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Lecture – 41
Pile Foundation - Under Compressive Load - 1

So, this lecture I will start a new topic on pile foundation. So, the pile foundation are already been discussed in a foundation engineering course, but this advanced foundation course. I will mainly discuss in detail those topics, those are not covered in foundation engineering course. Though to maintain the continuity, I will also discuss few of the portions, those are already been discussed in foundation engineering course, but not in detail in brief.

So, in this course, I will mainly discuss that how we can generate a load settlement behaviour or load settlement curve for pile analytically, because we know that we can get the load settlement behaviour of the pile by using pile load test. But in this course mainly I will discuss that how we can generate a load settlement curve for pile by analytical approach or theoretically. And then I will also discuss different cases for negative skin friction and other things are already been discussed in the foundation engineering course, so, I will briefly discuss those things and to maintain the continuity.

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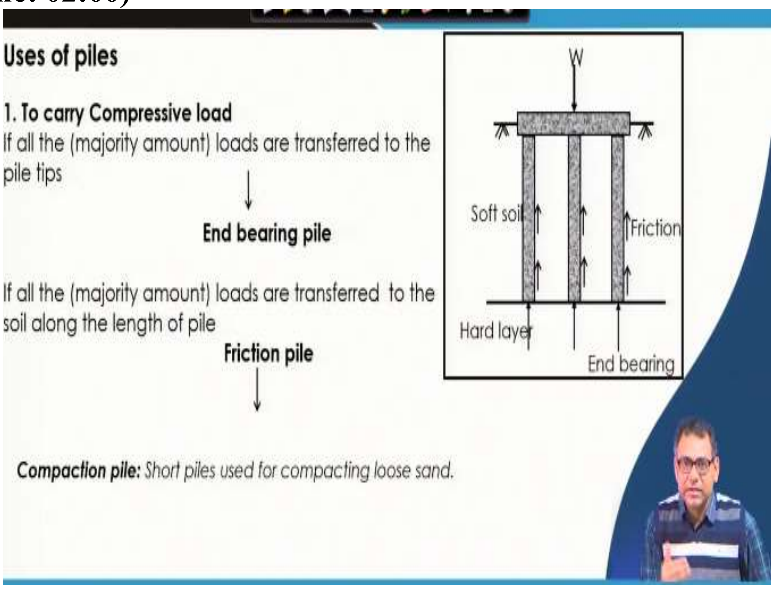

So, before I go to that main part of this topic. So, briefly I can discuss that what are the uses of pile? So, the pile can carry compressive load, pile can carry uplift load, pile can carry lateral load also, even inclined load also. Depending upon the type of structure we can provide a pile which can carry different types of load, not only compressive load, it can carry the uplift load, and the lateral load also.

So, we are talking about the pile under compressive load. So, this pile can get the resistance by two mechanisms, one is the skin friction and another is the tip resistance in the bearing. So, based on that we can classify pile into two groups, one is the end bearing pile, another is the friction pile. If all or the majority amount of the load are transferred to the pile tip then it is called end bearing pile.

That means most of or majority of the load is taken by the soil which is below the pile tip or that means most of the resistance pile is getting from the tip or the bearing. So, what is the example? That means suppose if we have a very soft soil and then there is a hard strata. So, that means this load is transferred to the hard strata through this pile, so, majority of the load will be taken by this hard strata and the pile will get the resistance from the tip.

But if all our majority of the load is transferred to the soil along the length of the pile then it is called the friction pile. So, when you are talking about the load transfer mechanism. So, that means, as I mentioned that there is a friction resistance and the tip resistance. So, first the friction resistance is mobilized then the tip resistance is mobilized. That means when you apply a load first pile will get the resistance from the skin friction in that time the resistance due to tip is also there.

But that amount is very less compared to the resistance that pile is getting from the friction. Once the friction resistance is fully mobilized then the tip resistance, finally get the tip resistance. So that when the second part once the friction resistance is fully mobilized then the resistance that you will get is due to the tip resistance only. So, suppose that friction resistance that pile is getting that is sufficient to take the bearing capacity or the load carrying capacity of the pile. Then that mean most of the resistance is due to the friction then that type of pile is called the friction pile.

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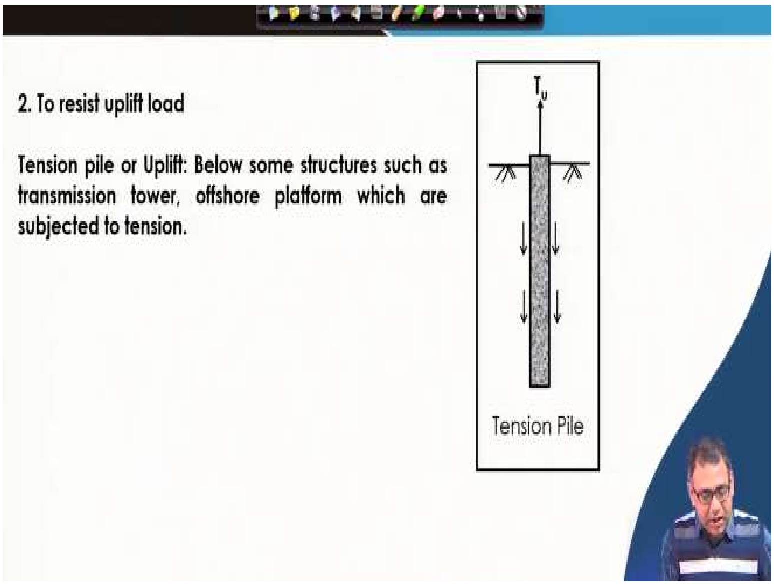

Then pile can get the uplift load also the application areas below some structures, such as transmission tower, offshore platform where the piles are subjected to uplift also. In transmission tower because when there is a wind, so, it will try to rotate the structure, so, one portion of the pile will be under compression, another portion of the pile will be under tension. So, that transmission tower then offshore platform where the pile can be subjected to uplift also.

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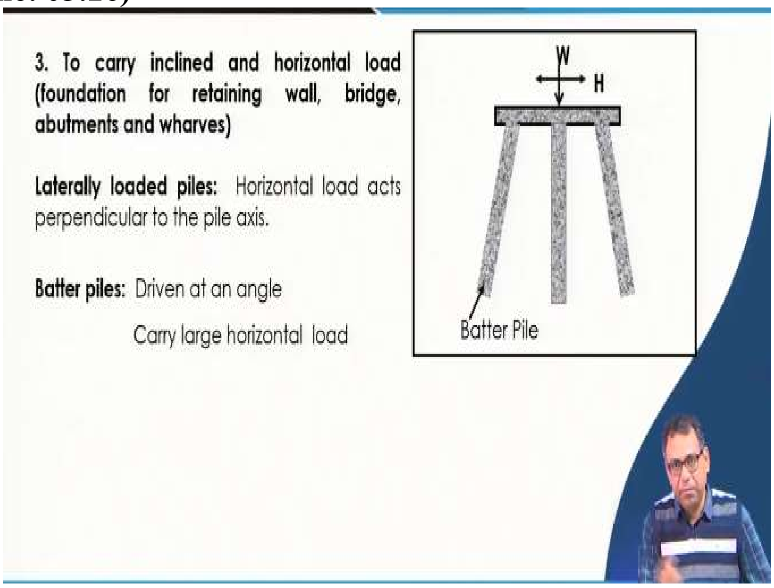

Then pile can be subjected to a horizontal or inclined load. For example, the foundation below the retaining wall, bridges, abutments and wharves when there is waves from the water then that type of situation pile can carry the horizontal as well as the inclined load. Now, lateral loaded piles means, if horizontal load acts perpendicular to the axis of the pile then that type of load is called lateral load and that type of pile is called the laterally loaded pile.

And then batter pile also, if pile is subjected to inclined load then you can provide an inclined pile or the batter pile so, which is driven with certain angle and carry horizontal load as well as the inclined load. Because the inclined load has two components, one is the horizontal component and another one is the vertical component. And if the horizontal load is perfectly perpendicular to the axis of the pile then it is called the laterally loaded pile.

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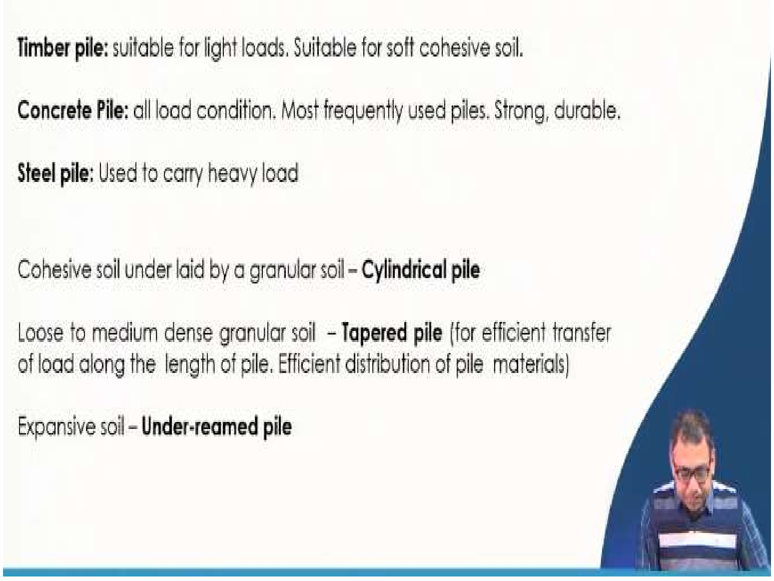

Now in terms of material, the pile can be timber pile, concrete pile, steel pile. Then timber pile is suitable for lightweight structures and suitable for soft cohesive soil. Concrete pile can be used for all condition; most frequently used pile strong and durable. Then steel pile can be used to carry heavy load. Now, there are different shapes of the piles, cylindrical pile, tapered pile then under-reamed pile that means bulbs are provided so that can be suitable for expansive soil.

Then cylindrical pile is suitable for cohesive soil underlain by a granular soil, loose to medium dense granular soil, tapered pile is suitable because here we can distribute the pile material or we can transfer the load along the pile very effectively if I provide the tapered pile.

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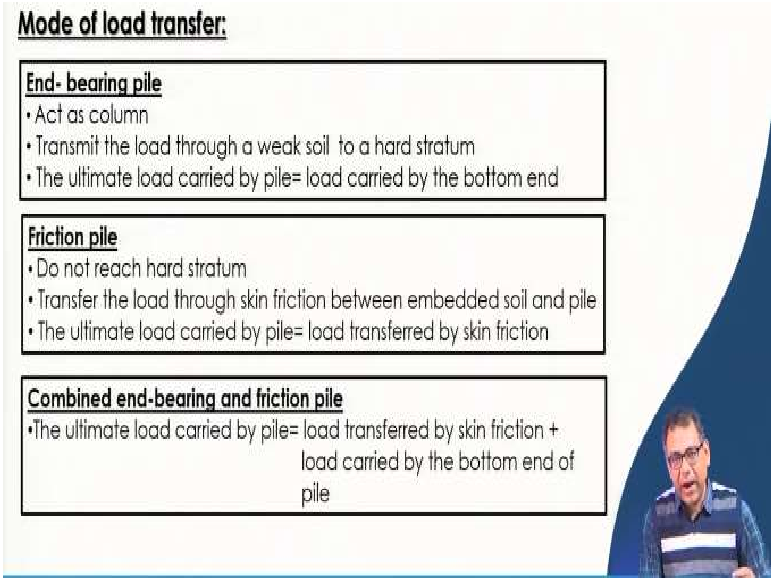

Then mode of load transfer as I discussed in end bearing pile and the friction pile and there can be a combination of these two. That means some portion of the resistance a pile is getting from the tip and some portion it is getting from the friction. So, for end bearing pile it transmits the load through weak soil to hard stratum and the ultimate load carrying capacity of the pile is equal to the resistance that pile is getting from the bottom.

And then the friction pile transfer the load to the skin friction between the embedded soil and the pile and ultimate load carrying capacity of the pile is equal to the load transferred by the skin friction. And if it is a combined pile then the ultimate load carrying capacity of the pile is the summation of the load transferred by the skin friction plus and the load which the pile is getting resistance from the tip.

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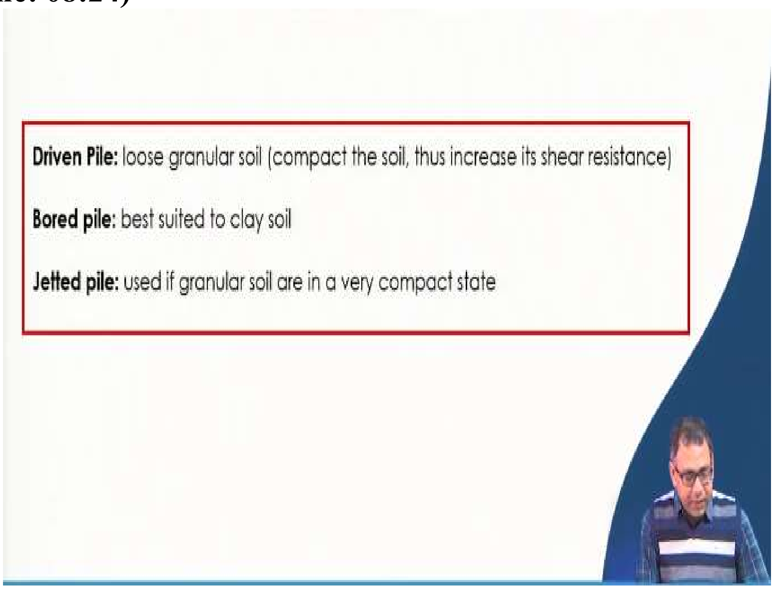

Now pile can be driven pile, bored pile and jetted pile. So, driven piles are suitable for loose granular soil where we drive the pile into the soil when there is a possibility of the compaction of the soil. So, that we can increase the shear resistance of the soil. Then bored pile is best suited for clayey soil and jetted pile is suitable if the granular soil is in very compacted state.

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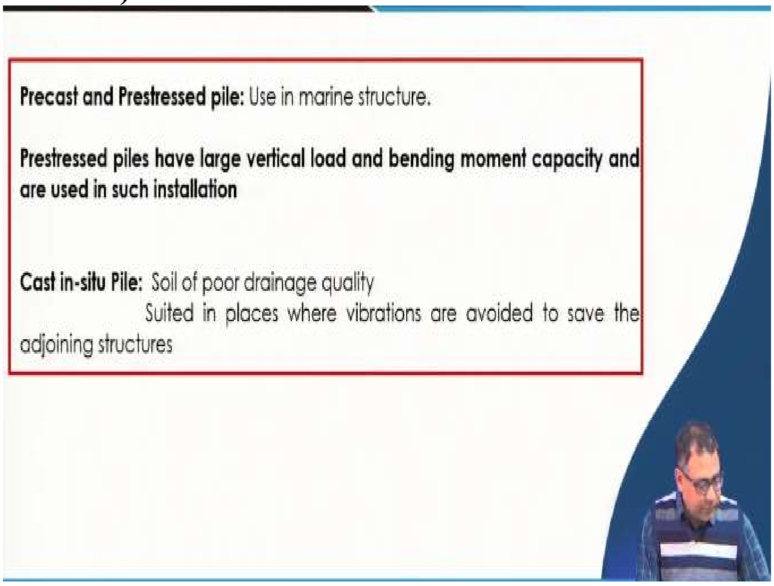

Then pile can be precast pile, pile can be cast-in-situ pile. So, pile can be precast or prestressed pile which can be used for the marine structure. And prestressed piles have larger vertical load and bending moment capacity and used in such installation where the bending moment and the vertical load are in very large amount. And then the cast-in-situ pile, soil of poor drainage quality and suitable for place where vibrations are avoided to save the surrounding structures.

That means in during the installation of precast pile there is a possibility of vibration and if the surrounding structure cannot take that vibration, then we can go for the cast-in-situ pile or we can go for the cast-in-situ pile for the site where the drainage quality is very poor.

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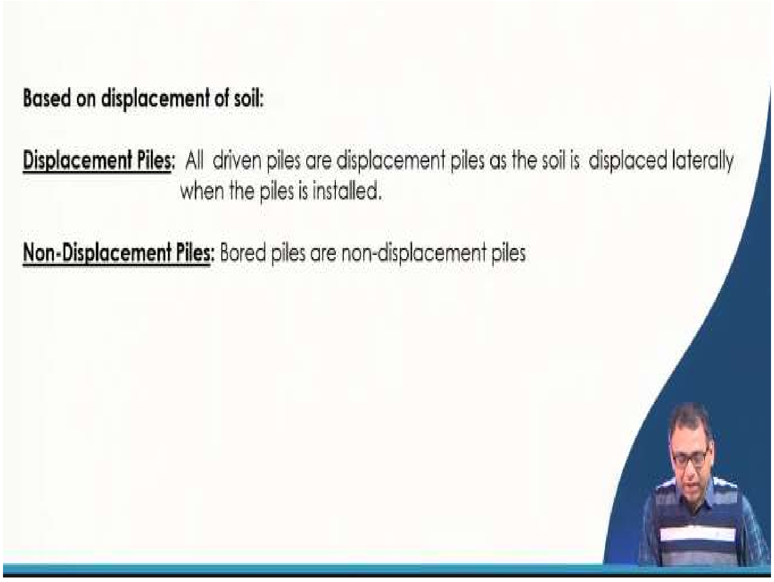

So, then we have the displacement pile and the non-displacement pile. So, all driven piles or the piles which are driven into the soil are displacement piles because the soil is displaced laterally during the installation of the pile. And bored piles are generally non-displacement piles where the possibility of displacement of the soil laterally is very less.

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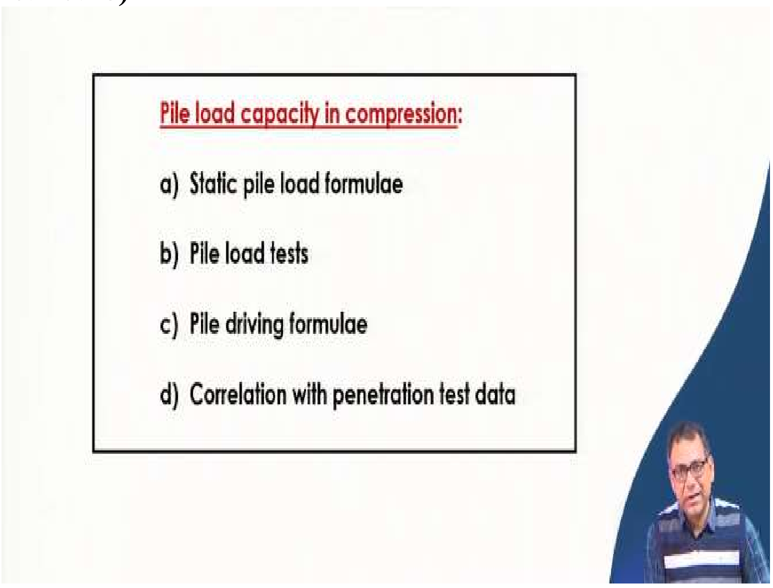

Then we have different pile load capacity methods, so, we can determine the capacity under compression by static pile equations, then pile load test, then driven pile equations, then correlations which is available based on the penetration test data. Penetration test data mean the SPT or the SCPT.

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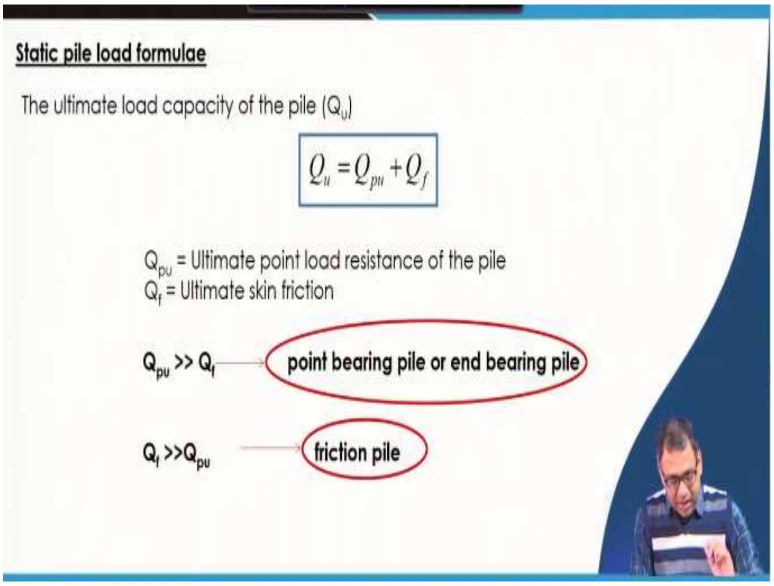

Then static pile load equations. So, as I mentioned the pile capacities is basically due to the skin friction and the tip resistance. So, that means the ultimate load carrying capacity of the pile is a summation of tip resistance or the point load resistance and the friction resistance or ultimate friction, skin friction. So that means the point bearing pile, the friction resistance is very less compared to the tip resistance and for the friction file, friction resistance is very high amount compared to the tip resistance.

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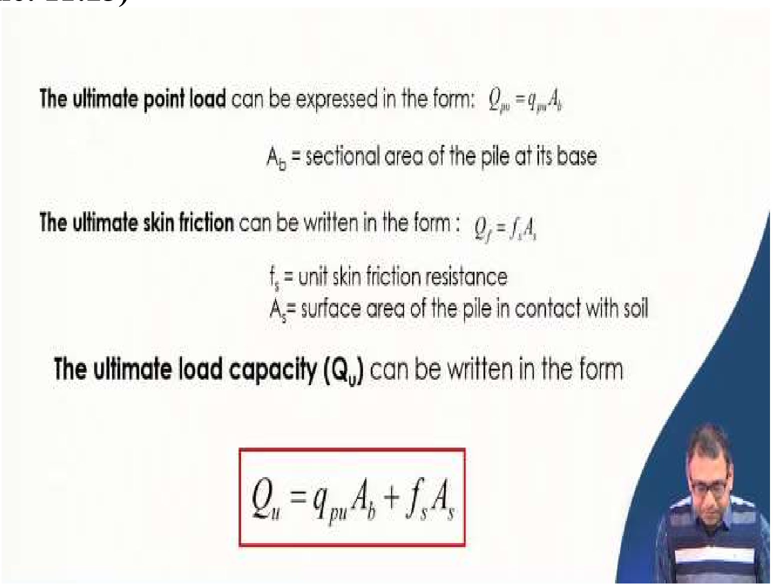

So, we have this equation, so that means here ultimate load carrying capacity of the pile is summation of the tip resistance and the friction resistance. Now, q_{pu} is the tip resistance. Now if I multiply it with the base area then I will get the total load that the pile is getting due to the tip resistance plus the friction resistance into the surface area that is the perimeter × the length of the pile that will give us the total fictional force.

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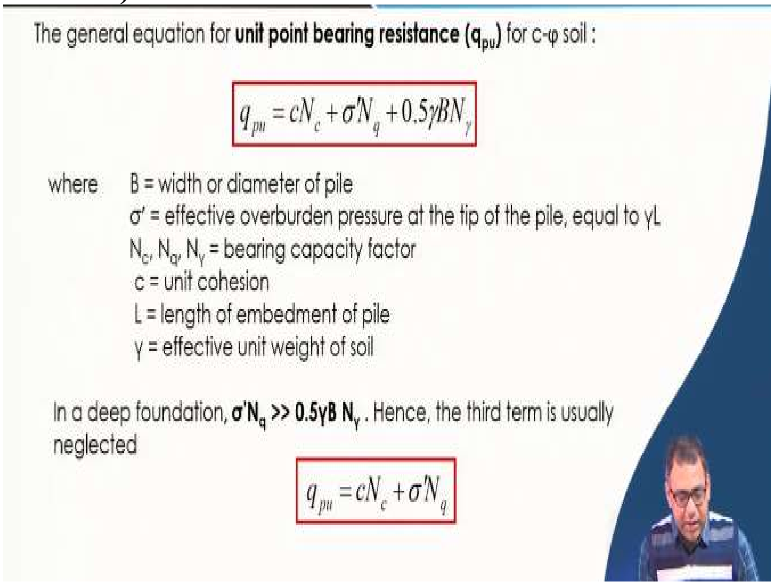

Then how to calculate the point bearing resistance or the tip resistance now, as we know this equation is the basic equation for bearing capacity calculation. So, $q_{pu} = cN_c + \sigma' N_q + 0.5\gamma B N_\gamma$, so, if I use the another general equation some factors are also multiplied but here this is the general equation, so, in case of pile. So, this third time term is very less compared to the second term because the length of the pile or the depth of the foundation is very large.

So, third term is very less compared to the second term, so, generally in pile load carrying capacity this third term has been neglected. So, we will get the $q_{pu} = cN_c + \sigma' N_q$, so, N_c, N_q are the bearing capacity factors and then σ' or is the effective overburden pressure at the tip of the pile and c is the unit cohesion and B is the width or diameter of the pile.

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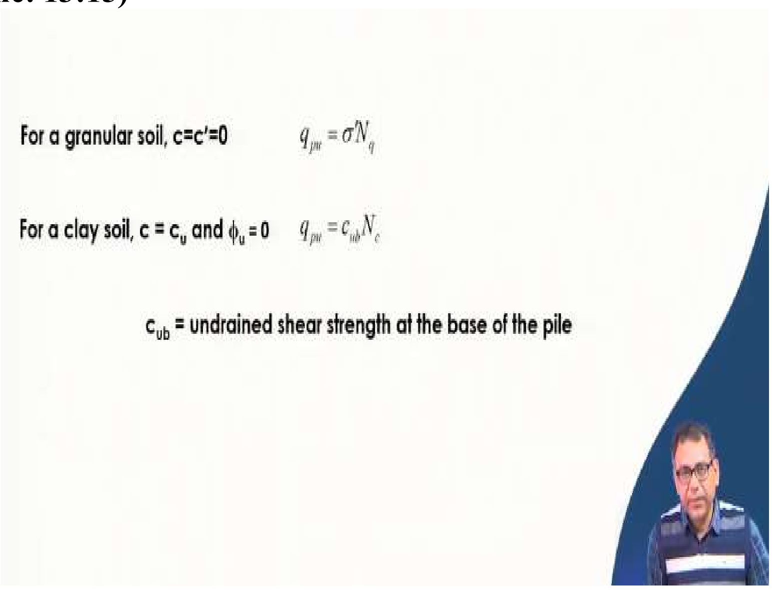

Now, for the granular soil the tip resistance is simply $\sigma' N_q$ even this first term is been neglected because c is 0. And for clayey soil the tip resistance is equal to $c_{ub}N_c$. Second term is also neglected, so, for the clayey soil, tip resistance is simple cN_c and for the granular soil tip resistance is $\sigma' N_q$ and c_{ub} is the undrained cohesion at the base of the pile.

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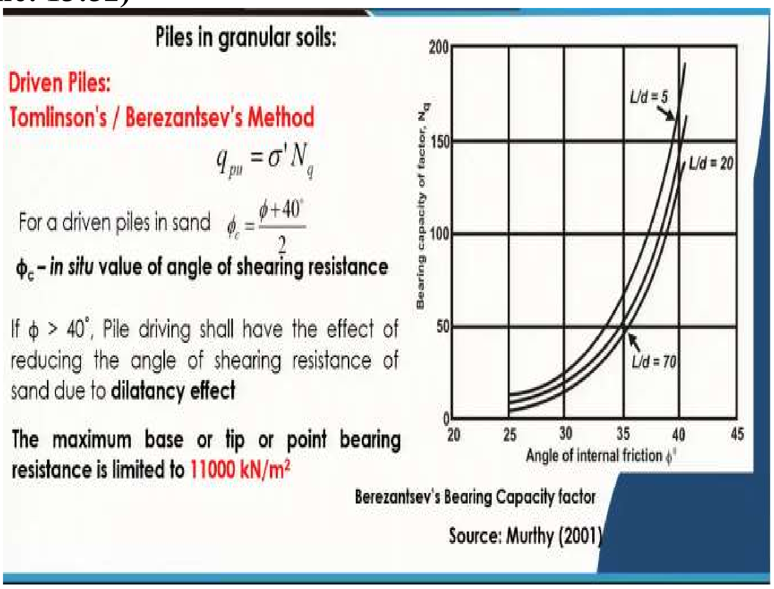

So, now, how we can determine the tip resistance for the pile? Different methods are available so, I will discuss two of them. So, first method is Tomlinson's method where the expression is same, the $\sigma' N_q$ and then the N_q value we will get from this chart suppose if this chart this is X axis is the ϕ value and this is the N_q is the Y axis different $\frac{L}{d}$, L is the length of the pile, d is the diameter of the pile and we can get the bearing capacity factor.

Now, if we put this factor here you will get the tip resistance but remember that in this method it is suggested the tip resistance is limited to 11000 kN/m^2 that means we cannot use the tip resistance more than 11000 kN/m^2 for this method. So, now, if the ϕ > 40° then when we apply the, I mean when we drive the pile there is a possibility of dilatancy, which may reduce the friction angle or the shearing resistance of the soil.

So, we have to reduce the friction angle, if is greater than 40° and that equation is given here $\phi_c = \frac{\phi + 40°}{2}$, but it is applicable if friction angle is greater than 40°. So, remember these equations are all given for the driven pile, if I want to use this equation for the cast-in-situ pile and the bored pile or both pile then you have to modify them, but these are for driven pile and not for bored pile.

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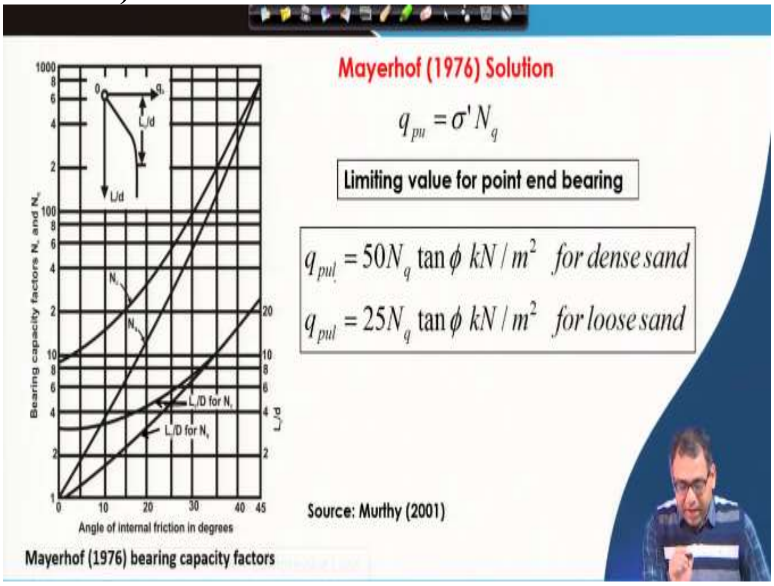

Now, similarly, there is another expression given by Meyerhof, the expression is same, but these tip resistance we can get this N_q value by using this chart, where again the friction angle and corresponding N_q are given. So, this Y axis the left side is for the bearing capacity factor and right side is for the critical length by *d*. Now, what is critical length? So, I will discuss this critical length part later on.

So, here from this chart I will get the N_q and this N_q I will put here and then, but like the previous method also, here also we have to give some limiting value, so, that limiting value is $50N_q$ tan ϕ kN/m^2 for dense sand and $25N_q$ tan ϕ kN/m^2 for loose sand.

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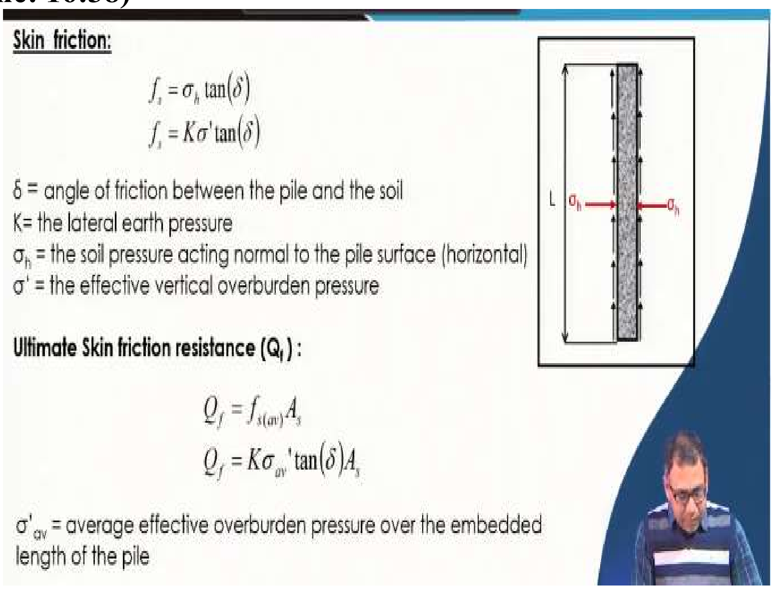

Now, we will go for the skin friction, we previously discussed for the tip resistance now, skin friction. So, skin friction, this is the skin friction. So, we will calculate the lateral resistance or lateral force or stress which is acting on the pile and we can calculate the vertical stress at any point and then we multiply with the earth pressure coefficient and $\tan \delta$, will get the total resistance or friction resistance that is acting along the pile.

So that is done here, the σ' is the effective vertical stress at any point if I multiply with the K; K is the lateral earth pressure coefficient. So, this is lateral earth pressure coefficient × $\tan \delta$, δ is the angle of friction between the pile and the soil. So, now, here remember that we have to take the average effective overburden pressure. So, suppose if we have a length of L, so, along that L what is the average effective overburden pressure that we have to use to calculate the skin friction.

Then, once we get this skin friction, we have to multiply with the perimeter × the length then we will get the area and then we will get the total frictional resistance.

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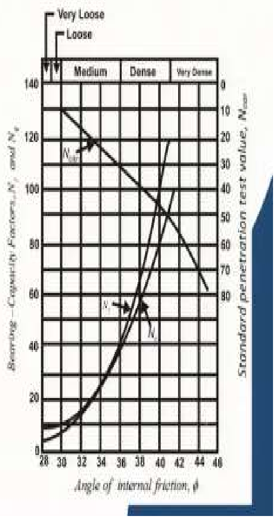
Broms (1966) recommends the value of K and δ shown in Table for piles driven into sand

Pile material	δ	Values of K	
		Loose sand	Dense sand
Steel	20°	0.5	1
Concrete	0.75ϕ	1	2
Timber	0.67ϕ	1.5	4

Source: Ranjan and Rao, 1991



Source :Murthy (2001)

So, now, there is a term K and the δ, so, Broms (1966) recommended some δ and K values which are given in this table. For loose sand steel pile K value is 0.5, for dense sand 1, concrete 1 to 2, timber 1.5 to 4. Similarly, δ for concrete is 0.75ϕ. So, now, when it is called loose sand and dense sand that is also given in this chart, if the ϕ value is less than 30° then it is called the loose sand.

If is 30° to 36° then it is called medium dense sand and it is 36° to 41° around 40° to 41° then it is called dense sand and 41° and above it is called a very dense sand. So, here for dense sand and loose sand you will get the different *K* values.

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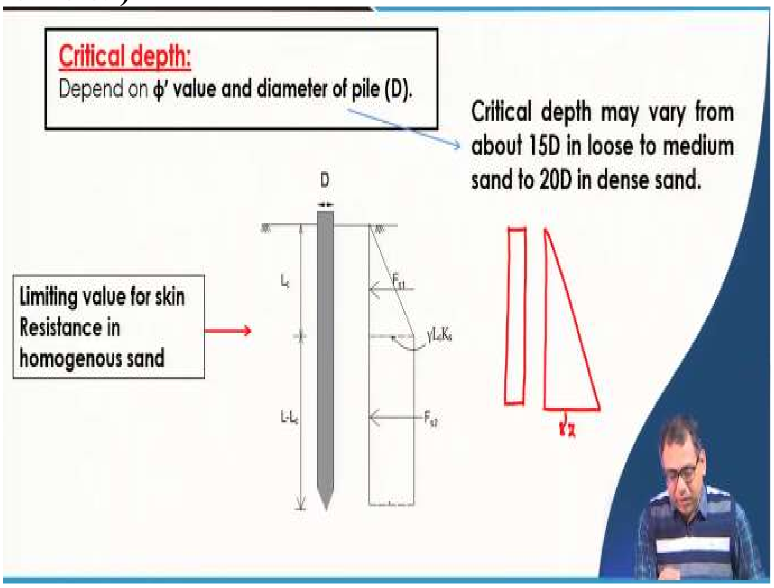

So, now, we have to calculate the effective stress or average effective stress. Effective stress or effective overburden pressure at a point to calculate the skin friction, now here, suppose if we have a pile and it is expected that as depth. *H* increases the effective stress or effective overburden pressure that is γH also increases.

But it is observed that after a certain depth in case of pile this effective overburden pressure will not increase and it will remain constant so that depth is called a critical depth. So, you can see, here up to the critical depth this is increasing linearly, but after that, it is uniform, so, this critical depth is varying from 15*D* to 20*D*. So, for loose to medium sand it is 15*D* and 20*D* is for dense sand, so, *D* is the diameter of the pile.

Now, that means, here we are providing some limiting values even in case of friction resistance calculated because we have discussed some limiting values for tip resistance calculation for both the method. Similarly, here also we can provide some limiting values for friction resistance calculation also. Now, this critical depth is obviously, the function of the soil condition whether it is a dense soil or loose soil and then, but some cases researchers observed that this type of critical depth does not exist in the field.

So, they have suggested that you take the full resistance and measure from top to bottom the effective overburden pressure increases linearly, but, I would recommend that you use the critical depth concept when you calculate the friction resistance.

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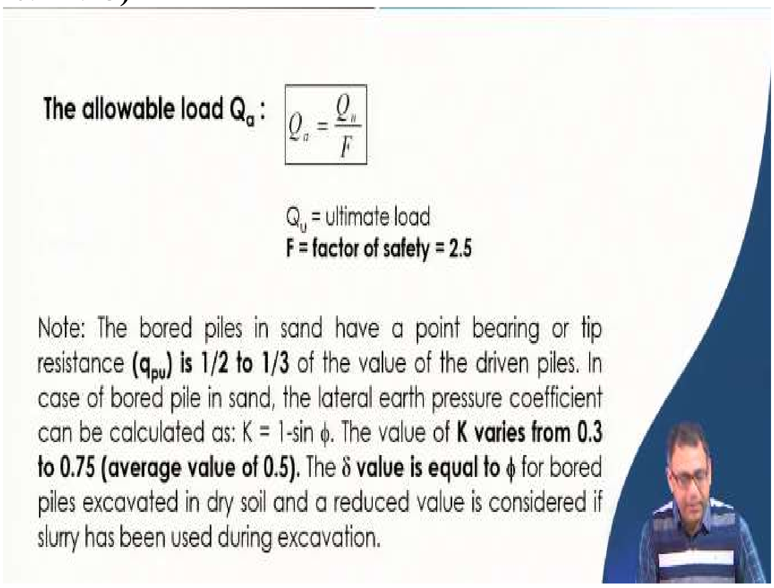

So, now, once you calculate the friction resistance and tip resistance and you add them then that will give you the ultimate bearing capacity of the pile and divided with the factor of safety that will give you the allowable load carrying capacity of the pile. Now, those equations are given for the driven pile. Now, for the bored pile the tip resistance is $\frac{1}{2}$ to $\frac{1}{3}$ of the tip resistance value that you will get for the driven pile.

And in case of bored pile in sand the lateral earth pressure coefficient can be calculated as $K = 1 - \sin\phi$. So, the value of K varies from 0.3 to 0.75 average value is 0.5, and δ value is generally taken as ϕ for the dry soil and if slurry is used during the excavation, then we have to reduce the value. So, that means for bored pile excavated in dry soil we can take $\delta = \phi$ and average K value is 0.5 this is for the bored pile.

And for the tip resistance, bored pile tip resistance varies from $\frac{1}{2}$ to $\frac{1}{3}$ of the tip resistance of driven pile. So, now quickly I will solve one particular example problem so, to calculate the friction resistance and the tip resistance for the sand and later on I will also solve one problem related to the clay.

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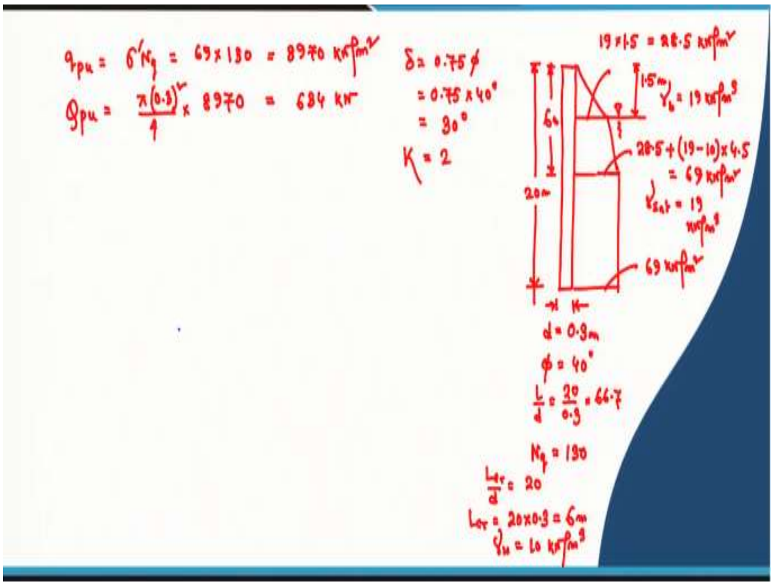

So, this is the pile, so, it is in homogeneous layer, but the water table position is at 1.5 m from the top and the total pile length is 20 m. So, diameter of the pile is 0.3 m, friction resistance is 40°. Then $\frac{L}{d} = \frac{20}{0.3} = 66.7$ so, corresponding N_q, as per Tomlinson's method, so, you can see as per Tomlinson's method, so, ϕ is 40° this is along here, so, this value will be around 130. So, N_q value will be around 130, if I use Tomlinson's method, so, N_q is 130.

So, now here it is a 40° means it is a dense soil, so, as I mentioned up to 40° to 41° it is a dense soil. So, for the dense soil, $\frac{L_{cr}}{d}$ is taken as 20. So, the critical length, L_{cr} will be 20 × 0.3, so that will be equal to 6 m, so, up to 6 m it is a critical depth of the pile after that, the effective overburden pressure will not increase or change. So, if I draw the distribution, so, this is up to the water and then this is up to critical depth, so, after that it will become uniform.

So, this is the effective overburden pressure distribution. So, here γ_{bulk} is given as 19 kN/m^3. And γ_{sat} is given as 19 kN/m^3, so, both γ_{bulk} and γ_{sat} are given as 19 kN/m^3. So, in this portion that means at 1.5 m below the ground surface the stress is 19 × 1.5. So that will be equal to 28.5 kN/m^2, at critical depth point the value will be that 28.5.

Now, it is below the water table + (19 – 10) × (6 - 1.5), so, this will be 4.5 m. So, you need to take the unit weight of water as 10 kN/m^3, so, this 69 kN/m^3 will continue up to the tip of the pile. So, now tip resistance of the pile q_{pu}will be $\sigma' N_q$. Now, σ' is here 69, so that is 69 × 130, so that is equal to 8970 kN/m^2, so which is within the limiting value. So, Q_{pu} is the total tip resistance.

So that is tip area which is $\frac{\pi d^2}{4} \times 8970$, so which is 634 kN. Now, we have to calculate the friction resistance, now, here we are taking $\delta = 0.75\phi = 0.75 \times 40°$, so, this is 30° and for dense soil it is concrete pile, say, so, dense soil *K* value is 2. So, for the loose soil *K* value is 1, dense soil is *K* value is 2, if the soil is in between that means, here it is 40° for $\phi = 40°$, *K* value is 2, 40° and above. And 30° and less *K* value is 1 for concrete pile.

So, if the soil is in between 30° and 40° then you can take *K* value in between 1 to 2 for concrete piles accordingly. So, now, this is the *K* value. So, in the next class I will discuss that how we can determine the friction resistance? Because I have discussed the tip resistance and I have also discussed the pressure distribution along the pile considering critical depth concept. And in the next class I will discuss how we can calculate the friction resistance and then we have to calculate the total load carrying capacity of the pile. Thank you.