Rock Mechanics and Tunnelling
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Lecture 45
Foundations (contd.)

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Hello everyone. I welcome all of you to the 4th lecture of Module 9. So, in Module 9, we are discussing about the foundations and we will discuss about also the rock support systems. So, today is the 4th lecture and today we will also discuss about foundations and in our 5th lecture, we will discuss about the rock support systems.

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So, we have covered shallow foundations till now. Today, we will cover the deep foundations. So, we will learn about the types of deep foundations. Then the end bearing piles, friction piles, estimation of load carrying capacity of bedrock and then we will solve a problem also related to that.

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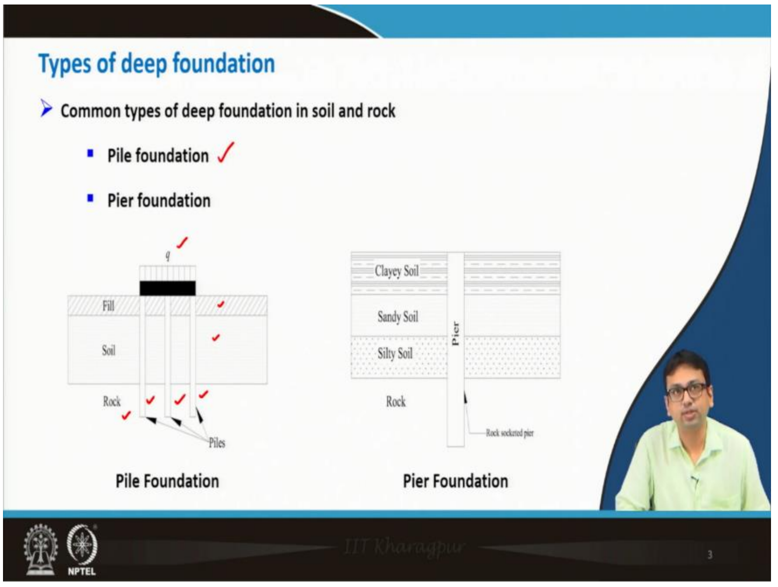

Now, the types of deep foundations. As we have discussed earlier that in general, if the depth of foundations is less than equal to the width of the foundation, we call it as a shallow foundation. But, as per the IS 12070 recommendation, if the depth of foundation is up to 3 m, then also we call it as a shallow foundation. But beyond that, if the depth of foundation goes more than 3 m or 3.5 m, we consider that type of foundations as the deep foundations. So, now, the most common type of deep foundation in soil and rock is the pile foundation.

In general, in the case of fill material, i.e., the soil, if they are very much compressible or weak in nature, the soil is not having enough capacity to sustain the load coming from the superstructure. In that case, we should go for the pile foundation and we try to socket the pile to the bedrock.

So, otherwise sometimes we go for also the friction pile also. Anyway, in general, if the upper soil layer is very weak in nature, then we should go for the pile foundation, which is type of deep foundation. Another common type of deep foundation is the pier foundation. So, pier is very similar to pile, only the diameter is higher as compared to the pile. So, other than that, like well foundation is there. Here, we will deal with the pile foundation. So, we mainly focus on the pile foundation part.

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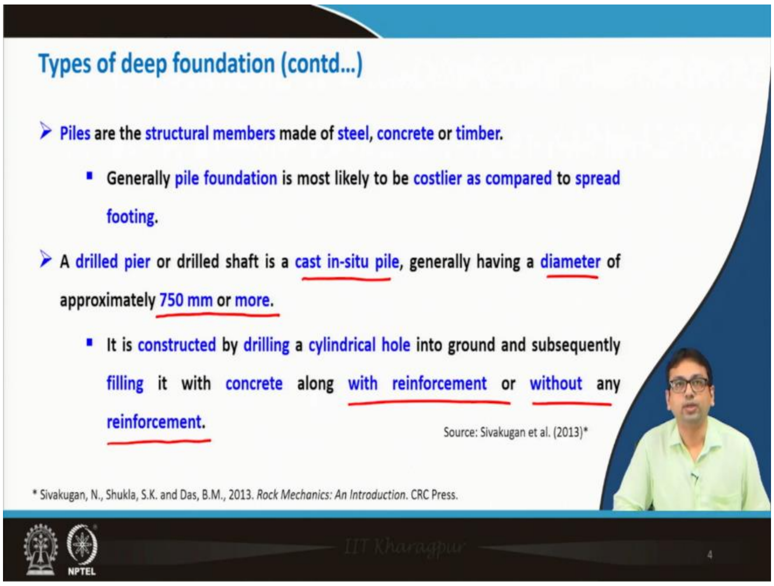

Piles are the structural members made of steel, concrete or timber. Now, generally, pile foundation is most likely to be costlier as compared to the spread footing. It is quite obvious as the piles are maybe of 10 m, 15 m, 20 m, 30 m of length. Now, the second category, a drilled pier or drilled shaft is a cast in-situ pile generally having diameter of approximately 750 mm or more.

So, it is a special type of pile having diameter 750 mm or more. Now, it is constructed by drilling a cylindrical hole into the ground and subsequently filling it with concrete along with reinforcement or without any reinforcement.

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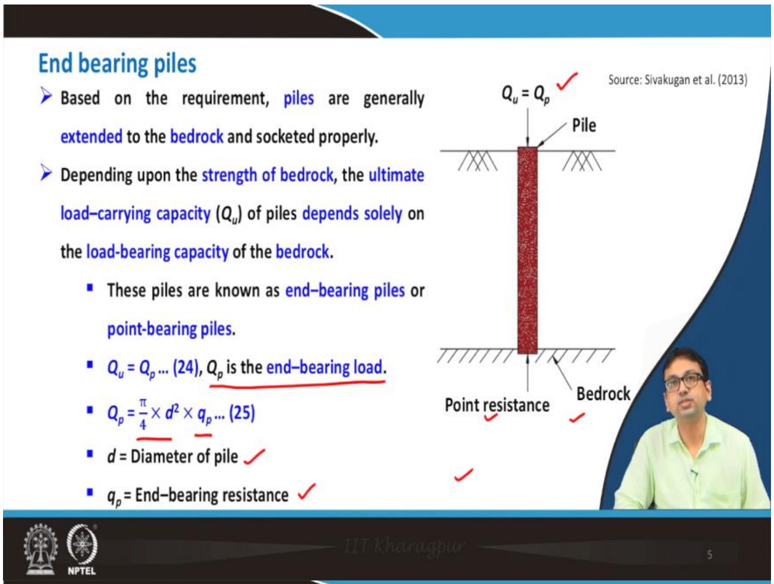

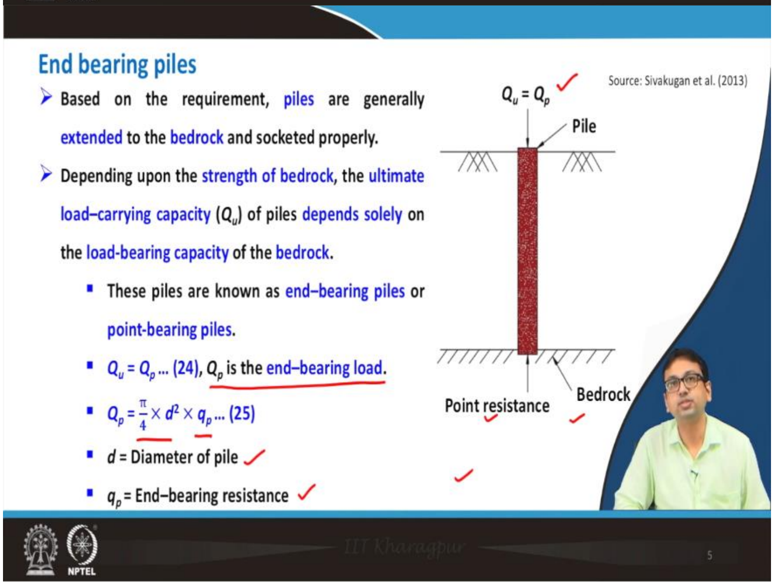

End bearing piles
Based on the requirement, piles are generally extended to the bedrock and socketed properly.
Depending upon the strength of bedrock, the ultimate load–carrying capacity (Q_u) of piles depends solely on the load-bearing capacity of the bedrock.
These piles are known as end–bearing piles or point-bearing piles.
$Q_u = Q_p$ ... (24), Q_p is the end–bearing load.
$Q_p = \frac{\pi}{4} \times d^2 \times q_p$ ... (25)
d = Diameter of pile
q_p = End–bearing resistance
Source: Sivakugan et al. (2013)
$Q_u = Q_p$
Pile
Point resistance
Bedrock
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Now, let us focus on the pile. So, the first one is the end bearing pile. Kindly look into the diagram. Based on the requirement, piles are generally extended to the bedrock and socketed properly. We can see here that it is in the bedrock and the pile is socketed. Now, depending on the strength of bedrock, the ultimate load carrying capacity (Q_u) will depend solely on the load bearing capacity of the bedrock. Now, these piles are known as end bearing piles or point bearing piles. The ultimate load carrying capacity (Q_u) is equal to Q_p, where Q_p is the end bearing load. Now, $Q_p = \frac{\pi}{4} \times d^2 \times q_p$, where d is the diameter of the pile and q_p is the end bearing resistance. So, the cross-sectional area of the pile is $\left(\frac{\pi}{4} \times d^2\right) \times$ the end bearing resistance, q_p will give the Q_p which is equal to give Q_u in the case of end bearing pile.

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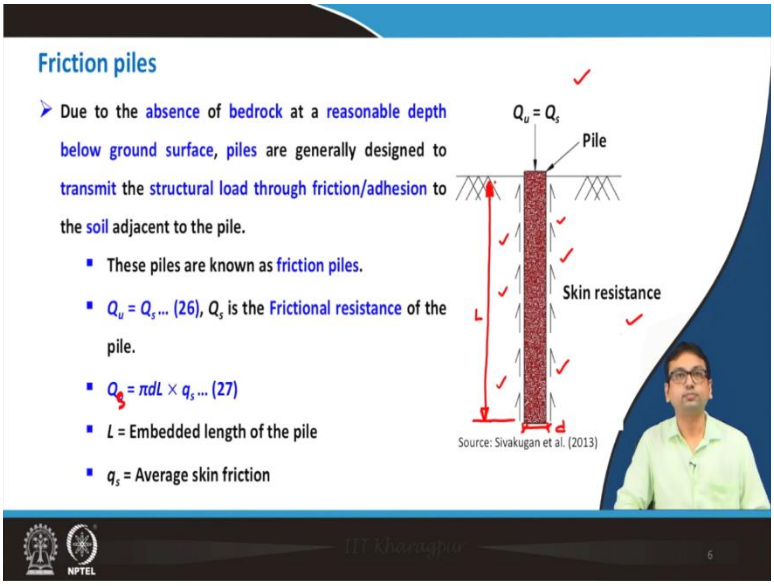

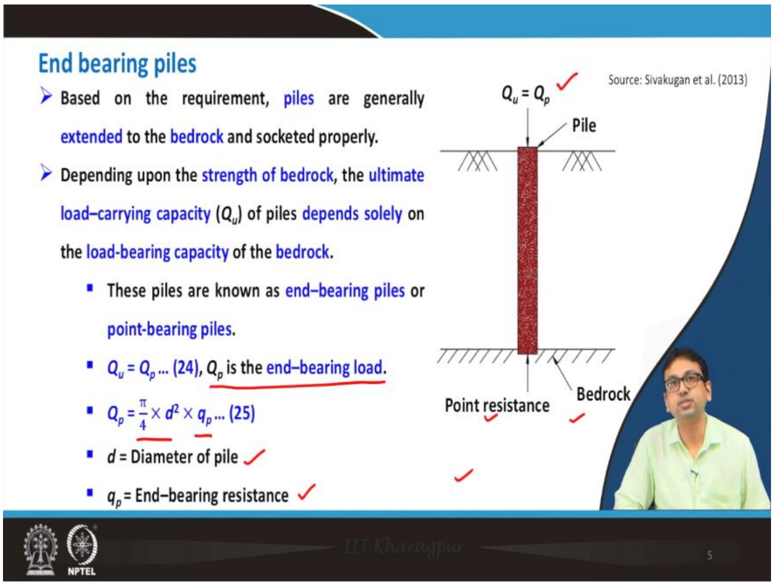

Now, the friction piles. Due to the absence of bedrock at a reasonable depth below ground surface, piles are generally designed to transmit the structural load through friction or adhesion to the soil adjacent to the pile which is also known as the skin resistance. So, that is the frictional resistance.

So, these types of piles are known as the friction piles. Here, $Q_u = Q_s$, where Q_s is the fictional resistance of the pile, whereas Q_p was the end bearing load. $Q_s = (\pi dL) \times q_s$, where πdL denotes the circumferential area of the pile, d is the diameter of the pile, L is the embedded length of the pile, and q_s is the average skin friction.

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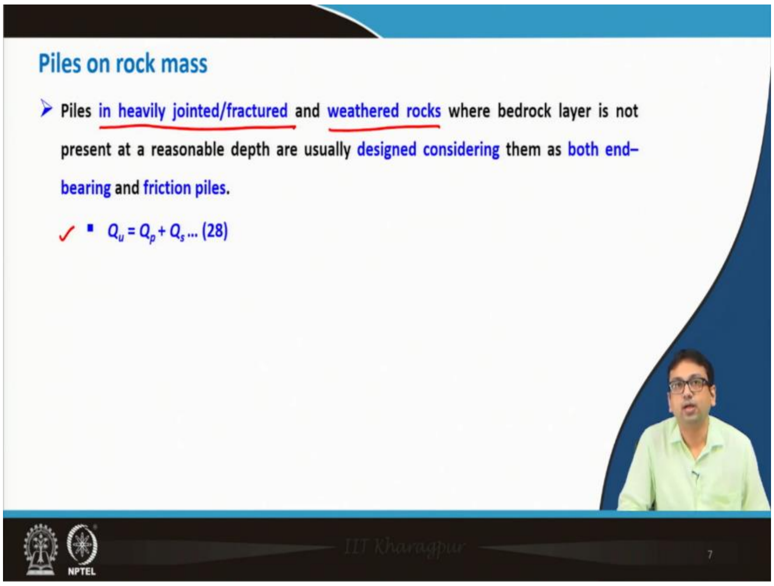

Now, piles are on the rock mass. So, piles in heavily jointed or fractured and weathered rocks where bedrock layer is not present at the reasonable depth are usually designed considering them as both end bearing and friction piles.

So basically, in that case, we consider $Q_u = Q_p + Q_s$. In the case of only end bearing pile, $Q_u = Q_p$ and in the case only friction pile, $Q_u = Q_s$, whereas in the case of pile in heavily jointed or fracture and weathered rock where bedrock layer is not present at a reasonable depth, the piles are usually designed considering both end bearing and friction piles.

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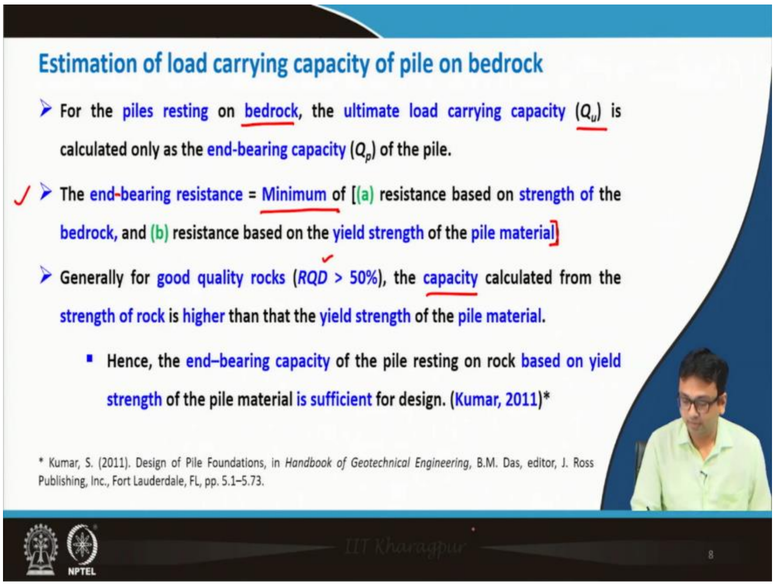

Now, estimation of load carrying capacity of pile on bedrock. So, now, for the piles resting on bedrock, the ultimate load carrying capacity (Q_u) is calculated only as the end bearing capacity of the pile. The reason is quite obvious as Q_p will be much higher than Q_s because it is resting on bedrock which is having higher compressive strength than soil, in general. Now, the end bearing resistance is equal to minimum of (a) resistance based on strength of the bedrock and (b) resistance based on the yield strength of the pile material.

So, basically what may happen that the if the bedrock strength is quite high, then what may happen if you keep on applying the load the pile may yield actually. The pile material is failing before the failure of bedrock. That is why, it is important that the end-bearing resistance is equal to the minimum of (a) resistance based on strength of the bedrock and (b) resistance based on the yield strength of the pile material. Generally, for good quality rocks, where *RQD* is greater than 50%, the capacity calculated from the strength of the rock is higher than the yield strength of the pile material.

So, the capacity calculated from the strength of rock is higher than that the yield strength of the material. Then the minimum end-bearing resistance that we will get when the pile material will fail as the *RQD* of bedrock is greater than 50%. So, the load carrying capacity of bedrock will be quite higher, but if the *RQD* is less than 50%, then we may find that the resistance based on the strength of the bedrock can be the minimum.

Now, in this connection what we can say that the end bearing capacity of the pile resting on rock based on yield strength of the material is sufficient for design. This is what I have explained here.

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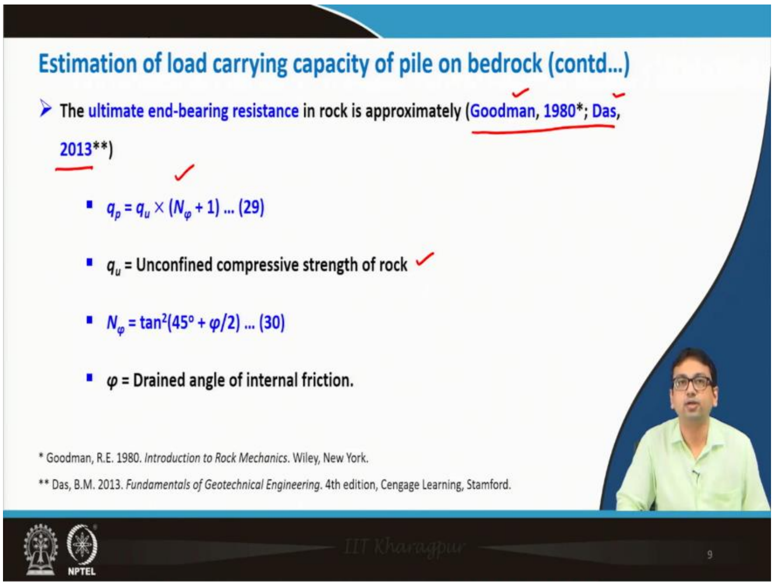

Now, the ultimate end-bearing resistance in rock is approximately as per these two references (Goodman 1980 and Das 2013) is $q_p = q_u \times (N_\varphi + 1)$, where q_u is the unconfined compressive strength of the rock and $N_\varphi = \tan^2\left(45^o + \dfrac{\varphi}{2}\right)$, where φ is the drained angle of internal friction. So, the equation is as per Goodman 1980 and Das 2013.

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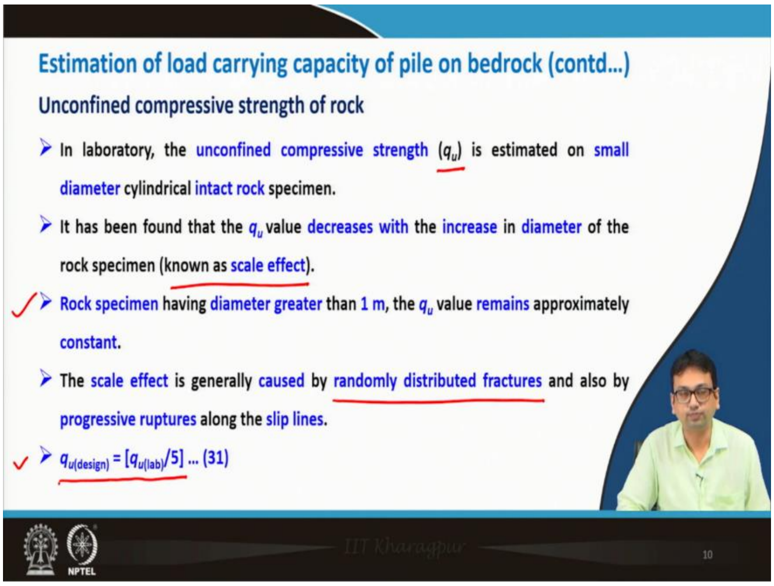

So, now the unconfined compressive strength of rock in laboratory. The unconfined compressive strength (q_u) is estimated on small diameter cylindrical intact rock specimen. Earlier we used to represent it by σ_c, but here, the q_u symbol has been used. So, in laboratory, the unconfined compressive strength (q_u) is estimated on small diameter cylindrical intact rock specimen. It has been found that q_u value decreases with the increase in the diameter of the rock specimen.

This effect is known as scale effect. So, the q_u value decreases with the increase in the diameter of the rock specimen which is known as the scale effect. Now, basically rocks specimen having diameter greater than 1 m, the q_u value remains approximately constant.

So, from the laboratory test of unconfined compressive strength, it is found that if we go for 1 m diameter sample and then if we keep on increasing given the diameter, we will find approximately constant value of q_u. So, that is what stated here, rock specimen having diameter greater than 1 m, the q_u value remains approximately constant. Now, the scale effect is generally caused by randomly distributed fractures and also by progressive ruptures along the slip lines.

So, that is quite obvious because if you have a bigger diameter sample, then obviously that the fractures will be distributed randomly. So, the chance of presence of fractures will be more so, that is why the scale effect is generally caused by randomly distributed fractures and also by progressive ruptures along the slip lines.

According to that, there is an equation, which is used for the purpose of design. So, $q_{u(\text{design})} = q_{u(\text{lab})}/5$. So, $q_{u(\text{lab})}$ is divided by 5 to get $q_{u(\text{design})}$ to be on the conservative side obviously.

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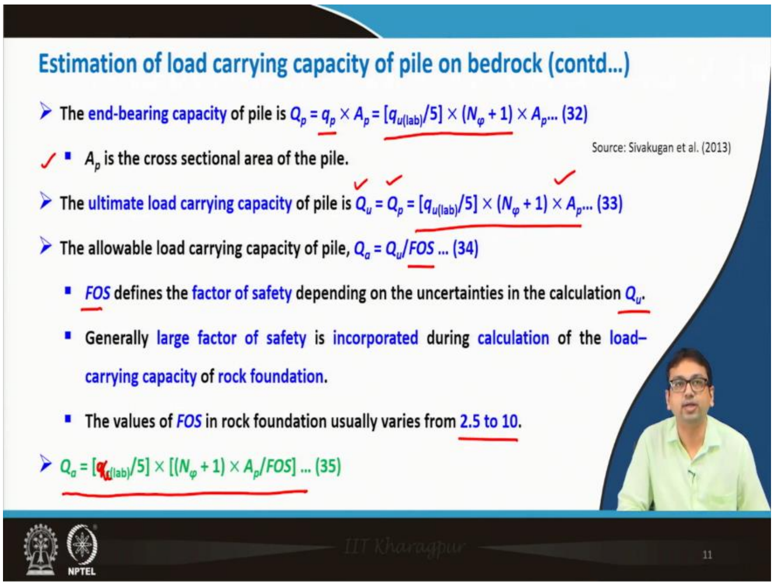

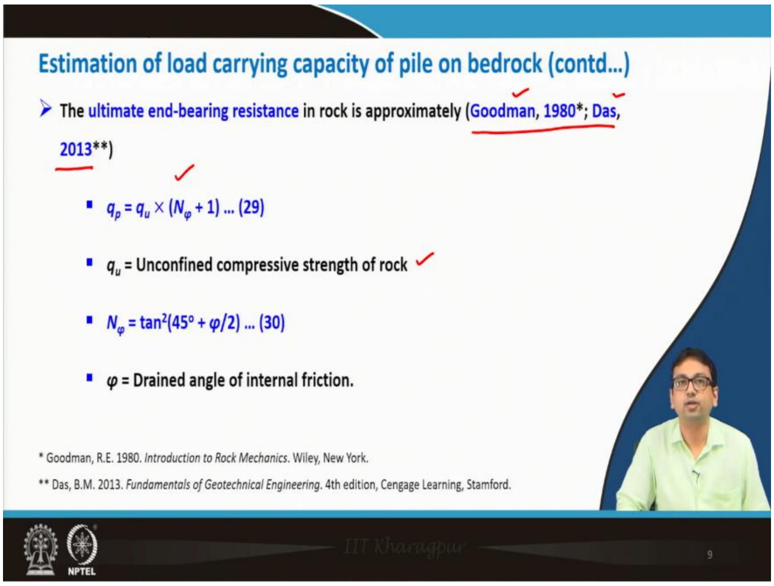

So, the final expression for the end bearing capacity of pile will be $Q_p = q_p \times A_p$. Now, $q_p = q_u \times (N_\varphi + 1)$. Now, $q_u = q_{u(\text{design})}$. So, $q_{u(\text{design})} = q_{u(\text{lab})}/5$.

Hence, $q_p = \dfrac{q_{u(lab)}}{5} \times (N_\varphi + 1)$. So, $Q_p = \dfrac{q_{u(lab)}}{5} \times (N_\varphi + 1) \times A_p$, where A_p is the cross-sectional area of the pile. So, then what we can say that the ultimate load carrying capacity of pile is Q_u which is equal to Q_p. Now, the allowable load carrying capacity of pile can be obtained as Q_u/ *FOS*, where *FOS* denotes the factor of safety.

As I have mentioned earlier that rock is highly heterogeneous and anisotropic material. So, there are several uncertainties associated with the rock properties. That is why, we need to use some factor of safety (*FOS*). So, the factor of safety (*FOS*) depends on the uncertainty in the calculation of this Q_u.

Now, see generally, large factor of safety is incorporated during the calculation of load carrying capacity of rock foundation because as I have stated that rock mass is highly heterogeneous and anisotropic. So, that is why, depending on the location of this construction, a large factor of safety is used.

Now, the value of factor of safety in rock foundation usually varies from 2.5 to 10. If, the *RQD* value of the rock sample is suppose greater than 80% then obviously we can go for the lesser factor of safety. *FOS* = 2.5 will serve the purpose, whereas if you find the *RQD* value is around 30%, then we need to use a higher magnitude of factor of safety.

Finally, the $Q_u = Q_p$ as we have seen in the equation. Now, Q allowable, i.e., $Q_a = \frac{Q_u}{FOS}$. So, $Q_a = \frac{q_{u(lab)}}{5} \times \frac{(N_\varphi + 1) \times A_p}{FOS}$. So, this is the equation which we may have to use for the pile foundation design.

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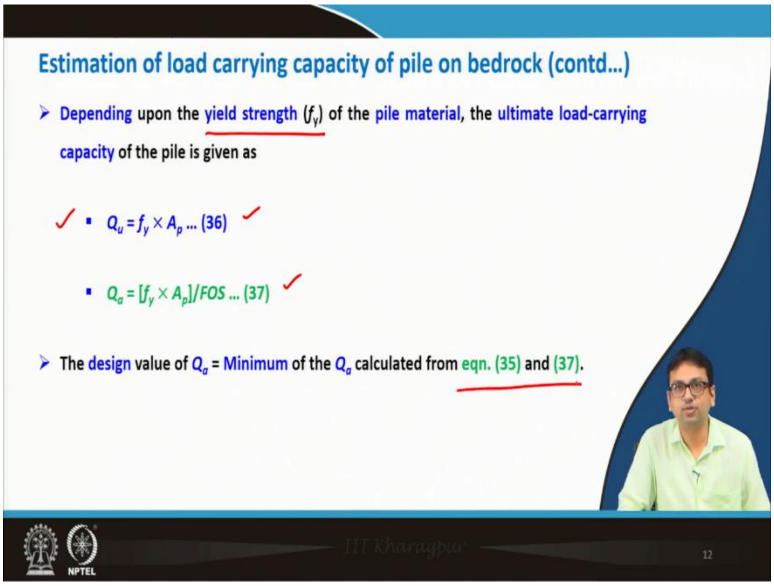

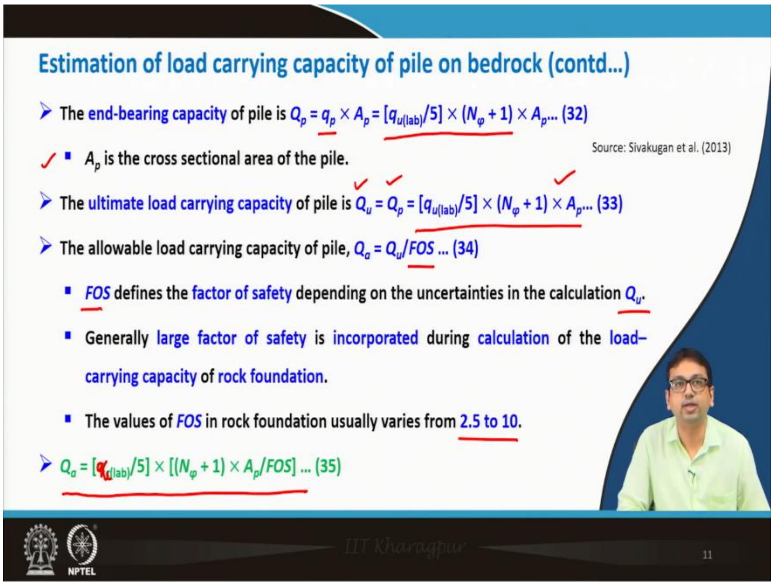

Now, depending on the yield strength (f_y) of the pile material, the ultimate load carrying capacity of the pile is given as $Q_u = f_y \times A_p$ which is governing here. As it has been mentioned earlier, for good quality rock (generally), the capacity calculated from the strength of the rock is higher than the yield strength of the pile material.

So, the end bearing resistance is the minimum of resistance based on the strength of the bedrock and the resistance based on the yield strength of the pile material. So, if we find that the magnitude of Q_u obtained from Eq. (33) is greater than the magnitude of Q_u obtained from Eq. (36), the ultimate load carrying capacity will be based on the yield strength. Then, yield strength will govern the situation.

The allowable load carrying capacity, $Q_a = \frac{Q_u}{FOS} = \frac{f_y \times A_p}{FOS}$. So, the design value of Q_a will be the minimum of Q_a calculated from Eq. (35) and Eq. (37).

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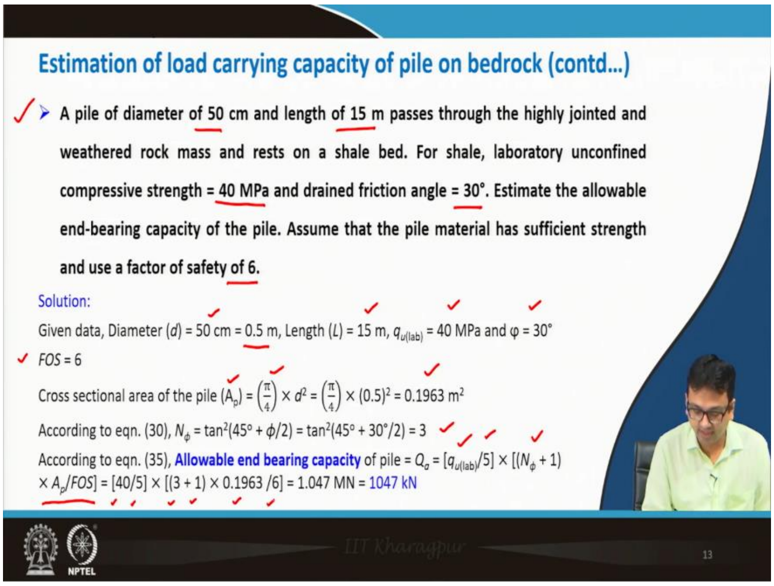

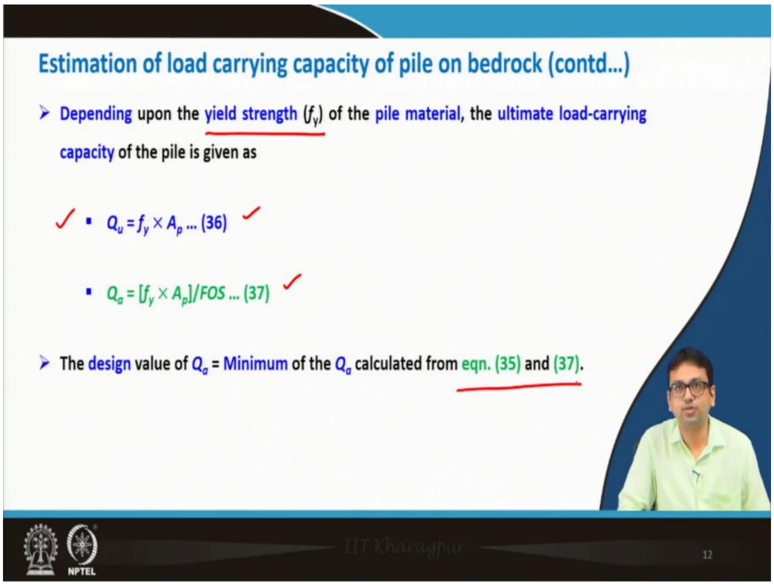

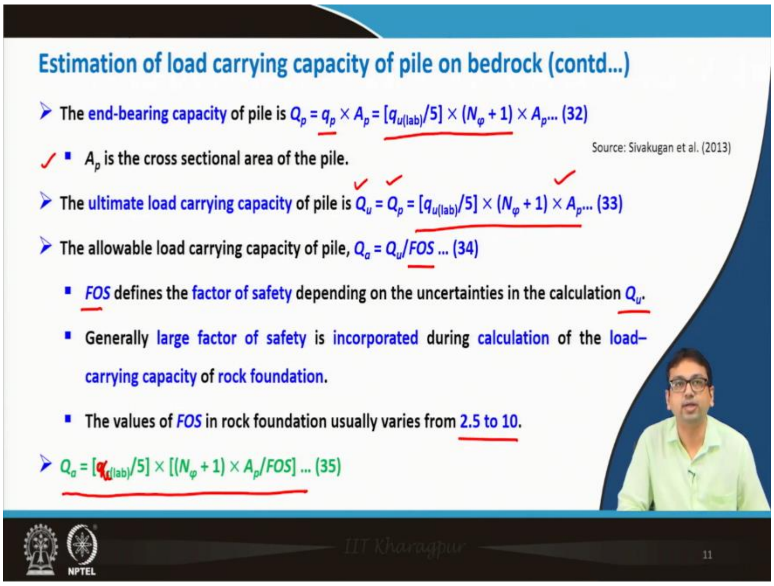

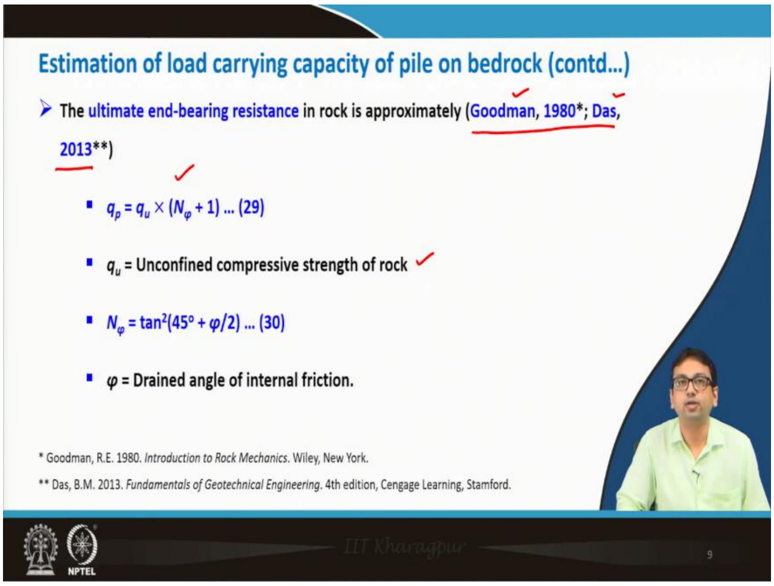

Now, based on this, let us take a problem to clear the doubts. The estimation of load carrying capacity pile on bedrock. So, here is the problem statement given that a pile of diameter of 50 cm. The length is 15 m passes through the highly jointed and weathered rock mass and rests on a shale bed. For shale, laboratory unconfined compressive strength is equal to 40 MPa.

So, the $q_{u(\text{lab})}$ is given as 40 MPa and the drained friction angle (φ) is 30°. Now, the question is to estimate the allowable end-bearing capacity of the pile and assume that the pile material has sufficient strength and use a factor of safety (*FOS*) of 6.

So, pile material is having sufficient strength, i.e., the obtained Q_a from Eq. (37) will be higher than the Q_a obtained from Eq. (35). Hence, for this problem, we have to use only the Eq. (35) to get the allowable end-bearing capacity of the pile. So, and also it is stated to consider the factor of safety as 6. So, the given data are: diameter, d = 50 cm = 0.5 m; length, L = 15 m. Now, $q_{u(\text{lab})}$ = 40 MPa and φ = 30° and FOS = 6.

First, the cross-sectional area of the pile, $A_p = \frac{\pi}{4} \times d^2 = \frac{\pi}{4} \times (0.5)^2 = 0.1963\,\text{m}^2$.

Now, $N_\varphi = \tan^2\left(45^o + \frac{\varphi}{2}\right) = \tan^2\left(45^o + \frac{30^o}{2}\right) = 3$.

Now, according to Eq. (35), the allowable bearing capacity of pile, $Q_a = \frac{q_{u(lab)}}{5} \times \frac{(N_\varphi + 1) \times A_p}{FOS} = \frac{40}{5} \times \frac{(3+1) \times 0.1963}{6} = 1.047$ MN = 1047 kN.

This is our answer. So, I think means we have learned a few important things about deep foundations.

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And with this I am concluding the lecture on deep foundations. So, in our next lecture, that is lecture number 5 of this module, we will discuss about the rock support systems. Thank you.