Rock Mechanic and Tunnelling
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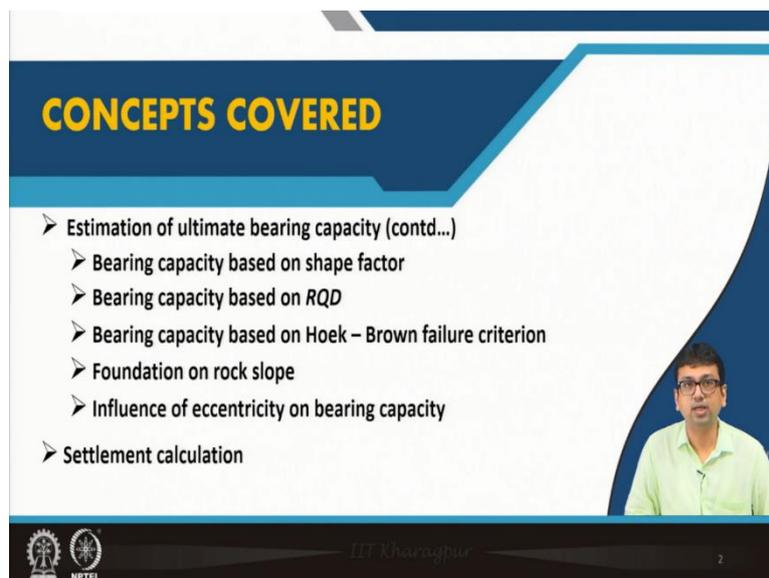**Lecture 44**
Foundations (contd.)

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Hello everyone. I welcome all of you to the 3rd lecture of Module 9. So, in Module 9, we are discussing about the foundations and we will also discuss about the rock support systems. So, today also, we will continue our discussion with the foundations.

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So today, we will primarily discuss about the estimation of ultimate bearing capacity, that topic which we have started in our previous lecture. We will continue with that topic. And we

will focus on the bearing capacity based on shape factor, bearing capacity based on *RQD*, bearing capacity based on Hoek-Brown failure criterion, then foundation on a rock slope, influence of eccentricity on bearing capacity and we will also discuss about the settlement calculation.

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So, 'Bearing capacity with shape factors'. So, it says like q_{ult} of strip footing in in rock according to Coates (1970) given in the following expression by considering failure along two planes. So, $q_{ult} = c' N_c + \gamma D N_q + 0.5 \gamma B N_\gamma$, where c' the effective cohesion of rock mass, γ is the effective unit weight that is submerged unit weight if the rock mass is below the water table. So, the effective unit weight of rock mass. B is the width of footing. D is the depth of the footing base below ground level. It is the depth of the footing base below ground level and c' is the cohesion of the rock mass.

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Now, the N_c, N_q, and N_γ can be obtained from these three equations [i.e., Eq. (13), (14), and (15)], and N_c, N_q, and N_γ are the functions of ϕ'. So, the friction angle of rock varying from 0°

to 45°. For the strip footing, $N_c = 5\tan^4\left(45^o + \dfrac{\phi'}{2}\right)$. But, for square and circular footing, it

should be 7 instead of 5.

The Eq. (16) is for square and circular footing and the Eq. (13) is for strip footing. Now, if the rupture surface is not likely to develop on either side of the footing due to site conditions or loading and the failure is likely to occur on one side, 50% of q_{ult} is taken into consideration.

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Now, the bearing capacity based on *RQD*. So, we have discussed about *RQD* earlier in our previous lecture. So, *RQD* is the rock quality designation. So, when no test data is available for c' and ϕ', then the q_{ult} can be calculated using the following equation based on RQD. So,

$$q_{ult} = \sigma_{ci} \left(\frac{RQD}{100} \right)^2.$$

So, σ_{ci} is the uniaxial compressive strength of intact rock which you can find out very easily and *RQD* can be obtained from the field. Thus, using this simple equation, we can roughly estimate the ultimate bearing capacity of the rock mass. So, $q_{ult} = \sigma_{ci} \left(\frac{RQD}{100} \right)^2$

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So, now 'the ultimate bearing capacity considering Hoek-Brown failure criterion'. As we have a basic idea on the Hoek-Brown failure criterion, the ultimate bearing capacity (q_{ult}) considering Hoek-Brown failure as per Hoek-Brown (1980) failure criteria for a surface strip footing is given by the Eq. (18).

The Eq. (18) was provided by Kulhawy and Carter (1992). So, this is the equation for q_{ult} which is based on the Hoek-Brown criterion and given by Kulhawy and Carter (1992). Here, s_j and m_j are the rock mass strength parameters depend upon *RMR* or *GSI*.

As you know that the concept of *GSI* came quite later. So, basically, the Hoek-Brown failure criterion was developed in 1980 and the Eq. (18) was provided in 1992. So, mainly at the time, it was dependent on the *RMR*. So, that is why, it is written over here. So, s_j and m_j are rock mass strength parameters depend upon *RMR* or *GSI*.

For square and circular surface footing, q_{ult} is increased by 20%. So, the Eq. (18) is for the strip footing. Now, for square and circular footing, we have to increase it by 20%. If surcharge load presents around the footing of intensity $q = \gamma D_f$, then the q_{ult} will be as per Eq. (19). Now the σ'_3 term is there in Eq. (19) which can be obtained from Eq. (20), where the q term is coming into picture. So, this is what Kulhawy and Carter provided based on the Hoek-Brown (1980) failure criteria for determining the ultimate bearing capacity.

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Estimation of ultimate bearing capacity (contd...)

Foundation on Rock Slope

➢ Foundation on sloping ground affects both the stability of foundation and the slope.

➢ The q_{ult} for the surface footing on the sloping ground can be obtained from:

▪ $q_{ult} = c'N_{cq} + 0.5\gamma BN_{\gamma q}$ ... (21)

▪ where, N_{cq} and $N_{\gamma q}$ are the bearing capacity factors depend upon the slope inclination (β), D_f/B ratio and φ'.

▪ When fractures or joints present in the sloping ground $N_{cq} = 0$

Next topic is the 'Foundation on rock slope'. So, the foundation on sloping ground affects both the stability of the foundation and the slope. So, obviously that is quite an obvious statement. Now, the q_{ult} for the surface footing on the sloping ground can be obtained from the Eq. (21) which states that $q_{ult} = c'N_{cq} + 0.5\gamma BN_{\gamma q}$, where the N_{cq} and $N_{\gamma q}$ are the bearing capacity factors depend upon the slope inclination (β), D_f/B, and ϕ'.

Now, when the fractures or joints present in the sloping ground, the effective cohesion (c') will be zero. Hence, the N_{cq} will become 0. So, when fractures or joints will be present in sloping ground, then $q_{ult} = 0.5\gamma BN_{\gamma q}$.

As we know that N_{cq} and $N_{\gamma q}$ are the bearing capacity factors depend upon the slope inclination (β) and D_f/B, and ϕ'. Now, regarding that the values of $N_{\gamma q}$ based on slope inclination (β) are given in the following table. This is actually given by Meyerhof (1957). So, it says the $N_{\gamma q}$ for strip footing on the face of the slope for cohesionless material. So, anyway $c' = 0$. So, the first term of Eq. (21) is vanishing.

So, only $0.5 \gamma B N_{\gamma q}$ will be there for the cohesionless material. Here, different sloping angles (β) are provided in 5, 10, 20, 30, 40, 45° and these are the values of ϕ' in degree. It is provided for 30°, 40°, and 45° with $D_f/B = 0$, i.e., the surface footing and also for $D_f/B = 1$. So, the footing is at some depth, i.e., $D_f/B = 1$, which implies that some overburden pressure is there.. So, the $N_{\gamma q}$ values are provided over here for 30°, 40°, and 45°.

So, the table is for the strip given by Meyerhof (1957). So, this can be a very useful table which can be used for designing the foundation on slope. Obviously, there are several new numerical modelling softwares using which we can model it or we can write our own program in finite element modelling to model these conditions. But anyway, these are the classical theories given by the authors like Meyerhof. So, these tables are still quite useful at the time of designing the foundation on rock slope.

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Now, influence of eccentricity on bearing capacity of rock. So, this topic is similar to that you have learnt in foundation design course probably. However, here, it has been explained for the rock which is similar to that we have for the foundation in soil. Hence, a brief description is provided here. When the rigid footings are subjected to moments with direct centric load.

We can see the moment M_l in the L direction along with this centric load P. So, when rigid footings are subjected to moments with direct centric load (P), the distribution of load intensity under the footing can be evaluated using the Eq. (22) which states

$$q = \frac{P}{BL}\left[1 \pm \frac{6e_l}{L} \pm \frac{6e_b}{B}\right].$$

So, e_l is (M_l/P) and e_b is (M_b/P). P is the centric load; B and L are the width and length of the foundation, respectively. M_l and M_b are the moments in the L and B directions, respectively as we can see from the diagram also.

Here, e_l is the eccentricity in the L direction and e_b is the eccentricity in the B direction. Now, what we can observe from the figure that if e is up to $L/6$. So, the stress distribution will be

like this. But, if the eccentricity, e becomes more than $L/6$, then this kind of stress distribution we can notice, i.e., the tension will develop there will be no contact between the foundation and the rock. So, this is not a desirable situation.

That is why, it is always tried to keep the eccentricity within (i.e., less than equal to) $L/6$ for L direction and for the B direction, it should be less than equal to $B/6$. So, e_l should be less than equal to $L/6$ and e_b should be less than equal to $B/6$ which is the most desirable condition. If it is more than that, then we will see this type of stress distribution which indicates that tension is developing and also there is no contact between the rock and the foundation in this region. Thus, using the Eq. (22), we can directly find out the loading density.

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Now, settlement calculation. So, already we have discussed the plate load test. At that time, we have discussed about the settlement and safe bearing pressure. But, anyway, the Eq. (23) we have seen in the case of foundation on soil. So, similar to that, settlement calculation can be done using this equation. Here, δ is the settlement in the direction of loading. p is the uniformly distributed load intensity.

Now, B is the width or diameter of the loaded area. Then μ is the Poisson's ratio. And, S_F is the shape factor considering shape of loaded area and the location of the point where settlement is required.

So, the shape factor considers the shape of the loaded area and the location of the point where settlement is required. And, another one is the E_j which is the elastic modulus of rock mass. The equation is provided by Schleicher (1926) and I hope all of you must have seen this

equation earlier also in soil mechanics. So, the same equation can be applied to find out the settlement in the case of rock.

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Now let us take a problem and clear our doubts. So, the problem statement is that determine the settlement of a footing 5×5 m resting on a rock mass having *RMR* is 55. So, rock mass rating is given as 55. Now, the Poisson's ratio is 0.25. Footing carries a load of 500 MN. Assume the shape factor S_F is 0.9.

So, S_F is given, B is given, μ is given and the only thing that we have to calculate, is E_j. We can find out E_j from RMR. If you remember in our previous earlier classes, we have discussed about that. I will just tell you now. I will show you what the expression is. So,

given data like width of the footing, B is 5 m, Poisson's ratio is 0.25, RMR is 55, load (P) is 500 MN = 500000 kN.

Now, we have to find out the load intensity of the footing in kPa. Here, the P is given; but, we are interested in p. As per the Eq. (23), we need to know the uniformly distributed load intensity.

So, the load intensity, not the load. So, we need p. So, we have obtained that. Now, the elastic modulus of jointed rock mass (E_j) can be obtained using this equation, $E_j = 10^{\frac{RMR-10}{40}}$ (we have discussed this equation earlier in module 5, lecture 5 and slide number 26). If you refer that slide, you will find we have discussed this equation earlier.

So, the RMR is given as 55. So, if you place over here, so, we will get it as 13.335 GPa. If you see that slides, module 5, lecture 5 slide number 26, then you will that E_j is in GPa.

So, you will get E_j in GPa. So, now if you convert it in kPa, it will be 13.335×10^6 kPa. Now, we have everything to estimate the settlement value. So,

$$\delta = \frac{S_F \times p \times B \times (1-\mu^2)}{E_j} = \frac{0.9 \times 20000 \times 5 \times (1-0.25^2)}{13.335 \times 10^6} = 6.327 \times 10^{-3} \text{ m} = 6.327 \text{ mm}.$$ So, this is the settlement of the foundation.

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Now, the shape factors (S_F) under surface loading on an elastic half space given by Winterkorn and Fang (1975) are given in the table. This table has been provided here as the reference as we can directly find out the S_F value using the table. In this case of the previous problem, the S_F value was provided but you may have to find out the S_F value from this table based on the conditions. So, let us spend some time on this table. See what are given like circular, circular rigid, it is rigid foundation, it is flexible.

So, with rigid foundation, we can see centre, corner, middle, middle of B and middle of L, everywhere it is basically same. So, it is 0.79 similarly, if you see square, it is flexible and it is rigid. Now here, for the rigid square footing, S_F values are 0.99, 0.99, 0.99, 0.99, 0.99 at centre, corner, middle of B, middle of L, and average, respectively, whereas, for the flexible circular footing, at centre, it is 1; for corner, it is 0.64; for middle of B; it is 0.64, and for middle L also, it is 0.64, and the average is 0.85. Likewise, for the flexible square footing, at centre, it is 1.12; at corners, it is 0.56; at middle of B, it is 0.76; at the middle of L, it is 0.76 and the average is 0.95.

However, these values were for the circular and square footings. So, apart from them, there are rectangular footings. So, L/B is very important there. So, in the case of circular and square footings, the S_F at the middle of B and middle of L are becoming the same. Even, if we consider square footing, then $L/B = 1$. So, obviously middle of B will be similar to the middle of L. So, obviously these two values has to be similar whereas here for the rectangular footing, L/B is 1.5.

So, for square footing, the L/B is 1. For rectangular footing, the L/B values are 1.5, 2, 3, 5, 10, 100 and 1000. For $L/B = 1.5$, we can see how the values are changing. So, at centre, it was

1.12 for $L/B = 1$ (i.e., for the square footing), whereas it is given as 1.36 for $L/B = 1.5$. Likewise, at corners, it is 0.67, then at the middle of B, it is 0.89; at the middle of L, it is 0.97 and here average is 1.15.

So, likewise, we can see for $L/B = 10$, at centre, it is 2.53, at corner, it is 1.26, at the middle of B, it is 1.45, then middle of L 2.12 and the average is 2.25. So, in this way, we can the table, if the S_F value is not provided.

Obviously, the required conditions will be provided and why that is important? If we look at the shape factor values considering different shapes of the footing whether the footing is circular, rectangular or square in shape of the loaded area and the location of the point where settlement is required. So, the location is also important that is why different locations are provided in this table (i.e., centre, corner, middle of B and middle of L). So, accordingly, we have to choose the S_F value using this table.

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So, okay I think with this let us conclude our today's lecture. So, thank you.