typically expressed using a factor K, and it is given as sigma h prime equal to K times sigma v prime. So, K is the coefficient of horizontal in-situ stress. Now, before we move forward, I want to introduce here one concept.

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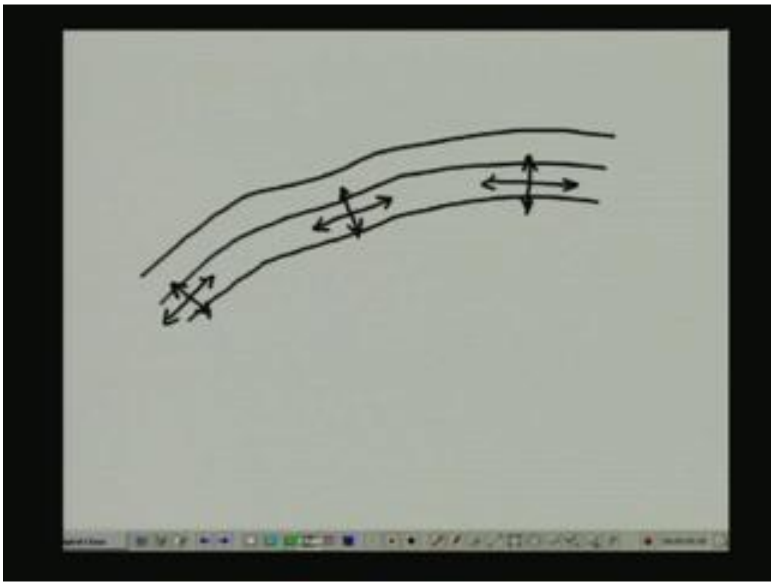

Let us consider topography of like that type. So, here what we will get is that the surface at the surface, there is no stress. So, what happens is that the surface topography that itself acts as a principle plane. If you recall from our previous discussion is that principle planes are those planes on which there is no shear stress. So, topographic surface is essentially a principle plane. Now, if you have got layering of that type, then what you would expect is that one of the principle planes is going to be like that, and another one of the principle planes is going to be aligned in that manner.

Similarly, when we come near the right of this particular sketch, then the alignment of our principle planes are going to be like that and consequently, the alignment of the principle stresses are also going to be in that manner. So, principle stresses typically follow the topography, and they typically follow the pattern of the bedding planes. In this case, one of the principle stresses typically is going to be sigma v. If you have got approximately horizontal layering, then one of the principle stresses is going to be sigma v and another one of the principle stresses is going to be sigma h because there is no shear stress typically on a horizontal plane in a horizontal topography.

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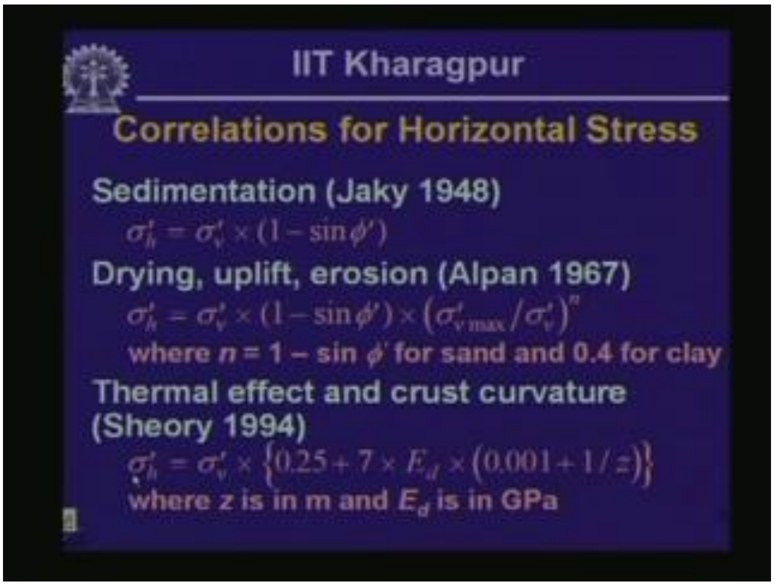

So, then we have got some of the correlations for horizontal for estimating horizontal stress. If you have got unlithified sediments, freshly deposited unlithified sediments that has consolidated or that has stabilized under its own rate. In that case, sigma h prime is going to be equal to sigma v prime multiplied by 1 minus sin pie prime, and this is the expression proposed originally by Jaky, and it appears to actually work quite well in case of unlithified or soils that are here to get cemented and become rock like. Then, considering the effect of drying uplift and erosion, Alpan in 1967 gave the following expression. Sigma h prime equal to sigma v prime multiplied by 1 minus sin pie prime multiplied by a ratio and that ratio is equal to sigma v prime max divided by sigma v prime to the power n, and this exponent is equal to 1 minus sin pie prime for sand and approximately 0.4 for clay soils.

This first two expressions that we are looking here is for very shallow soil layers, normally for rock layers these equations are not applicable. Now, I have to explain what is meant by sigma v prime max sigma v prime. As you know it is equal to in-situ effective stress and sigma v prime max is equal to the maximum vertical effective stress that this particular soil element has undergone at any point of time in the past. So, this value could actually be much larger than sigma v prime, and the layers of the soil of the soil layers that have encountered sigma v prime for which sigma v prime max is larger than sigma v prime. Those types of soils are called over consolidated soils. Let us take an example of an over consolidated soil.

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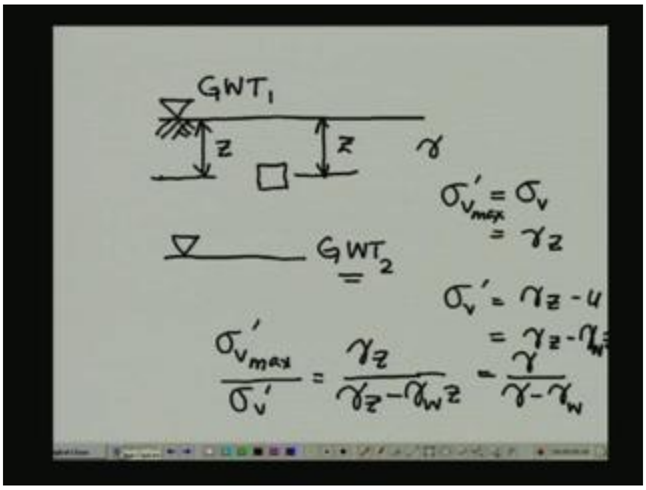

Let us say we have got an element at some depth below the ground, and the depth in this case is z and the total unit rate of the soil, let us consider this soil to be homogenize. The total unit rate of the soil is gamma, and let us say originally the water table, the ground water table was at surface and after a while the water table has gone down to great depth. So, this is the first position of ground water table. Then, let us consider a second position of ground water table and finally, the ground water table has again come back to the surface.

So, in this case, if you consider the soil element for the position of ground water table given by GWT 2, in that case the soil has stabilized under a vertical effective stress of gamma times z. Notice in this case, sigma v prime is going to be equal to sigma v because there is no pore water pressure and as a result, u in this case is 0. So, that was the state of consolidation or the state at which the soil element got stabilized when the water table went down to ground water table went down to the deeper location, and then finally the ground water rose to the surface. In this case, sigma v prime becomes equal to gamma z minus u, and u in that case is going to be gamma z minus unit rate of water times z once again because the water column that is exerting pressure is also going to be equal to z in this case.

So, then what we have got is the ratio of sigma v max sigma v prime max over sigma v prime is going to be equal in this case. So, we can also write here that this value is going to be sigma v prime max. So, this is going to be equal to gamma z divided by gamma z minus gamma wz. So, after simplification, it will be equal to gamma by gamma minus gamma w. So, that is how a soil can become over consolidated. Then, if we consider thermal effect and the curvature of the Crust Sheory in 1994 gave this expression. Sigma h prime is equal to sigma v prime multiplied by 0.25 plus 7 times e d multiplied by 0.001 plus 1 by z. Here z is going to be in meters, and e d which is an average deformation modulus Young's modulus in fact is in giga Pascal.

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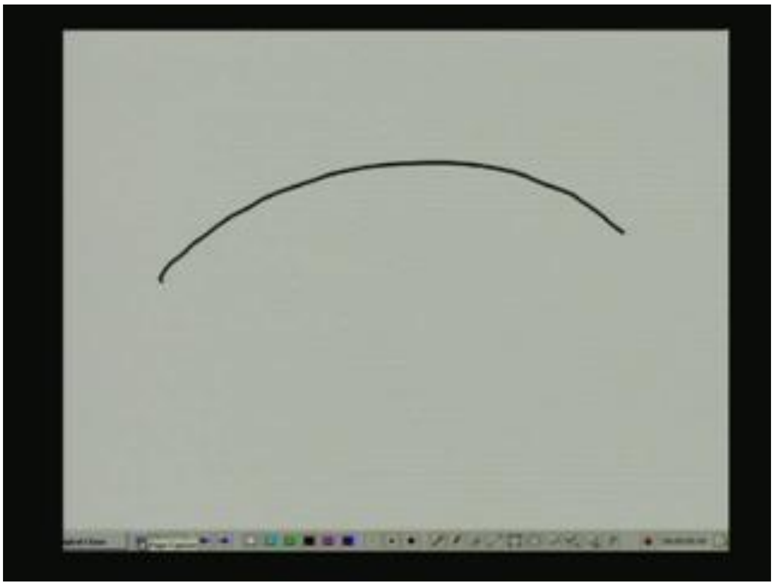

So, what he is considering? He is considering the curvature of the earth, he is considering curvature of the surface of the earth and he is considering the fact that as the magma cools, the stresses within the block, within the mass of magma is going to get locked up. So, these factors are considered by Sheory, and as a result he got that theoretical expression using elasticity theory.

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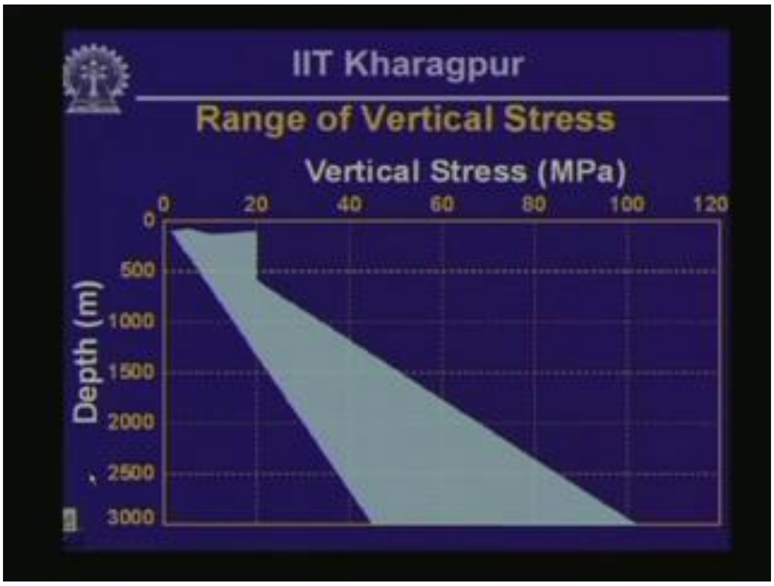

Now, this particular plot shows the range of measurements of vertical stress in rock without considering topographic effect from across the world. This particular plot is adopted from the data compiled by Brown in their book, and you can see that there is a wide range of variation in sigma v prime, but what you can approximately say is that roughly speaking if the depth with depth vertical stress increases linearly, and the linear increase is approximately computed. If you consider a unit rate of rock approximately in the range between about 20 kilo Newton per meter cube to about 28 kilo Newton per meter cube. So, that will be giving you an approximate estimate of the vertical stress within a mass of rock at some depth below the surface. This estimate is not going to work that well very near the surface, but if you go down to relatively greater depths like 500 to 1000 meters, then this particular method is going to work quite reasonably.

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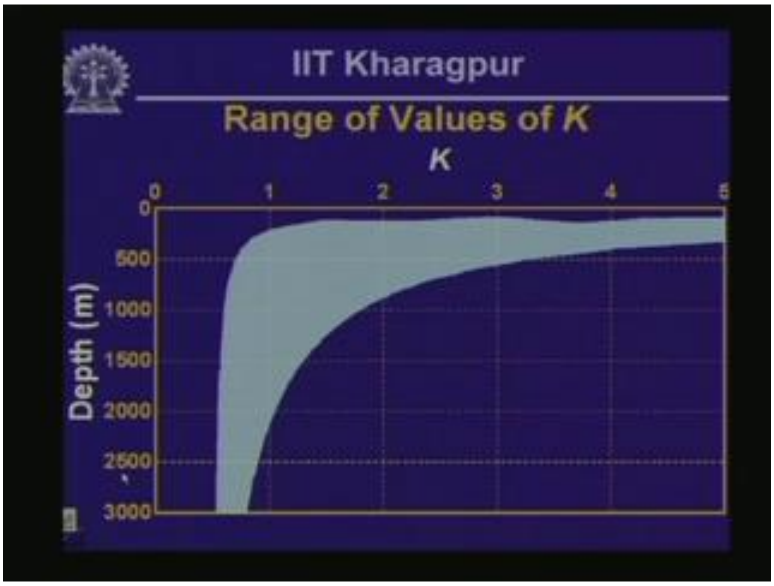

This is a plot of the range of values of K. If you recall K is the ratio of the horizontal effective stress to the vertical effective stress, and you can see that the value of K could be quite large near the surface and as you go deeper, then K becomes, roughly speaking K becomes smaller than 1 and horizontal stress becomes relatively smaller as the depth increases substantially.

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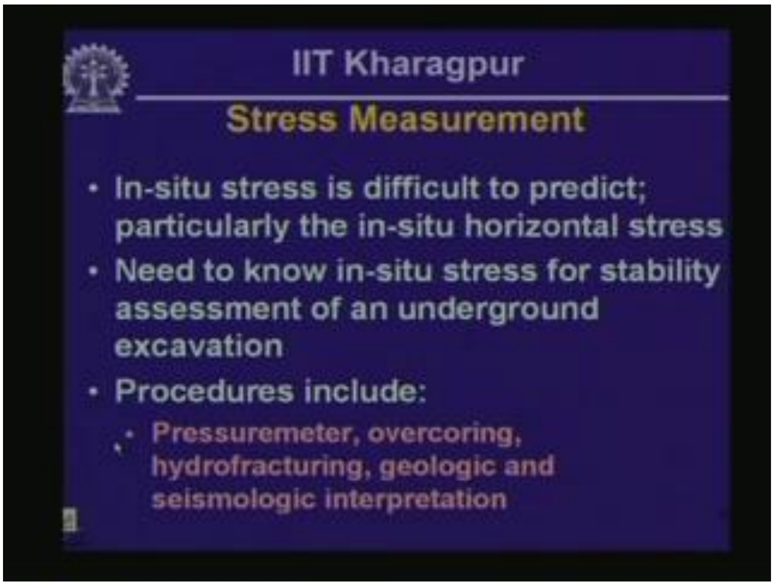

Then, the question arises how we can measure stress. What was apparent from the two plots that I showed is that the variation or the range of values of vertical and horizontal stress is quite large, and it is difficult. In fact, in many situations to effectively predict what would be the value of sigma v prime or sigma h prime, what will be the value of sigma v prime or sigma h prime and the thing is considering topography, considering all the different aspects such as the gravitational effect, topography stress, locking up because of deformation, ongoing deformation process within the mass of rock and so on and so forth. So, it is almost given that if you have got an important project of engineering geology, then you have to go with an experimental determination of in-situ state of stress. So, the question then comes what are the procedures for determination of in-situ states of stress.

Now, we need to know these stresses are because we want to ascertain the stability of underground excavation, or any project that is going to be constructed over or within a particular stratigraphy. Now, there are several procedures available for measuring stresses. They include pressure meter testing, over coring hydro fracturing or geologic and seismologic interpretation. Now, let us look at these things one by one.

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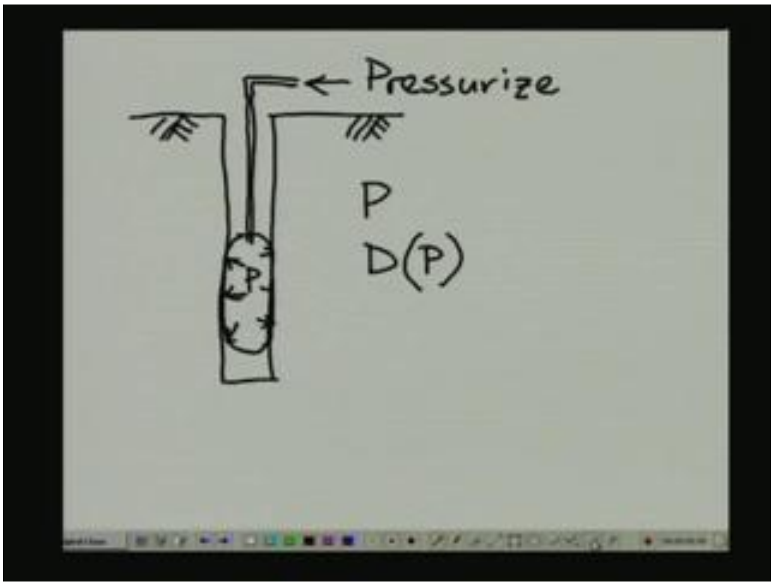

Let us look at these things one by one. So, what is pressure meter testing? It is that you have to drill a hole within the ground using the procedures, drilling procedures that we have discussed. The hole to be relatively smooth and circular in this hole, an inflatable probe is inserted and then, what we do is we pump some fluid inside this inflatable section and increase the stress within the inflatable probe. So, what we do here is pressurize and we monitor the deformation or the radius of the bore hole wall as a function of the pressure which is inside the cavity.

So, we keep track of both pressure and the diameter of the bore hole as a function which is going to be a function of the pressure. Interpreting these data, we can actually find out the in-situ state of stress as well as other deformation characteristics of the rock around the bore hole. Now, what we could also do is to pump water within the joints, and pressurize at high pressure and this process is going to actually start opening up the joints. When the state of in-situ stress is overtaken by the pressure which is there in the fluid that has been pumped in and this procedure also allows us to find out to estimate the in-situ state of stress, and the procedure is called hydro fracturing. We also can do over coring and the procedure of over coring is like this.

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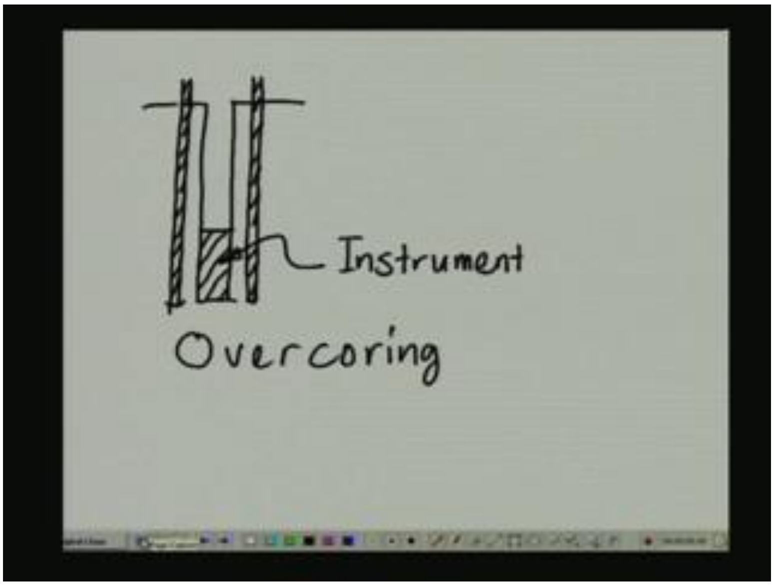

First of all, we have to drill a small diameter hole and inside the hole, we insert an instrument which allows us to measure strain in several different directions and after this particular instrument is inserted within the hole, a larger diameter drill hole is constructed is opened up in advance around the instrumented probe, and what you can imagine is that as soon as the annular drill bit which is drilling the larger drill hole around the probe, around the instrument, it crosses, it goes fast the instrument. Then, there is a sudden change of deformation recorded within the instrument, and this particular deformation change can be related to the in-situ state of stress. So, this procedure is called over coring and it is used quite extensively in determining the state of stress around underground excavations.

So, then we can also do geologic and seismologic interpretation. We can actually try to see how faults are moving or fault movements are taking place in a particular geologic area and from those fault movements, we can estimate what is the state of stress in the vicinity. We are going to look at the details of this aspect later on in this particular lesson.

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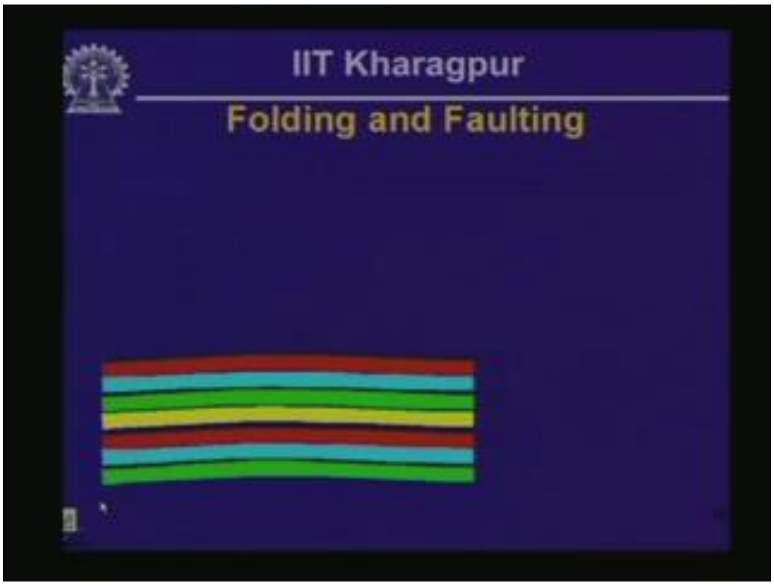

Let us consider folding and faulting are the problems of structural geology. From the perspective of what we have learnt so far from the perspective of mechanics, what we are going to consider is, these processes as deformation and failure processes. So, first of all we are going to consider the development of a fold.

Let us look at an approximately horizontally stratified series of sedimentary rock. For example, schematically shown on the slide there and let us assume that what we are going to, what we are trying here is to squeeze this rock mass by applying very high stress in the horizontal direction. Now, what is going to happen to this particular rock mass?

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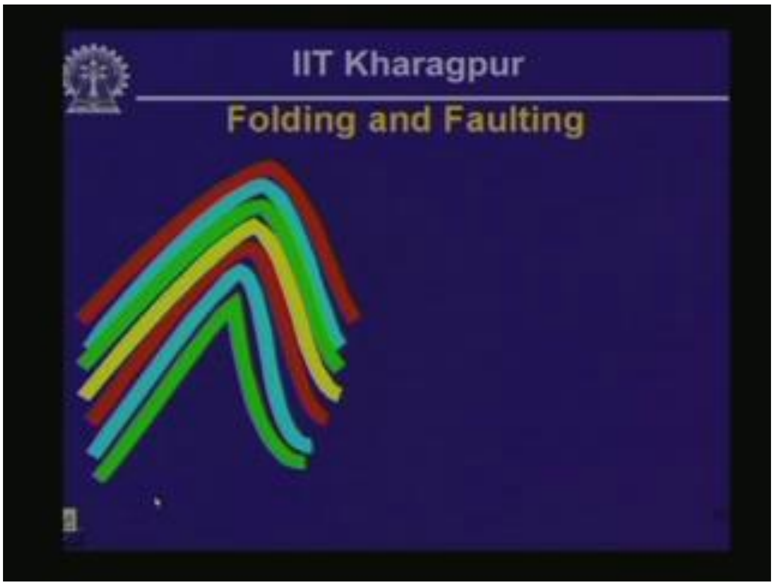

If we try to squeeze the rock mass, then the deformation is going to be like that. Then, what is going to happen is near the crown of this particular fold and this is the process of folding you know that already from what we have discussed earlier in our previous lessons, and what is going to happen is that strain near the crown of these folds is going to reach a very large value. As a result, failure is likely to take place and then, let us see what happens and how the process continues.

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So, the rock layers, they are going to start failing near the crowns as I suggested and if we continue with the lateral squeezing process, then they are going to be sliding off the limb of the fold that is towards the left, over the limb that is towards the right. Now, this particular configuration is nothing, but a fault really. So, what is going to happen here is that the rock mass which is to the left of the plane here is called the fault plane. It is going to start sliding up and to the right whereas, the block that is on the right of this fault plane is going to start moving to the bottom left. Let us look at it once again.

So, what we are doing here is, we are trying to squeeze a sequence of horizontally layered bedrock by applying very high horizontal stress. First of all, we are going to develop a fold, and then if we want to continue the deformation process further, then the rock is going to fail and a fault is going to develop.

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This is how you are going to end up finally with the configuration of the rock mass. So, this actually shows the influence of stress regime on development of folds and faults. So, these are essentially, these can be viewed as deformation process and from the perspective of mechanics as a process of failure. Pre-failure deformation slow stressing ductile rock is going to develop folds, where as failure of brittle rock is going to lead to faulting. This is important. Actually ductility is the main function here. You should notice that. So, you can imagine that rock mass becomes more ductile as temperature increases.

As a result what we normally see is that near the surface rocks behave in much more brittle manner, and as a result, faulting is a prevalent structural geologic feature whereas, as you go deeper at great depths in few kilometers, there folding becomes more prevalent in comparison with faulting. Typically below 20-25 kilometer depth below the surface of the earth, faulting does not occur.

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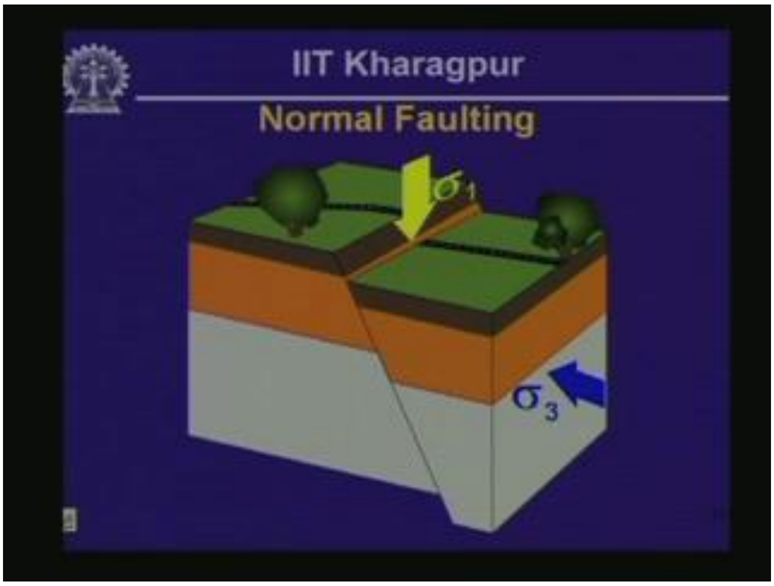

So, then let us look at the process of normal faulting. We know what normal fault from one of the very early lessons is in this series of presentations, how normal faulting can be viewed from the perspective of failure, perspective of mechanics and as a problem of failure of rock mass. So, this is how normal fault develops. We know that already and here what is happening is that sigma 1 or the major principle stress is going to be in the vertical direction.

What we are considering here is that you should have noticed that already that the layer of rocks and soils are horizontal. If the layer was to be in an inclined manner, then also we could have normal faulting, but there sigma 1 would have been in the direction perpendicular to the layers. Then, the minor principle stress is going to be in a direction perpendicular to the direction of sigma 1 is in the horizontal direction, and that is how the direction of sigma 3 is shown on the right of this particular animation.

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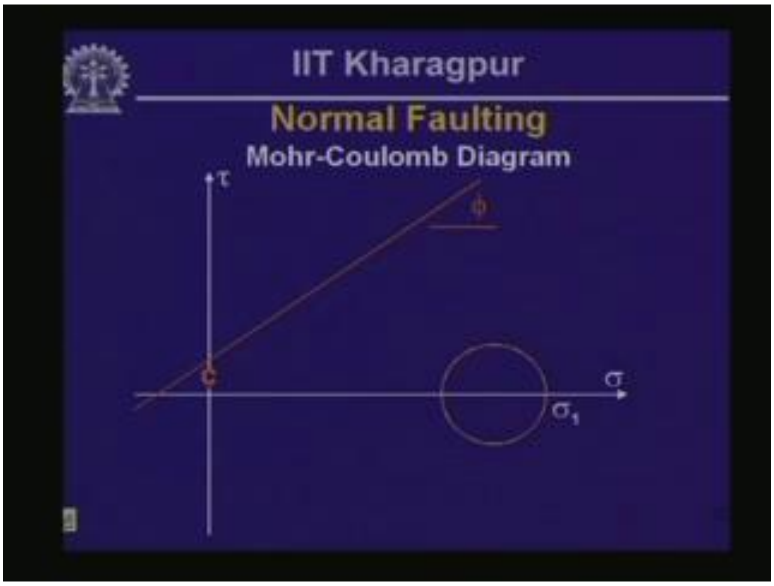

So, what is happening here can be viewed as Mohr-coulomb problem as a problem of failure. So, the failure circle of Mohr of the state of stress initially is represented by Mohr circle. That is shown on the plot there on Mohr-coulomb plot. Mohr-coulomb diagram also shown on the diagram is the Mohr-coulomb failure (( )). Now, let us see how this particular Mohr circle is going to evolve during normal faulting.

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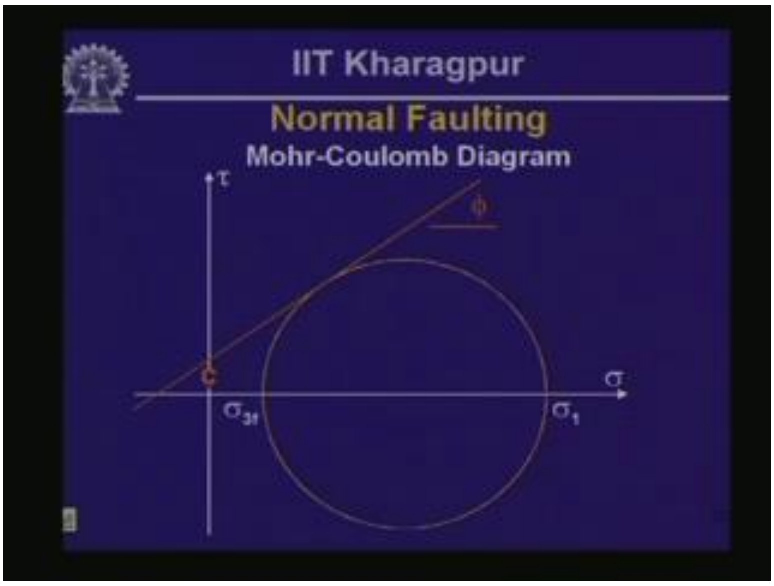

So, essentially what we are going to have is sigma 1 is going to remain constant, and the minor principle stress is going to start decreasing until we reach failure, and once the failure is triggered, then the blocks of rock, they are going to start sliding with respect to each other. So, what we have here is sigma 3 or the minor principle stress at failure shown on the plot there, and that is essentially the normal faulting process viewed from the perspective of Mohr-coulomb failure problem.

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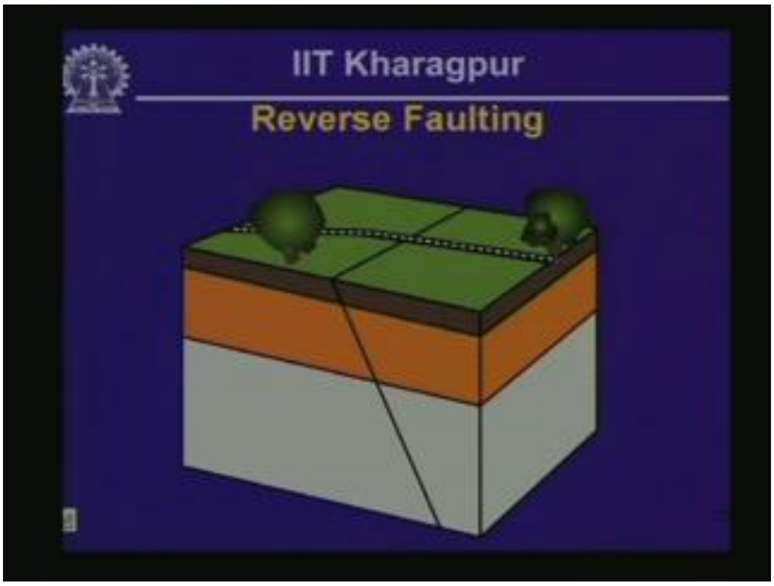

Now, let us look at reverse faulting problem similar to in stand using a similar methodology as we did in case of normal faulting problem. So, what is reverse faulting is shown here in this animation.

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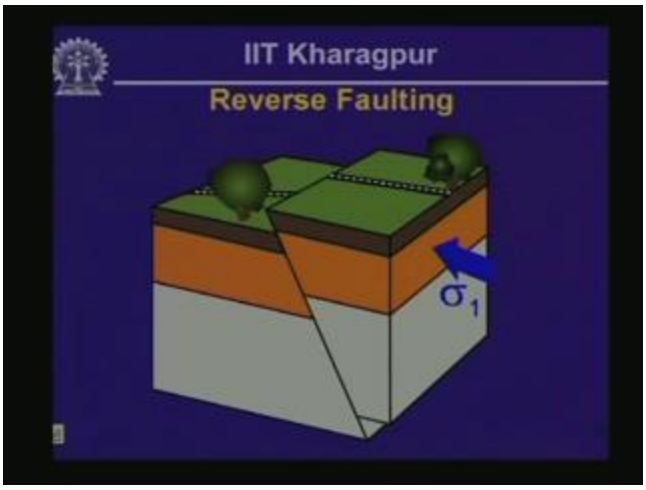

So, here instead of a block sliding down with respect to another, the block on the right is climbing up and it is obvious that this is compressional regime given by the major principle stress acting in a horizontal direction really, and here also you should notice that the layer of rocks are horizontal. So, the sigma 1 in this case, the value of sigma 1, the direction of sigma 1 is horizontal and sigma 3, the minor principle stress in this case is going to be vertical.

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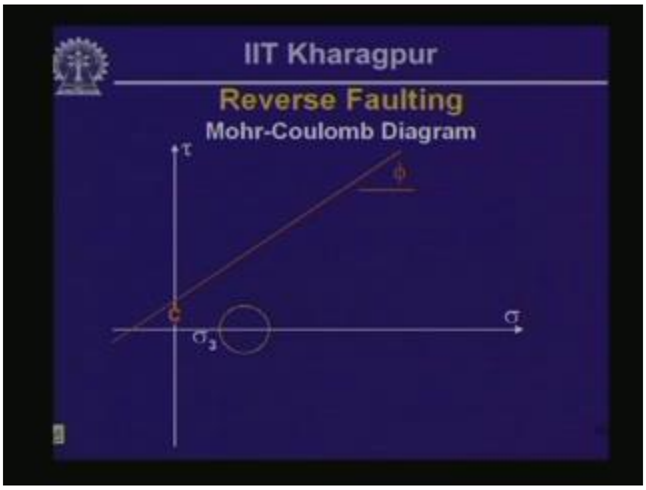

Now, let us look at the Mohr-coulomb failure diagram of this particular problem. So, the initial state of stress is shown by the yellow circle there, and as earlier we also have got Mohr-coulomb failure figure.

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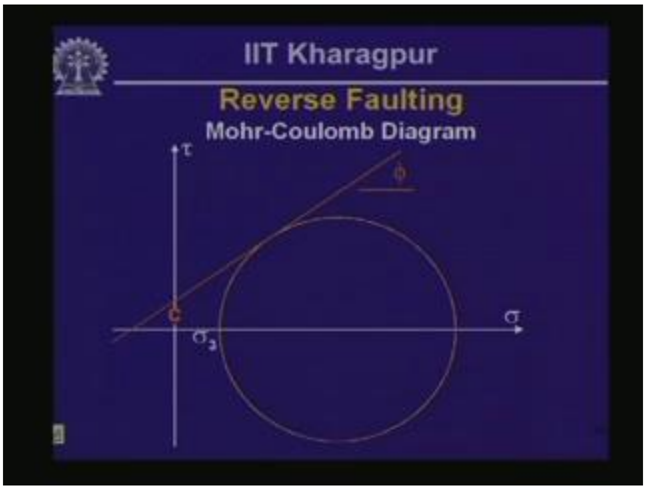

So, let us look at the evaluation of this Mohr circle. Here what we were going to have is sigma 1 is going to increase until failure is reached, and sigma 1 at failure is that the value there shown on the right extremity of the circle.

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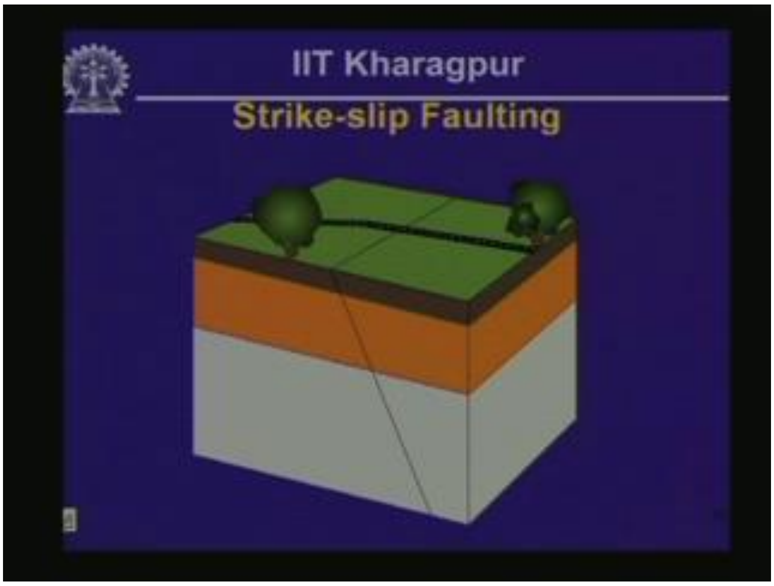

Now, finally we look at the strike-slip faulting which is the third type of faulting. If you recall from your earlier lessons, strike-slip faulting is going to occur in this manner.

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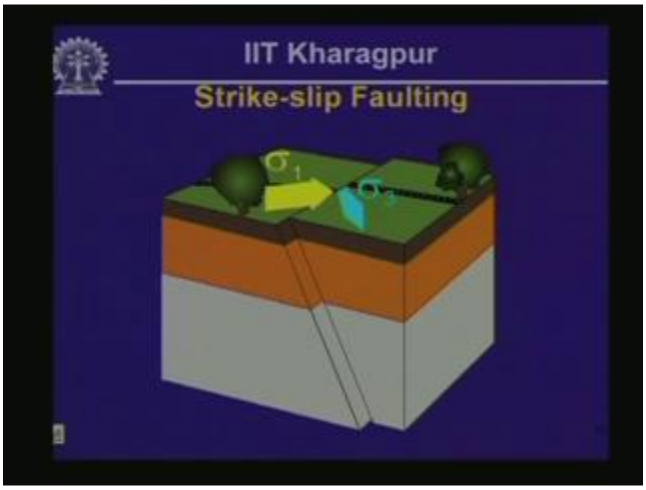

So, here what is happening is that sigma 1 is going to be oriented in the horizontal plane itself in that manner, and sigma 3 is going to be again oriented in horizontal plane as shown on the animation there.

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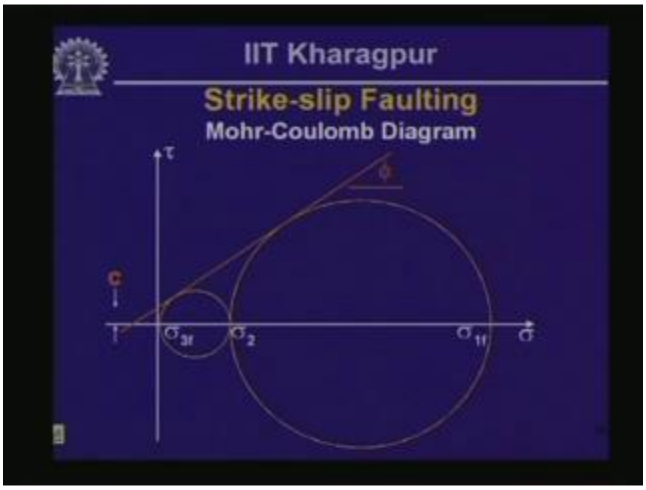

Now, we look at Mohr-coulomb diagram for this particular case. It is slightly more complicated than Mohr-coulomb diagram that we had for the normal stress and normal fault, and the reverse fault. So, here what we have is sigma 2 is occurring in the vertical direction, and that is the intermediate principle stress really and if we have got an intermediate principle stress. Then, you have got which is different from the other two principle stresses and then, you have to construct two more circles. One of the Mohr circles is going to be between the major principle stress and the intermediate principle stress shown on the right there.

So, this is the first one, and the other Mohr circle is going to be between the intermediate principle stress and the minor principle stress shown by the smaller circle to the left of this particular plot of Mohr-coulomb plot. So, that shows how we can view the faulting problem as Mohr-coulomb failure problem.

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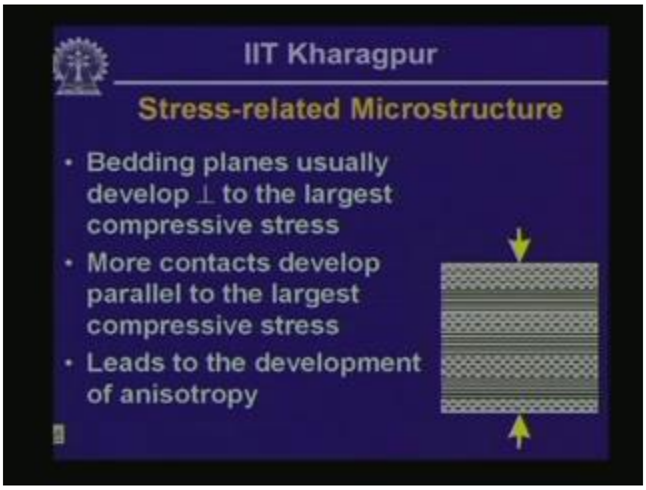

Now, we will look at how stress actually gives rise to the development of micro structure. As we have already seen that contacts develop predominantly in the direction of gravity during the deposition process. As a result what happens is bedding planes usually develop perpendicular to the direction of gravity, or perpendicular to the direction of the largest compressive stress because this is the direction in which the soil has or the rock has to develop maximum strength, and then this leads as we have discussed to an anisotropic fabric or an anisotropic particle arrangement.

We look at this procedure or this particular process by considering a block horizontally, bedded rock horizontally laminated rock subjected to very high stress in the vertical direction originally because that was the stress regime under which horizontal bedding is going to develop. Now, let us say we are going to rotate the major principle stress in an inclined direction as shown there, and in this case you try to notice how the structure is going to evolve.

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Finally, what we are going to end up with is a lamination is a set of lamination within the body of rock. That is again perpendicular to the direction of the altered stress regime, and this is indeed what is absorbed in case of laminated rocks, such as gneiss and (( )) of the regime because of the change in the stress regime.

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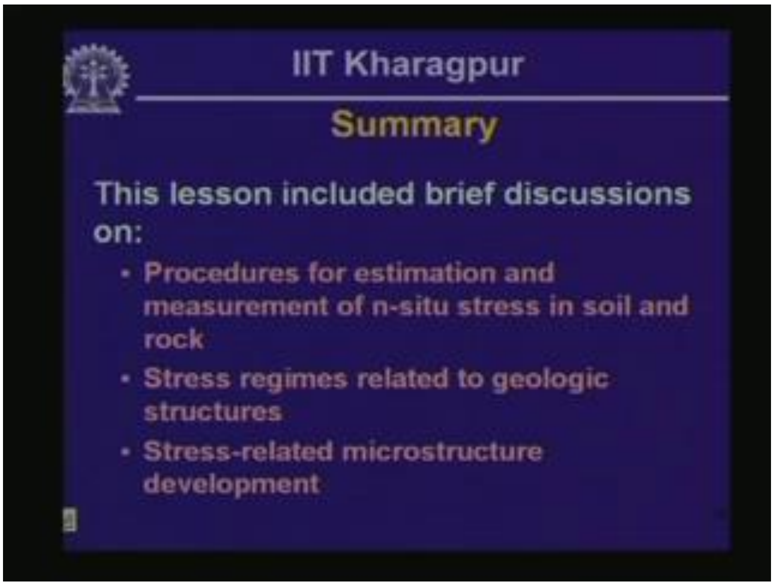

Now, we try to summarize what we learnt in this lesson. We looked at the procedures for estimation and measurement of in-situ stress in soil and rock. There is a spelling mistake here. We looked at stress regimes related to geologic structures. We also looked at stress-related microstructure development within rock masses.

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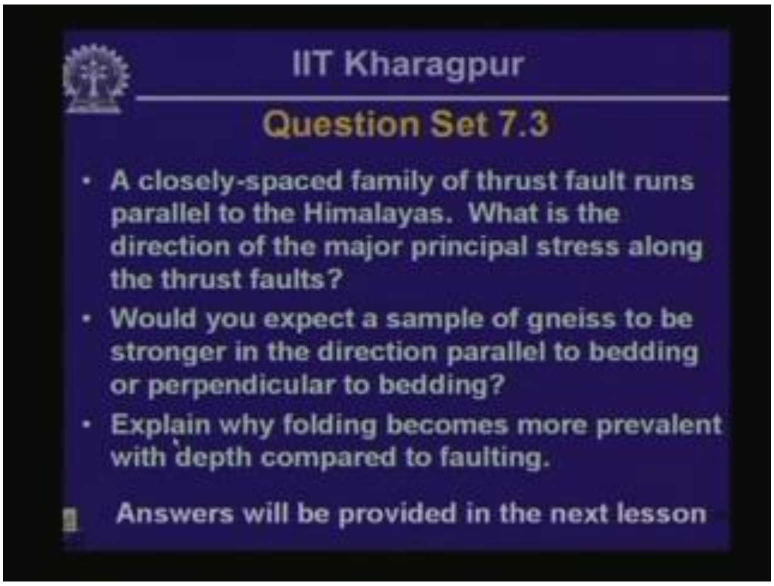

Then, in order to wrap up this particular question, this particular lesson, I give you a question set. Try to answer these questions at your convenience. The first question is a closely-spaced family of thrust fault runs parallel to the Himalayas. What is the direction of the major principal stress along the thrust faults? Then, the second question is would you expect a sample of gneiss to be stronger in the direction parallel to the bedding, or perpendicular to the bedding planes? Third question is explain why folding becomes more prevalent with depth compared to faulting. Try to answer these questions in your time, and I am going to give my answers when I meet you with the next lesson. Until then bye for now.