Engineering Geology
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Lecture - 24
Geologic Considerations in Dam, Bridge and Road Construction

Hello everyone and welcome back. Today we are going to look at list of geologic considerations that are looked at in construction of dam, bridge and roads, but before get on with the today's topic, we are going to look at the question set of previous lesson.

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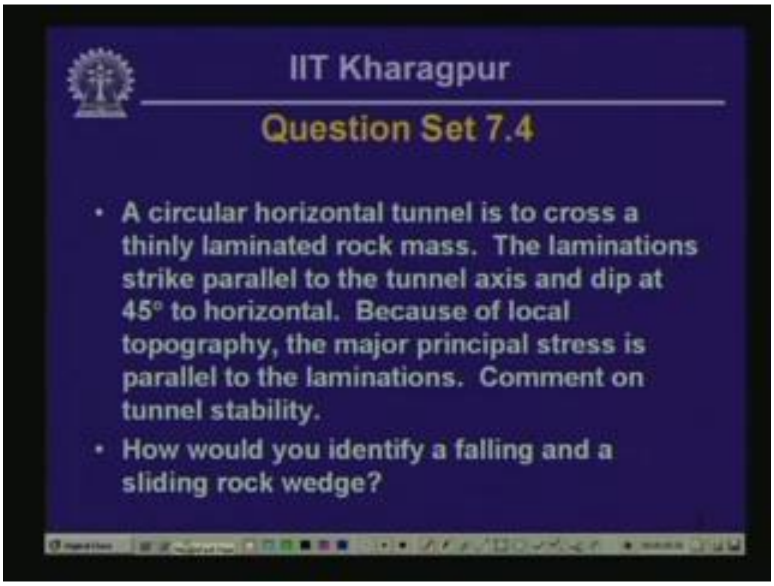

And here are the questions. The first question that I asked was a circular horizontal tunnel is to cross a thinly laminated rock mass. The laminations strike parallel to tunnel axis and dip at 40 degree to horizontal. Because of local topography the major principles stress is parallel to the laminations. You are asked to comment on tunnel stability.

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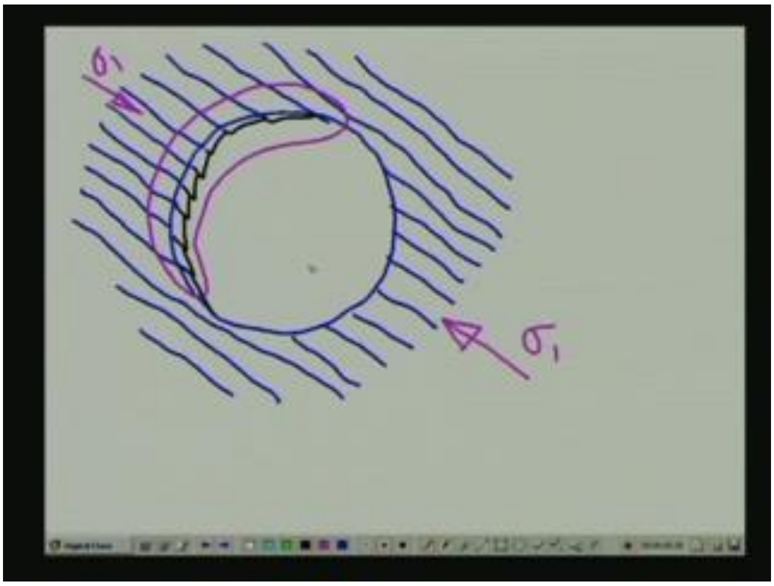

Now this problem is quite similar actually to the north polar tunnel headrace tunnel that we discussed when we were talking about geologic considerations of tunnel in the previous lesson, but in that one the tunnel had a horseshoe alignment. And here for simplicity I asked you to consider the tunnel to be circular. So, this is the tunnel cross-section, and let us say the laminations are like this. In fact, the beddings are going to be much more closely spaced than what I am drawing here.

If you recall from the discussion that we had while talking about classification of structural features within rock masses on laminations; anyway, so this is a rough sketch. So, what is the direction of major principle stress in this case is like this. So, this is our direction of sigma one. So, in this case what is going to happen? The laminations to the top and left of this particular tunnel particularly in this area are likely to squeeze into the tunnel because of the release of stress during tunnel excavation. And so, what is going to happen perhaps after a while, you are going to end up with a tunnel bore of this type.

So, you can notice easily here that the tunnel dimensions are smaller than it was originally planned is going to be smaller than it was originally planned near the top and left of this particular configuration. So, that is the answer of the first question. The second question was how do you identify a falling and a sliding rock wedge?

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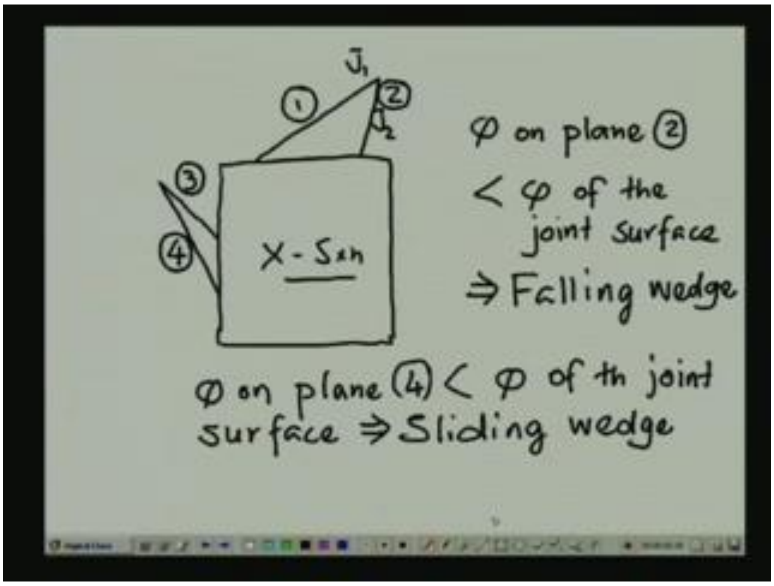

So, this one here, and let us consider first a falling wedge. Let us say the tunnel cross section is like this for simplicity square cross-section, and let us say we have got a wedge which is of this type. This is going to be a falling wedge. Now in this case if we neglect the dilatancy on the top surface. And actually what we are considering joint set J 1 and J 2 in this particular case both strike parallel to the tunnel axis. So, this one is the tunnel cross-section of the tunnel. So, joint J 1 and J 2 both strike in the direction parallel to the tunnel axis in this case.

So, if we neglect in this case the resistance due to dilatancy on surface one and purely consider the frictional resistance mobilized on plane two at the bottom of the wedge. In that case if the friction angle mobilized on plane two. So, if phi on plane two is greater than or equal to the friction angle of the joint surface; in that case we are going to have no problem, Whereas if we had this one less than phi of the joint surface. Then we would have had falling wedge. So, this is a very simple way of identifying a falling wedge.

And similarly, on the sidewall, the considerations are going to be quite similar; in this case let us say we have got two joints again making planes three and four. Here if we have phi on plane three or rather plane four is greater than or equal to phi of the joint surface. This could be different from the phi on joint J 2. Then we are going to have no problem and if we reverse the sign of the inequality. So, if we go reverse on the inequality, then we are going to have sliding wedge.

This actually the configuration that I used in this particular illustration is very simply, because what I assumed here is that the joint sets strike parallel to the direction of the tunnel axis. Now if the joint set was to be skew with respect to the axis of the tunnel, then the calculations or the sketches become much more complicated could become much more complicated in fact. But the principles of identifying the possibility of rock fall remain the same as the illustration that we considered here, okay. So, these are then the answers to the questions that I gave you in the previous lesson.

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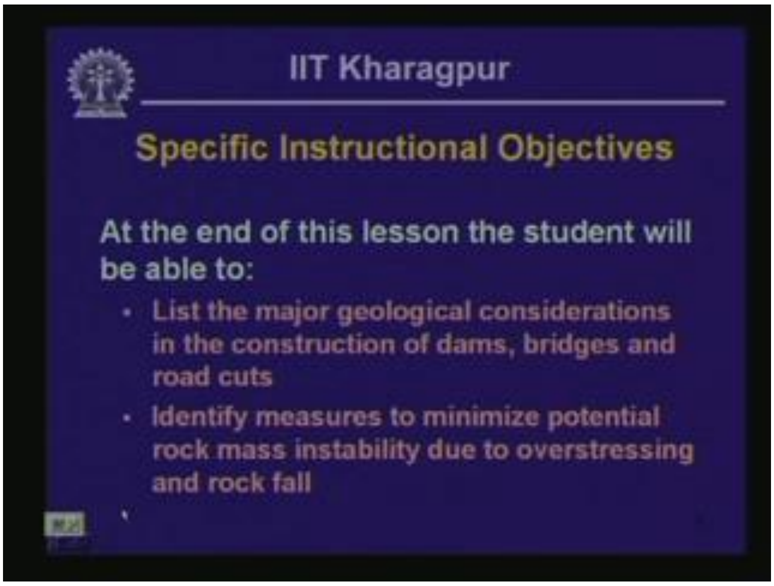

Now we move on with today's lesson. So, what we want to accomplish at the end of this particular lesson are the following. We should be able to list the major geological considerations in the construction of dams, bridges and road cuts. And we should be able to identify countermeasures against rock mass instability due to for instance overstressing as result of the construction of dam, bridges or road cuts and rock fall. So, those are the objectives. And then let us begin the discussion; we are going to move in sequence. First of all we are going to consider the geological aspects used in dam design.

Then we are going to move on with the geologic considerations in bridge foundation design. And finally, we are going to look at the aspects concerning road cuts. Now first of all then the question comes what are the different types of dams, what is dams? Dams are basically some barriers that are used to retain either water or to retain some other waste material such as mine wastes. In the first case the dams are called water retaining dams. And in the second case the dams are called tailings dams. So, all the illustrations here we are going to use the examples of water retaining dams, but in principle the discussion is going to hold for tailings dams as well. Now let us first look at what are different types of dams used in civil engineering.

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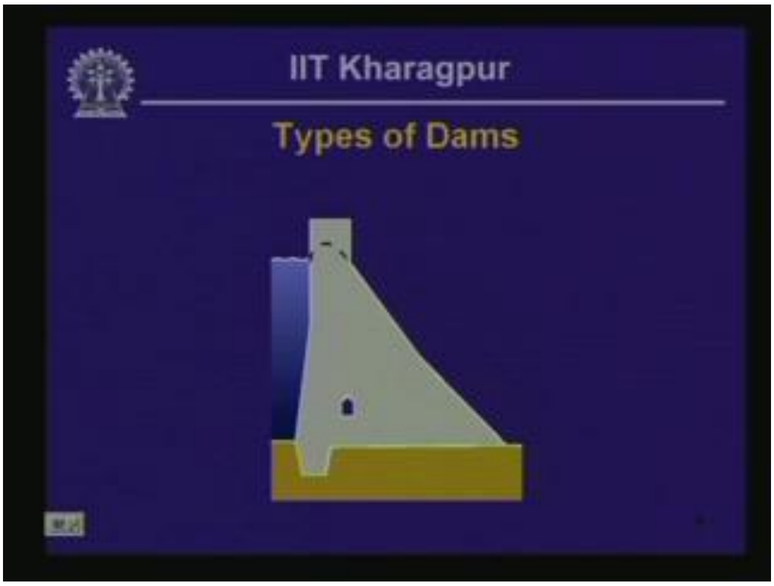

Now a dam could be a structure which actually counteracts the lateral forces because of the material retained in the illustration; here I have shown water retained by the dam cross-section of which is shown on this particular sketch water as you can see is on your left. And the dam is a triangular is of a triangular cross-section to the top right of this particular sketch. Now this dam actually is going to counteract the lateral forces exhorted on the dam body by the water by virtue of its self weight.

So, this type of dam is called a gravity dam, and a gravity dam could be constructed using masonry or concrete or even using other kind of open work or open type of structures with some water type cladding on the face. Now let us consider another type of dam.

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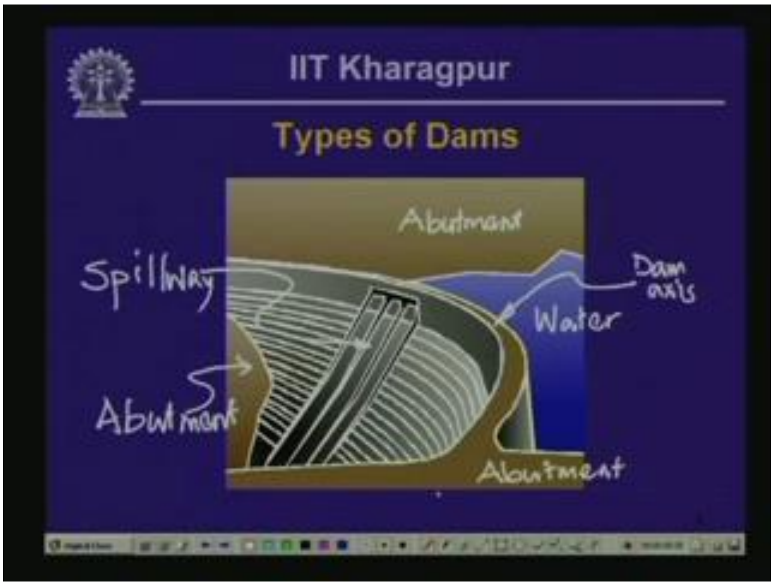

This dam is called an arch dam. The sketch that is shown here is actually an oblique view of a dam looking from little above from the downstream side of the dam looking upstream. So, here what you have? We have got water to the right. And this one here is our dam axis; it has got a curved shape in plan as you can see. This one is the right abatement. So, this is essentially the right bank of the reservoir. And this one here at the bottom is another abatement; in this case this is left abatement.

So, this one you can see a small block of rock on the left of the sketch here. And this one here is again the right abatement of this particular dam structure. Now you can also see near the middle a structure, and this structure is called spillway, because it allows release of water when the water tries to exceed the highest water level for which this particular structure is designed, okay. So, that is in a sense a sketch of an arch dam. This type of dam is called an arch dam, because here the load because of water the lateral pressure that is exhorted on the dam body by the water is counteracted by arching action, where the arch meets the right and the left abatement as well as through the action of the gravity.

And most of the load is taken, in fact, here by the arching action shown by purple arrows on this particular sketch that I just now have drawn, okay. So, that is another type of dam. Then let us go to another class of dam.

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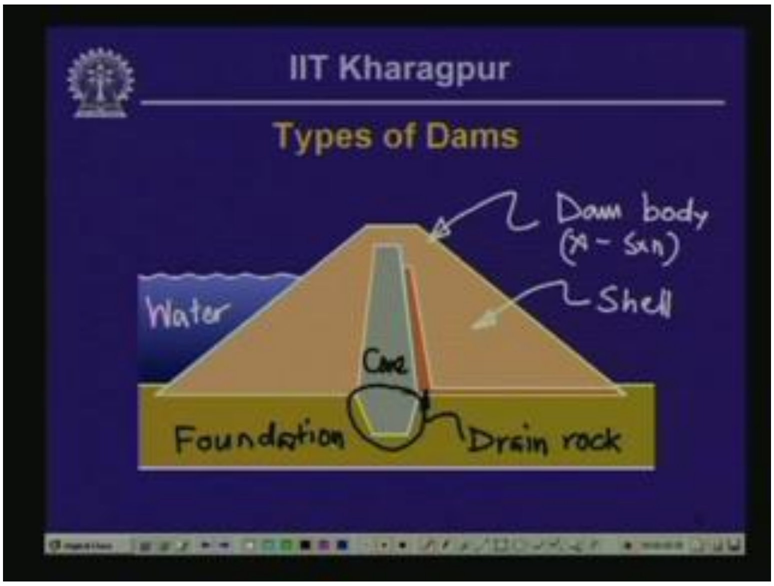

This type of dam is called arch embankment or a rock field dam. So, basically it is an embankment; it is a multi zone embankment here. And in this case we have got water retained on the left, and this is our dam body. This is the cross-section of the dam in fact; this is the dam body cross-section. And here we can see that the embankment is a multi zone embankment. The outer part is called the shell, and typically shell is constructed of semi pervious heavy material. And the inner part here is called a core, and core is typically constructed using well selected fine grained soils such as clays; that is in order to prevent water from seeping through the body of the dam.

And what you also see on the downstream face of the core we have got another feature and this particular thing here is made of drain rock which is free flowing. So, the purpose of this is that if there is any water flowing across the core that is going to be intercepted and carried away through the drain and the upright part of this drain is called chimney drain, whereas the horizontal part of the drain is called a drainage blanket. And of course, at the bottom we have got a foundation which may be composed of soils relatively impervious soils and rod rock.

Now also you should notice here is that the core is taken down deeper into the foundation material by a trench. So, this particular part and the bottom of the core is called core trench. Now this is done in order to prevent or in order to minimize the water seeping through the foundation material. So, this type of dam is called an embankment dam. I should also state here is that there are several variants of this particular concept. You can construct shell using again a multi zone approach with the facing constructed using a concrete face.

And inside of it you can construct the shell using rock field. So, those types of dams are called concrete face rock field dams, and they are also very popular in India as well as internationally. So, these are different types of dams.

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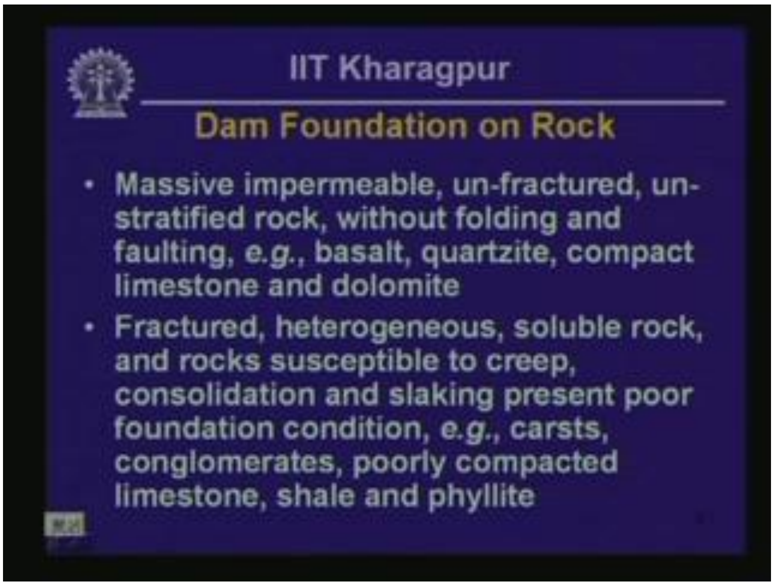

And then what we have to look at is what are the considerations while selecting a dam site. So, which areas in fact are going to provide a proper foundation for a dam? So, first we consider dam foundation on rock, and then we are going to move on to dam foundation on soils. So, the desirable characteristics of a rock foundation for a earth dam or gravity dam or an arch dam; anyone of them are as follows. The rock should be massive, impermeable, un-fractured, un-stratified without folding or faulting, examples being basalt, quartzite, compact limestone and dolomite/

So, these are preferred foundation options that a dam designer would like to have, but that is not always possible. And we might have to end up in selecting a site underlying by fractured heterogeneous or soluble rocks or rocks susceptible to creep and consolidation and slaking. I am going to define what is meant by the term slaking in the next little bit. These type of rocks actually present poor foundation conditions; examples of such type of rocks include carstic limestones, conglomerates, poorly compacted limestone, shale and phyllite.

Now before I move on with the desired characteristics of foundation on soil, let me explain what is meant by slaking. Now slaking is a term used to quantify the characteristic of a rock which makes it susceptible to chemical weathering. So, what is done in order to determine slaking is to take a certain amount of rock specimen in a drum constructed using a screen. And that drum is partly submerged in water and the rock specimen within the wire mesh drum is rotated using a pre specified manner, so that it comes in contact with water several times.

And what is done afterwards is the amount of rock material that is retained within the wire mesh drum is measured. And it is expressed as a percentage of the weight of the rock specimen that was originally taken within the wire mesh drum. Now the more the weight retained within the drum after the exposure to water, the less will be the susceptibility of the rock to chemical weathering.

And In fact, soils or rather rock samples such as volcanic rocks or sandstones, they exhibit quite high slake durability. In other words if you test those type of rocks for in a slaking test, then a large proportional of the original weight is going to be retained after the repeated exposure to water, whereas rocks such as shales are expected to exhibit a remarkably small slake durability. So, that is in a sense what is meant by slaking.

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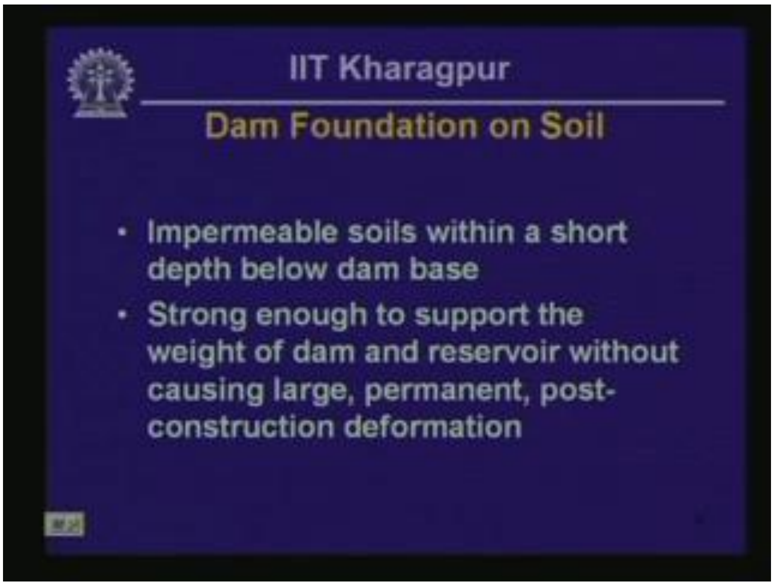

And now with that explained, let us move on to the characteristics or the considerations that one needs to look at while selecting a dam site or at a site underlying by soils. So, the soils underlying the dam need to be impermeable or impermeable soils need to be present within a reasonable depth underneath the base of the dam. And the soil should be strong enough to support the weight of the dam and reservoir without causing large permanent deformation.

So, these are the aspects to consider when selecting a soil site for constructing a dam. So, this requires some measures like for example, if there is a soil site earmark for dam construction at which the top few meters are underlying by compressible organic soils. Then those organic soils need to be excavated and replaced before the dam construction can be taken up at that particular site.

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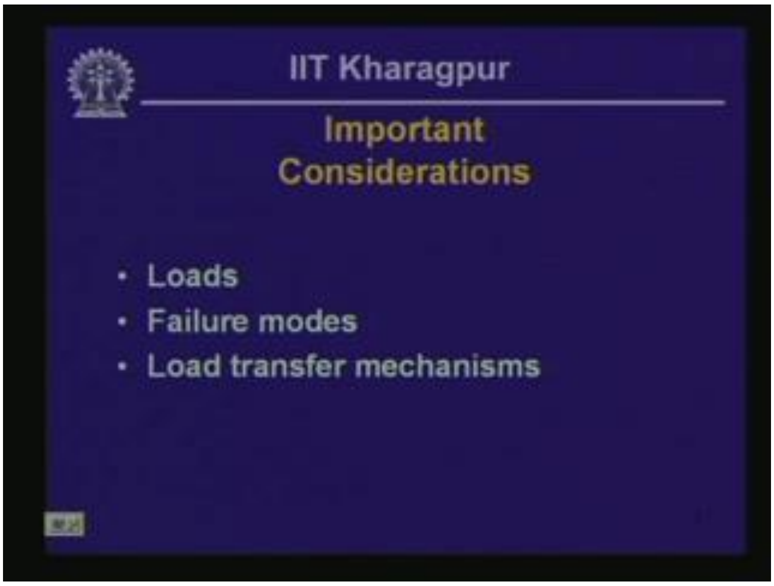

Now with these stated we can now consider, what are the important aspects we need to look at while selecting a dam site? Now the main three aspects that we are going to look at are loading, failure modes of dams and load transfer mechanisms. We are going to look at these topics one by one.

So, first we consider loads that are imposed by a dam and the reservoir that is going to be supported by the dam or the tailings mass that is going to be retained by the dam. Loads are of two types; loads could be permanent. They include the weight of the dam and water and permanent pore water pressurize and load on the other hand could be incidental. Such loads include earthquakes, temporary pore water pressure increase or wave loading because of veins or other factors such as earthquakes.

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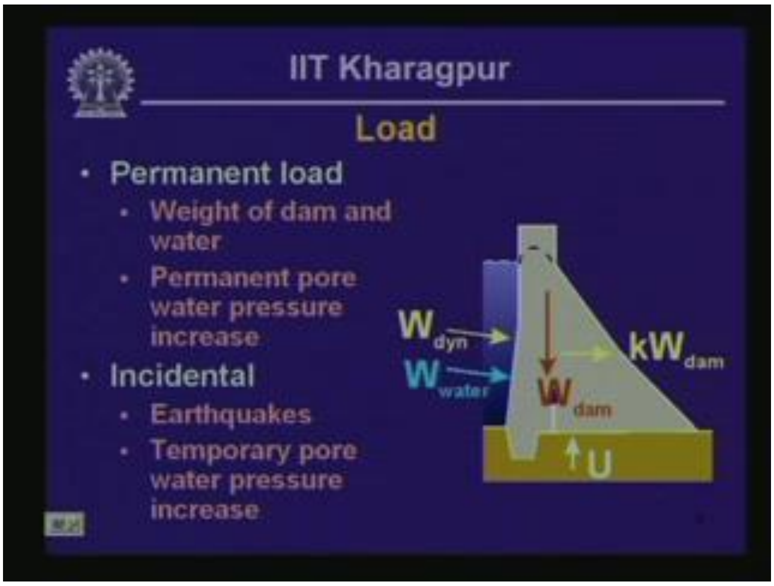

Now let us consider these things using a few sketches. Let us consider a gravity dam the weight of the dam; I label that here using W subscript dam. Then we are going to have the weight of water and I have labeled that on the left using not the weight of water actually; the water pressure on the dam in this one I have used the symbol W subscript water. And then we are going to have an uplift force because of the presence of water on the left of the dam, and I have used U for the uplift force.

So, these are actually the three major permanent loads that the dam has to transfer to the foundation. In addition to it, we are going to have a bunch of incidental loads. And the first one that I have considered here is the inertial load for instance because of an earthquake. And this particular inertial load is going to be typically a multiplier times the weight of the dam. This is a very simple approach that I am discussing here. There could be other more involved approaches. The factor K depends on how strong is the earthquake.

So, if the earthquake is very strong then you are going to have a large value of K. It could go up to say 0.3 or 0.4 or 0.5 even. If you have got a smaller earthquake then k is going to be much smaller; typically k could be 0.1 or 0.05 or that kind of number for smaller earthquakes. Then in addition to it we could have a dynamic water pressure because of earthquakes or because of water waves caused by strong winds within the reservoir. So, these are the incidental loads a few of them anyway that needs to be transferred to the foundation.

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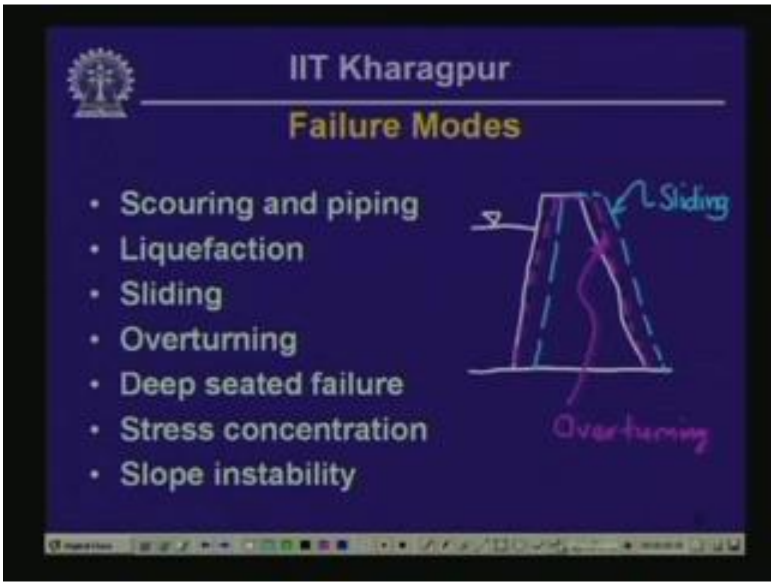

Now let us look at the failure mode; the second important consideration is the failure mode. Now first failure mode and this is perhaps the most important one is scouring and piping. If there is a pathway for seepage to take place across the body of the dam, then particularly in case of earth dam or embankment dams if the velocity of water flow becomes too high. Then it is going to wash out material that comprises the dam body. And as a result the entire dam may fail. This type of phenomenon is called scouring or piping.

Then there could be liquefaction; liquefaction could be triggered statically or during an earthquake. For instance, if the speed of construction of a dam is too high, then the weight that is imposed when the embankment is being constructed. The weight is transferred to the soil underneath, and if the foundation soils are saturated then the pore water pressure the weight of the embankment is transferred immediately to the pore water. And as a result the pore water pressure increases. And if you recall from our discussion on effective stress, the increase of pore water pressure is going to lead to a reduction in effective stress.

And consequently, the strength that can be mobilized by the soil mass also decreases. And this may actually lead to failure, and this type of failure is called failure because of static liquefaction. The third type of failure mode is sliding failure and here what happens? The lateral pressure because of the retained water or because of the retained tailings mass becomes too great. And as a result, the dam slides downstream; that is another failure mode.

There is another failure mode called overturning failure. In this case because of the lateral pressure, the dam tries to tip over towards the downstream side by supporting its weight at the toe of the dam. Let us draw a few sketches here. So, let us consider a gravity dam, and here let us say we have water out here. So, in case of sliding failure we are going to have the dam sliding downstream like this in this manner. And in case of overturning, what we are going to have is the dam tipping over in this manner.

So, this one here we are going to call overturning, and this one we are going to call sliding. Then there could be deep seated failure which actually will lead to the development of a failure surface through the foundation soils underneath the dam. Then there could be distress because of stress concentration when the dam tries to transfer the load to the underlying soil or bedrock. The stress could become too high, and that might trigger failure or it might trigger inordinately large deformations, or there could be slope instability like this. Let us consider an earth dam.

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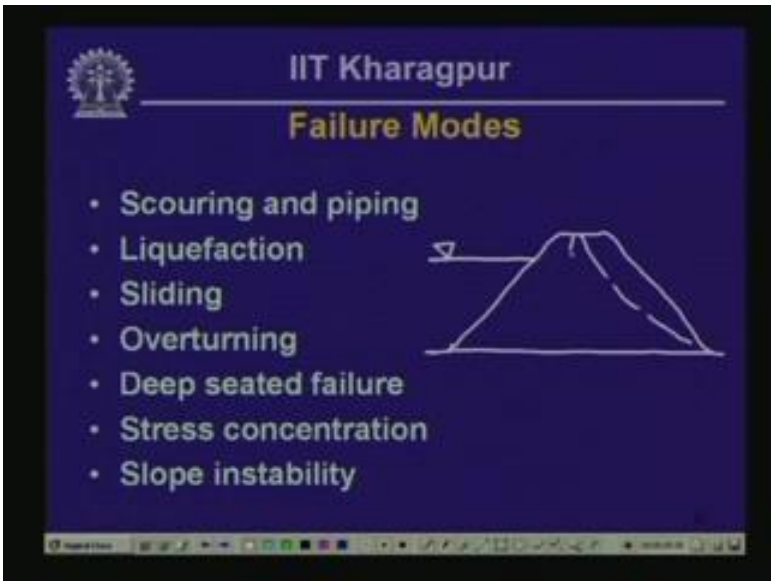

Let us consider an earth dam like the one we have shown in this sketch a few minutes back. So, here the water is on your left, and this particular dam actually may be affected by stability of downstream slope or the upstream slope also may become unstable. And it may actually slide into the reservoir, and the downstream slope may become unstable and slight downwards like that. So, it may actually lead to the failure of embankment dams if the stability in all types of loading cannot be assured.

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Then we consider load transfer. The major points to consider here include whether there is bedding or fractures or faults or shear zones. And what is the orientation of these planes or weaknesses with respect to the direction of the water flow, whether they are dipping towards the upstream side or horizontal or dipping towards the downstream end. Then we also need to consider the direction and the location of load transfer. We are going to look at the relative direction of the resultant that is imposed on the foundation soils. And what is the orientation of these resultants with respect to the planes of weakness that we might have within the foundation rock. So, let us consider those things in the following.

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So, if you have got bedding planes or laminations or joints which are normal to the resultant, we are going to have a situation which is relatively better. If on the other hand the bedding planes or laminations or joints are parallel to the resultant we are relatively worse off. And why that is so? That is because from our previous discussion it is apparent that strength for the rock mass that is underneath the dam is going to be the maximum if the rock mass is loaded perpendicular to the planes of weaknesses. And the strength mobilized is going to be minimal if the rock masses are loaded parallel to the bedding planes.

So, these are the reasons why we want to have in an ideal situation the orientation of the bedding place or orientation of the planes of weaknesses perpendicular to the direction of the resultant of the load that is imposed on the rock mass because of the dam and the reservoir.

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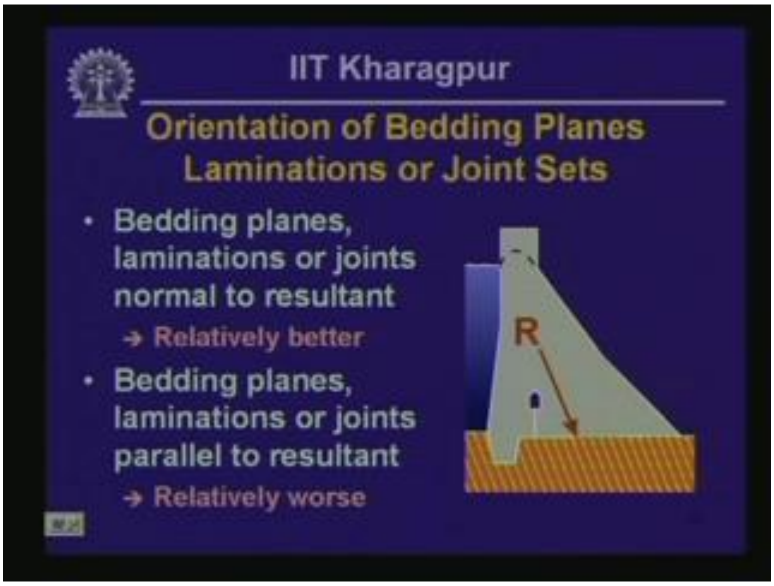

So, that is illustrated in this particular sketch; this is again the same gravity dam that we considered earlier. Now here we have got the resultant parallel to the direction of the bedding planes of the jointed rock underneath the dam body. It is obvious that this type of loading with respect to the direction of the jointing of the rock is going to be the worst possible scenario, whereas in this particular case the planes of the joints are roughly perpendicular to the direction of the resultant. And by the way by resultant what I mean is the vector sum of all the temporary and permanent loads that are being transferred by the dam to the foundation. So, in this case we have got the resultant of all the forces to be transfer to the foundation perpendicular to the bedding. So, here we are much better off in this configuration, alright.

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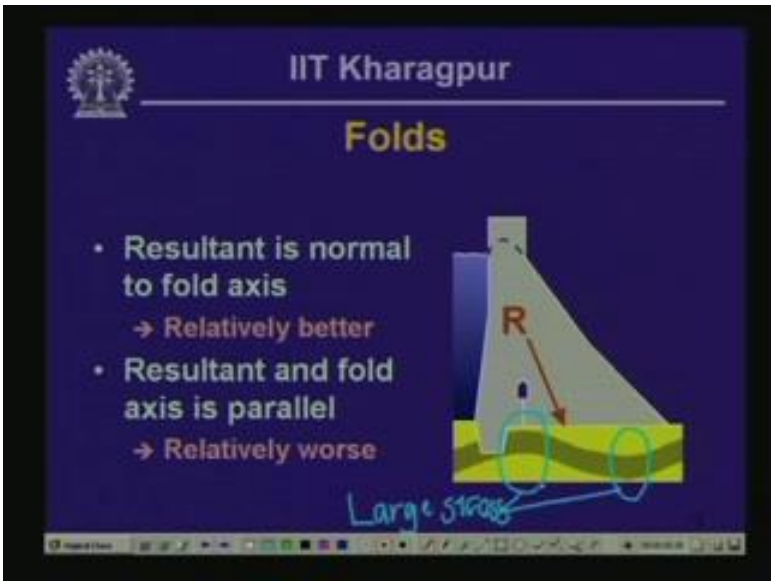

The second aspect with respect to heterogeneity of the rock is whether or not are the structural within the bedrock whether there are folds or not within the rock underlying the dam. So, what we want to have actually is that the resultant is normal to the axis of the fold. If you recall our earlier discussion, the axis of the fold in this case is like that. So, this is the axis of the fold. So, if we have the axis of the fold perpendicular to the direction of the resultant, then we are better off. And if the resultant is parallel to the axis of the fold, then we are relatively worse off.

So, in this particular configuration we are somewhere at an intermediate situation, but since the dam axis is parallel to the axis of the fold, this configuration is not considered the most optimal siting of a gravity dam. Now why that is so? That is because if you recall our previous discussion on folding, the stress concentration within the rock mass is maximum at the crown of the fold and at the bottom of the fold. So, this one here; these are two locations where you are going to have large stress concentrations. Large stresses and if on top of it you apply the resultant, then the stresses within the rock mass at these locations where the stresses were very large to begin with; that might actually trigger larger deformation or even local dislocation within the rock mass. So, this is the fundamental reason why we want to orient a dam in a direction perpendicular to the axis of the fold, okay.

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Then we move onto dams in a faulted terrain. So, the considerations are almost the same here as we did in case of tunnels in the previous lesson. So, what we want to do is to avoid sites underlying by active faults. Then we want to place the resultant normal to the fault plane, because fault plane here is a plane of weakness. And we want to actually place our resultant perpendicular to the plane of weakness in order to derive maximum strength mobilized in order to make it possible that maximum strength is mobilized.

Then the weight of the reservoir and the dam could actually lead to a large readjustment of in-situ stresses. And this might induce seismicity, and such type of earthquakes is called reservoir induced seismicity. You also need to consider while siting a dam in faulted terrain is that fractured rock near fault could provide pathways to water seepage. And this in fact has led to dam failures in the past; we are going to discuss this in detail a little bit later on.

Now these jointed rock mass or fractured rock mass in the vicinity of the faults need to be either excavated or replaced, or they need to be grouter in order to preclude water flowing past underneath the dam through the foundation. So, these are the major considerations that one needs to satisfy while siting a dam in a faulted terrain.

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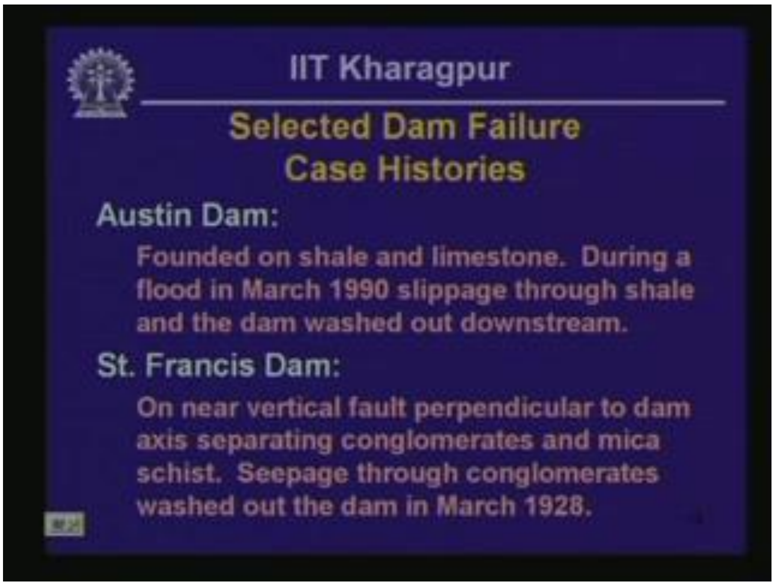

Now we look at a few cases histories involving failure of dam. The first case history that we consider here is that of Austin Dam, and this particular dam failed in March 1990. This is a dram across the Colorado River in southern United States near Austin Texas. This dam was founded on shale and limestone bedrock. Now what happened? The dam washed out during a high flood in March 1990 because of slippage through the shale bedrock. And the dam, in fact, washed out quite a ways downstream of the original location of the dam.

The second failure that we consider here is that of the failure of St. Francis Dam. So, in fact, let me highlight here before I move on with St. Francis Dam that the failure of the Austin Dam is one of the failures because of sliding. Then as I stated earlier that failure could also be because of scouring and piping. Saint Francis Dam, in fact, was another dam that failed because for seepage and piping and scouring. And this particular dam is another embankment dam, and it was cited on a site underlying by a very steeply dipping fault perpendicular to the dam axis separating conglomerates and mica schist.

What happened? The conglomerates were badly fractured because of the presence of fault, and you can also imagine that conglomerates by their inherent nature are composed of coarse grained particles. As a result they themselves could be quite permeable if they are well compacted, and here we have got fractured conglomerates. So, this particular rock mass was prone to seepage and the seepage through conglomerates actually washed out a portion of the dam in March 1928. And this led, in fact, to the failure of this dam.

Both these dams both Austin Dam and St. Francis Dam; both these dams were constructed as embankment dams, but you could have similar problems in case of other dam types such as gravity dams. And you need to design the dams in such a manner that such possibilities are, in fact, precluded; it can be totally avoided. Of course, in case of gravity dams you would not have to consider the possibility of seepage and piping, piping and scouring, but the possibility of seepage has to be addressed in case of gravity dams as well, okay.

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Now a couple of other case histories involving dam construction in India. First of all, we consider Obra Dam. This dam is a gravity dam constructed across river Rihand near the border of UP and MP in the southern fringes of Uttar Pradesh. And this particular dam is sited in an area which is underlying by limestones. And you can imagine that if there are limestone’s which are soluble; un-compacted limestones are quite soluble. And such limestones actually could develop caverns and cavities within the rock mass because of their solubility, and this type of terrain is called caustic terrain.

So, Obra Dam was constructed in a terrain underlying by cavernous limestone. And what happen? In cavernous limestone seepage through foundation becomes a very major issue that might jeopardize the functionality of the water retaining dam and the reservoir that it is suppose to create. Now in order to preclude seepage in this particular case, heavy grouting was undertaken and grouting had to, in fact, go to a depth of as large as 75 meters to tie in the bottom of the dam with the underlying impervious shale bedrock underneath the cavernous limestone unit.

The second case history that we consider here is that of Nagarjuna Sagar construction. So, this particular dam was crisscrossed by several low angle reverse faults in gneiss and granite bedrock. And because of that fact that fractured gneiss and granite could be weathered, because of excess of water they could be weathered. And they might actually more often than not, they become quite soft, and several such soft areas were identified underneath the foundation of the Nagarjuna Sagar gravity dam. And these pockets had to be excavated and replaced before the construction of the dam in order to ensure that the dam is founded on sound rock mass.

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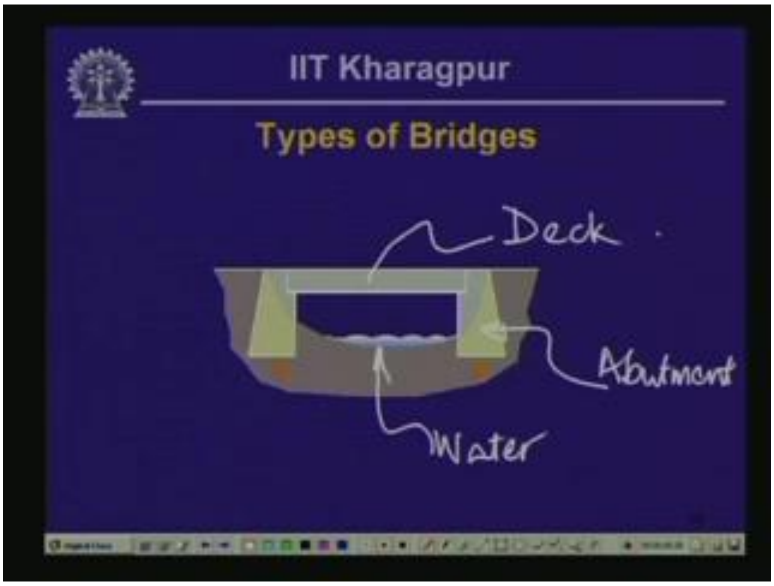

Now we move on to bridges; first we consider type of bridges. This is basically a slap type bridge. So, what you can see here is the water cores are here. So, this is the water cores, and these are the abatements, and the bridge deck is here. Now there could be other types of bridges such a frame bridges like the one that is shown; you should also notice that there are orange arrows in these sketches that indicate the direction in which the load is transferred by the bridge superstructure to the foundation soil or rock. This is an example of arch bridge.

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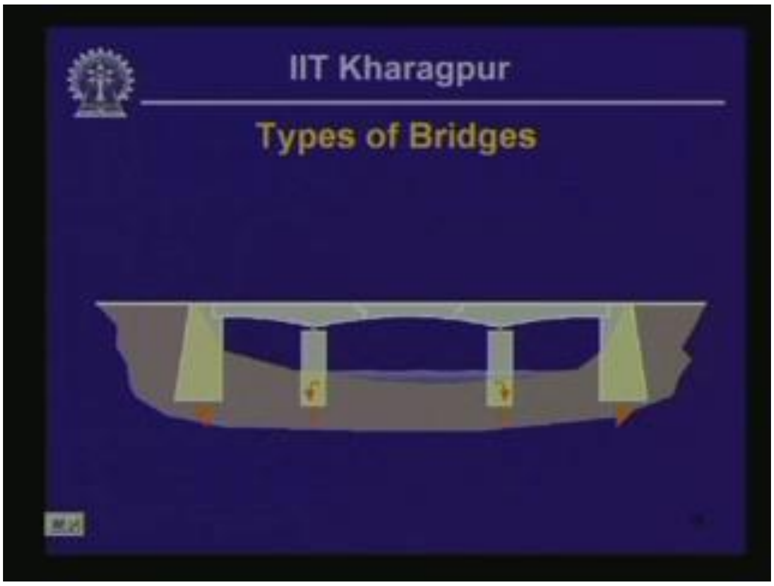

This one is an example of beam and cantilever bridge.

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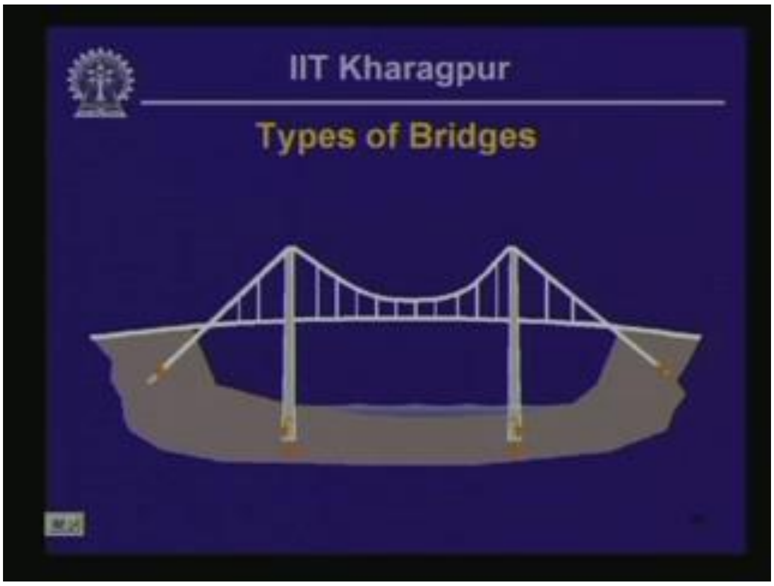

And this is an example of cable stayed bridge, and you should notice in all cases carefully the direction in which the loads are transferred.

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So, the considerations here are essentially the same as we did in case of dam foundations; only thing that you need to consider here in addition to it is that the loads are transferred within a relatively smaller area to a larger depth. As a result, the bridge foundation is affected more significantly because of heterogeneity in soil and rock. So, a very thorough subsurface geotechnical investigation is a must at the location of all the abatements and foundations before a bridge construction can be taken up. If the investigation is inadequate or does not go to sufficient depth, the bridge construction would have to encounter inordinate delay because of constructability problems.

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Then road cut; if a road cut is constructed parallel to the strikes of planes weaknesses, and if we have got dipping inside the cut, then there could be potential for instability. And if the dipping is outside of the cut, then the road cut is going to remain relatively stable. If the road cut is normal to the strike, stability is better. There are other considerations such as weathering of bedrock, because of the road cut you might actually given entry pathways of water entry through the planes of weaknesses into the rock mass that might trigger chemical weathering. Creep is another issue that needs to be accounted for during construction of a road cut as well as the possibility of falling rock from the top of the road cut.

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Rock fall countermeasures around road cuts, we can try to intercept the blocks of rock that might actually mobilize down slope. We could have a catchment ditch near the base of the rock. We could have cladding on the slope face in form of metal nets shotcrete facing, or we could have fencing parallel to the road cut parallel to the slope. These acts as barriers and intercept the falling rock or other debris or we could install bolting to secure potentially unstable rock mass on the slope face.

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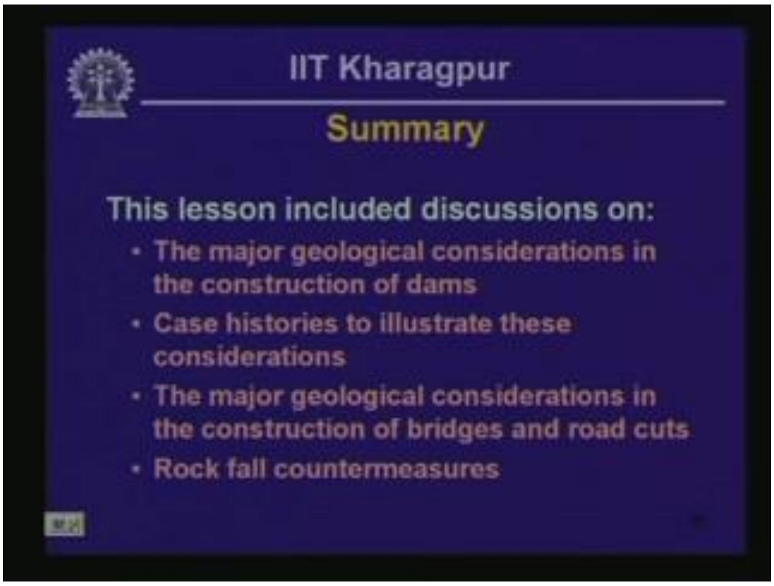

So, we now summarize this particular lesson. What we learnt here are major geological considerations in the construction of dams, roads and bridges. We also looked at some cases histories to illustrate the geologic considerations in dam, and we looked at a list of rock fall counter measures.

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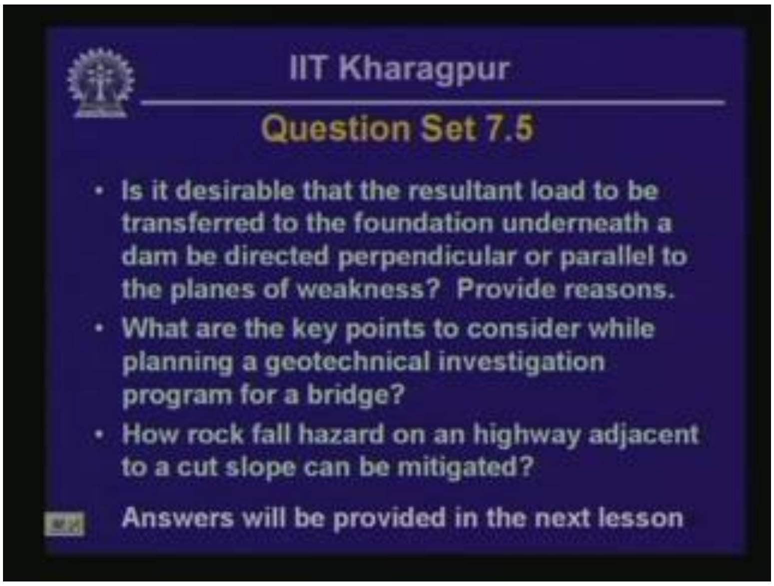

Finally, we wrap up this particular lesson with a question set. The first question is, is it desirable that the resultant load we transferred to the foundation underneath a dam be directed perpendicular or parallel to the planes of weaknesses? Provide reasons. What are the key points to be considered while planning a geotechnical investigation program for a bridge? And how rock fall hazard on a highway adjacent to a cut slope can be mitigated? Try to answer these questions at your leisure. When we meet with the next lesson I am going to provide you my version of these answers; until then bye for now.

Thank you.