Advanced Foundation Engineering
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Lecture - 19
Pile Foundation Load Carrying Capacity-III and Settlement Calculation

In last class a class on pile foundation lecture I have discussed about the bearing capacity calculation of a single pile, and then group pile. Now, today I will discuss about the bearing capacity calculation for the under reamed pile; and then how to calculate the settlement of the pile. And then first I will go for the load bearing capacity of the under reamed pile.

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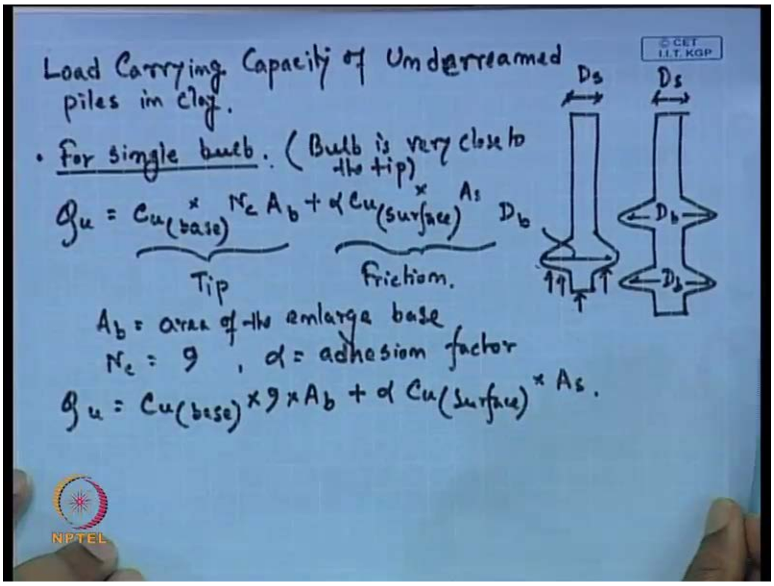

Now, this is the load carrying capacity of under reamed pile, so that means the load carrying capacity of the under reamed pile in clay. Because as I have already discussed the under reamed pile means where we will provide a bulb in the pile, or in the base, to increase the load carrying capacity of the pile. So, this is the bulb on different diameter, suppose this is the diameter of the shaft or this is the diameter of the shaft; and this is the diameter of the bulb. Similarly, this is the single bulb; this can be two bulbs also. Suppose, this is the, again diameter of the shaft or the pile shaft; this is the diameter of the bulb D b; and this is again the diameter of the path.

So, this is a single bulb under reamed pile; and this is double bulb under reamed pile. So, this is the two bulbs. Now, first I will discuss about the single bulb under reamed pile; that first one will the, for the single bulb. Now, for that purpose ultimate load carrying capacity of the pile Q u will be that C u cohesion at the base level C u at the base into N c into A b at the base plus alpha cohesion at the surface into A s. That means, this C u base is the cohesion at the base level, because this is the contribution from the tip, and this is the contribution from the friction, surface friction.

Now, here, this cohesion at the base level, N c is the bearing capacity factor, and area A b is the area of the base. Now, if this bulb is very close to this tip of the pile then we can consider this area of the base is basically the area of this enlarge portion; if this is, this bulb is very close to the tip of the pile, so then we can neglect this portion resistance. And here we are considering the, this tip resistance is basically in this portion which is the area of this enlarge portion; and C u is the cohesion at this base level, N c is taken as 9, as I have mentioned. And now finally if I write this expression that is C u at the base into N c is 9 into area of the enlarge base plus this alpha is the adhesion as the surface of between the pile and the soil. So, this is the adhesion factor.

So, this alpha value, this chart I have already given. So, from there we can calculate the alpha, alpha is the adhesion factor and C u, this cohesion and that cohesion is at the surface level of the bulb. So, this is the cohesion of the surface into A s is the, is the area of the pile shaft surface area, A s is the surface area of the pile shaft. So, this is the friction portion, this portion is the area of the, surface area of that shaft; and, this is the C u is the base cohesion, and A b is the area of the enlarge base. So, this is for single bulb if the bulb is very close to the, so first one if this bulb is very close to the tip. This is the first case or a single bulb pile, the bulb is very close to the tip.

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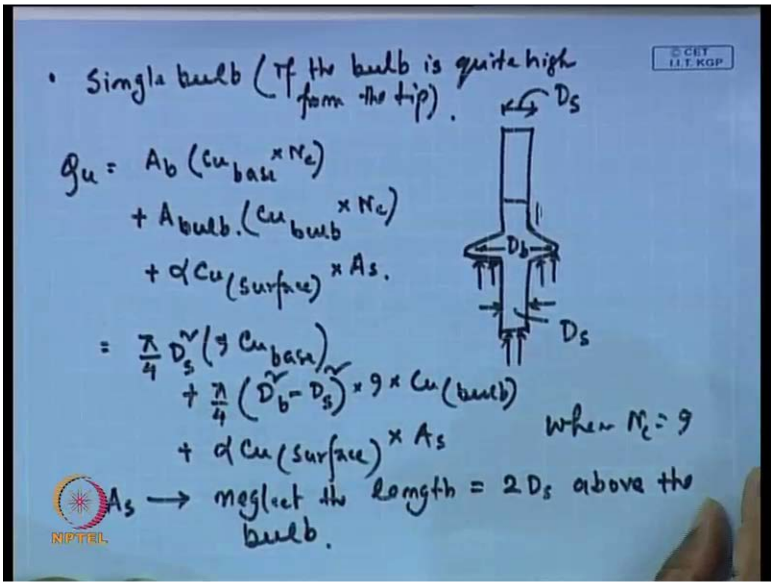

Now, if the single, this is the single bulb pile. Now, if the bulb is not very close to the tip, then how, what is the bearing capacity for the, or load carrying capacity of that pile? This is also single bulb, if the bulb is quite high from the tip. So, in that case, suppose this is the condition, the bulb is quite high, say, from the base of the tip, from the tip. So, we have the friction resistance at this bulb level we are getting.

And another tip resistance we are getting from the pile tip resistance. So, here we are getting, suppose this is the, again this is the diameter of the shaft and this is the bulb diameter D b. Now, we are getting this tip resistance, the tip of the pile and at this bulb level also, from this enlarge portion plus, when this bulb is very close to the tip of the pile then we are getting these we are considering, we are getting resistance only this enlarge portion of the bulb.

Now, for in that case, we can write that Q u ultimate load carrying capacity of that portion; this is the A b, area of the base; then C u, at the base level into N c; this is the tip resistance we are getting from the base; then plus, we are getting another tip resistance from this enlarge portion, so that is the A bulb or bulb level; this is A b base means this is the base level; this is the bulb level; again C u at the bulb level into N c plus the alpha into C u at the surface into A s. So, in that case we are getting the surface resistance or the friction resistance of the pile, as usual. When the tip resistance we are getting at the tip, tip level or the base level or at, and the base bulb level also. So, base level the area will be, if it is a circular pile then pi by 4 into D square, then into N c is 9 into C u at base level; and the area of the bulb level is pi by 4 into D b minus D s or this is also we can say this is D s because this one is also D s, D b by D s. So, this D b square D s square into 9 into C u at bulb level plus alpha C u at surface level into A s, area of the shaft this outside area of the shaft.

Now, this, because this is the difference, because this, here we are getting only this area, this resistance we are getting from this enlarge portion not the center one because here already this pile shaft is existing. So, that is why this is D b square minus D s square into 9 because here, where N c were taken is equal to 9, same alpha is again the adhesion current.

Now, here that as the pile said is generally, when we calculate the A s, doing the calculation of A s, generally it is recommended the length of the shaft equal to 2 D above the bulb using neglected. So, neglect the length equal to 2 D s above the bulb, this is the; that means, when we calculate the A s, we neglect the 2 D shaft diameter, two times the shaft diameter above the length of the bulb that portion is neglected, because the reason is that due to the settlement, settlement of the, or during the settlement of this pile, it is some kind there is a separation, possibility of separation because of this bulb, during this region.

During this region above the bulb portion, this is separation between the soil and the pile, during the settlement because of this enlarge bulb. So, that is why it is recommended we neglect, this is better to neglect this portion, because here there is no contact between the soil and the bulb, and the pile. So, there we will not get any resistance from that portion. So, it will, it will be better if we have neglect this portion when you calculate the A s, during the calculation of frictional resistance.

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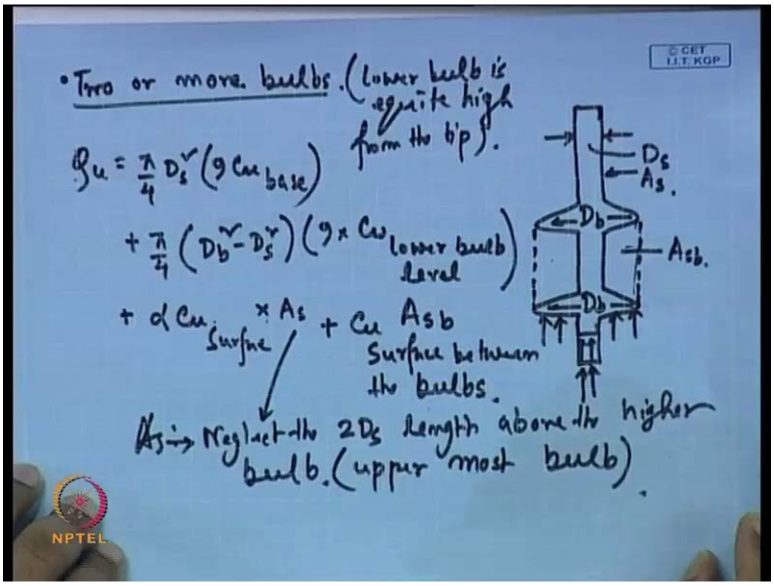

So, next one is the double bulb or the two or more bulbs. This case, this is for the two or more bulb, in this case, this is the, suppose one bulb, this is another bulb; again, this is the diameter of the shaft D s; and, if we consider same bulb diameter for the two bulb this will be D b. So, this is D b and this is the bulb, shaft. So, this is the two or more bulb, we are considering two bulb case here. So, bulb diameter is D b, shaft diameter is D s.

In such case Q u, so here we are getting the resistance, one is at the tip level and it is, it is suppose this bulb, the first bulb D s bulb is quite high from the tip of the pile, so that means, we will get resistance from here, and another resistance we will get, we will get from this enlarge portion. So, here also the lower bulb is quite high from the tip of the pile. So, first we will calculate this resistance. So, this is pi by 4 D s square, again N s is 9 into C u at base level.

So, this is the C u at base level, this tip level plus we will get this resistance from this enlarge bulb portion. So, that is pi by 4 into D b square minus D s square into 9 into D u at lower bulb level, these are the base level or the tip level, this C u is at the lower bulb level, then you will get the resistance. So, here we will get the, this is the, for the tip resistance or base resistance. Now, we will get the friction resistance. So, friction resistance as usual for the shaft we will get. So, this is for the alpha into C u at the surface into A s as usual. So, this is the adhesion factor, plus here additional one, if I take this is the cylinder, one cylinder we consider so that tip resistance we are getting at this tip, and the another resistance we are getting at the due to this enlarged bulb, and the shaft resistance you are getting from the upper shaft, and this from the lower portion during the two bulb, if we consider one cylinder we are getting the resistance, from this two cylinder, these cylinder or for the due to this two bulbs movement. So; that means, another resistance we will get, that is C u at the surface between the two bulbs, this is the surface C u at the surface between the bulbs, then we will get the surface A s at bulb between the bulb.

So, this is the area of the A, this area is basically this one is A s b; here, this is A s, this is the base, and this one the enlarge portion. So, again, when we calculate the, here the C u dash we take the average cohesion, during this shaft and average cohesion or A s b during this C u the surface between the two bulb, here this is the average cohesion in this region. So, again when we calculate this A s, we neglect the 2 D s length, when we calculate this A s during the A s calculation, then again neglect the 2 D s length, above the higher bulb. Now, the higher bulb we are getting, this A is basically the resistance we are getting from the shaft, above the upper most bulb, or a higher bulb, or the uppermost bulb; and, this A s this resistance A s b we are getting between the two bulbs, and then we get the tip resistance, and the, from this enlarge base resistance.

So, this is the total four parts, one is from the tip, one is from the enlarge base resistance, one is for the shaft resistance above the upper uppermost bulb, and another is the shaft resistance between the two bulb, this four part we are getting when we calculate the ultimate load carrying capacity of the under reamed pile, for the two or more piles, for this type of array unit. So, if there is a three bulb, then also it will get the, this lower bulb is all the things same, when we calculate the A s b then we will get the, this cylinder between the this three bulbs. So, in this way, we can determine the load carrying capacity of the under reamed piles.

The next section, we will go for the settlement calculation of the pile, any way we have to calculate, how to calculate the settlement of the pile, so that means, the settlement of the pile in group.

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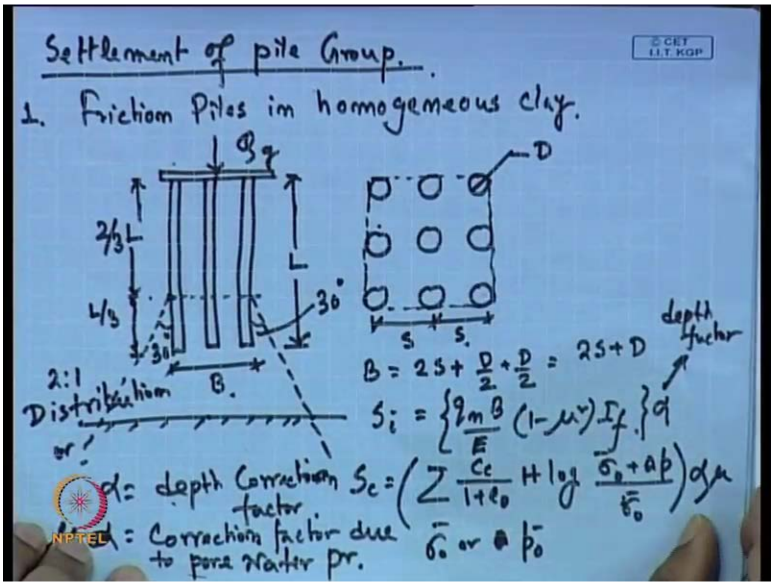

Now, first one, for the first case, suppose for the displacement piles or friction piles in homogeneous clay. So, first pile, first the pile is, suppose this is the homogeneous soil, this is the pile cap, this is the Q in the group, and where, this is the length of the pile L, and which is installed and the pile, so this is L. So, now, this arrangement is say, this is the 3 by 3 pile group arrangement. And this one is B say, now here the center to center spacing between the pile, say S, and this is the diameter of the pile. So, this is the diameter of the pile. So, the B value will be, the B value is basically for, if I take the total block, B value will be for this particular case, is twice S plus because this is the half D by 2 plus D by 2. So, this will be twice S plus D, D is the diameter of the pile, S is the spacing between the two piles.

So, now, if we, in such case, how to calculate, so this is the homogeneous clay which is, the piles are installed within this homogeneous clay. Now here, it is recommended that we have to take the, as if this total B load is transferred at this level. So, distance from this level is, from the top is L 2, L 2 by 3 into L, and this distance is L by 3. So, as if all the load, all this Q load is transferred at this level, then it is distributed into the ground. So, this distribution can be two is to one distribution, or this angle can be 30 degree, this is the one is to two distribution, or this angle can be 30 degree. So, this one is also 30, and this one is also 30 degree.

Now up to how much you have to consider this? Now, it is the same technique of this settlement calculation for the, suppose one rapt foundation or math foundation which is placed at depth of two third L, in the top of the pile, and then the load is acting on the rapt is Q g, width of this rapt is B, and which is distributed this load. And now, this extension will be up to twice B, for the settlement calculation, as it is mentioned during the calculation of settlement, for the rapt foundation. So, this extension of the B will be upto twice, extension of this influence zone, up to twice B of the pile.

Now, this is the, now we can calculate the spacing, if there is a, another pile is there and this will be 3 S plus D. So, then this total influence zone will be twice B, and then for if it is a, then every other center point of that influence zone, or we can divide that part into number of segment, and each segment center we have to calculate the set stresses, and then we will calculate the settlement, as we have discussed for the same, as for the rapt settlement. As if that rapt is placed at a depth of twice, two third L from the top of the pile, and then it is this load is distributed, at this two is to one distribution, or at a angle B angle 30 degree. Now, the calculation of the settlement, the same as for the immediate settlement S I, this value will be again, this q n, q n into B by E 1 by mu square into I f is the influence factor. So, those things are same as the shallow foundation rapt bearing capacity calculation, now here, you have to again multiply it by the depth factor, the alpha, where alpha is the depth factor.

So, depth factor, you have to multiply it by the depth factor, in case of immediate settlement, and in case of confidential settlement, we have to be alpha multiplied by the depth factor, as well as the pore water pressure correction. And for the consolidation settlement, as this is the summation say C E 1 plus E 0 H log sigma 0 bar or del 0 bar into del P by sigma 0 bar, sigma 0 bar or P 0 bar. So, this sigma 0 is the effective over burden pressure at any point, and del P is the increment of stress due to the application of this load. So, again here, we have to multiply it by alpha and then the mu. So, there alpha is the, alpha is depth factor correction, depth correction factor, and mu is the correction factor due to pore water pressure, due to pore water pressure. So, these are the due to…

So, these two corrections we have to apply. Now, this how to calculate this depth factor, this is mu. How to calculate this depth factor, depth correction factor in mu correction factor, due to over burden, or pore water, due to pore water pressure; these things I have already explained, during the calculation of a given calculation of the rapt foundation.

The same way you have to determine this depth correction factor, and correction factor due to overburden pressure. And in the same process, we have to multiply this correction factor with the correction settlement, that we will get for the consolidation settlement, and then for the immediate settlement, we have to apply only the depth correction factor, because here we will not apply the consolidation, I mean correction factor due to the pore water pressure.

So, then the total settlement will be the immediate settlement plus consolidation settlement, then that should be within the permissible limit. So, in this way we have to… Now, if there is any hard stratum, within any layer. So, in that case, we have to go up to that hard stratum, not up to twice because within that soil we will be settled, this hard stratum will not be affected. So, we have to go up to the hard stratum, from this two third L from the top of the pile up to that hard stratum that will be the influence zone, same as the, their foundation settlement calculation.

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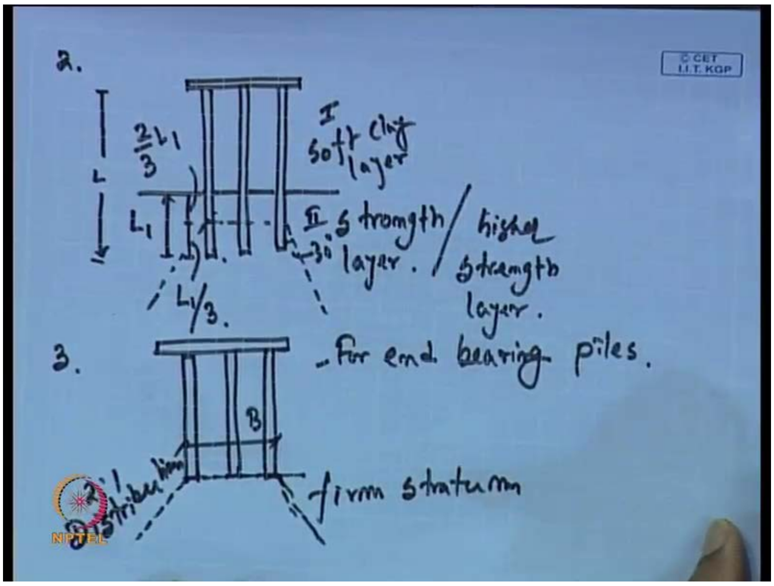

Now, this is for, the first case, if the friction pile is in the homogeneous clay. Now, the second case, we will go for the next one, the second case. Now this is the pile, pile cap which is installed in the soil. Now, this is a layered soil, this is different layer, this is one layer, and this is the soil, is this is the clay layer, or soft clay layer; and, this is the second layer, this is strong layer, now this strong layer or the higher strength layer, this soft layer, strong layer. So, these are the two different layer, layer 1 and layer 2. Now, in the strong layer of the bearing layers, suppose the pile is, length is L or L 1, now the total length is say L, from that L, L 1 is within that strong layer, or layer 2.

This is the soft layer, or this is the high strength layer, we can say this is higher strength layer, this is the higher strength layer. Now, here the distribution will be at this level, that that is this will be the distribution layer. So, this distance is L 1 by 3, and this distance is, two third by L 1.

So, previous case, if the pile is inserted in a homogeneous soil, in the clay layer. So, in that case, this is the distribution point, it will start two third of the total length of the pile from the top. Now, if this is the upper layer is soft, and lower layer is strong layer, or this is the higher strength layer, then the distribution level is start, the two third of the top of the stronger layer from that point, the distribution is same as two isto one distribution, or this angle is say 30 degree, and then the process is same, as I have discussed for the first case. So, only difference here, only this is the two third of the L 1, not two third of total length.

In third case, suppose it is the, both pile, or this is this pile is listing on a strong layer, or this is the end bearing piles. So, these are the, say n bearing pile, in previous cases, was pile in a soft clay; now, these are the end bearing piles for. So, now this is the firm stratum. So, this one is firm stratum. So, now, that firm stratum, now this equivalent rapt, because here equivalent rapt is acting at this level, now here equivalent rapt will act within this one is D, now here this equivalent rapt will act at the base of the pile, then the distribution is same 2 is to 1 distribution, or this angle is 30 degree. So, this will be either 2 isto 1 distribution, 2 isto 1 distribution. So, these are the cases by which we can determine the settlement of the pile group, and then we have to check whether that settlement will need the permissible limit or not.

So, next we will go for some empirical expression, by which we can determine the settlement of the pile, if we know the settlement of the single pile.

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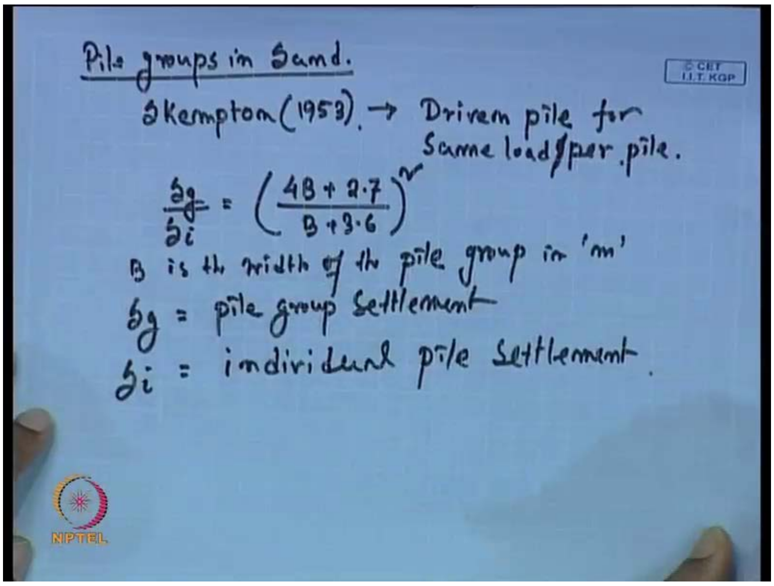

Now first one, this is the if the pile group is in sand, because in the previous calculation, in the previous calculation the pile group are mainly in the clay soil. Now here the, if the pile group are in sand, then how to calculate the settlement from that, on this proposed expression.

Now, the Skempton 1953 suggested that for the driven pile, driven pile for same load per pile; that means, per pile; that means, all the piles are taking same load, in that case S g settlement for the group, divided by individual settlement is equal to 4 B with a width of the pile group, plus 2.7 into B plus 3.6 whole square.

So, where B is the, of the pile group in meter, so here B is the width of the pile group in meter, and S g is equal to pile group settlement, S i is the individual pile settlement. Now here, the advantage of this expression, if I found a single pile load test, if I know the settlement of the pile, individual pile, then by using this expression we can determine, what will be the settlement of the pile group.

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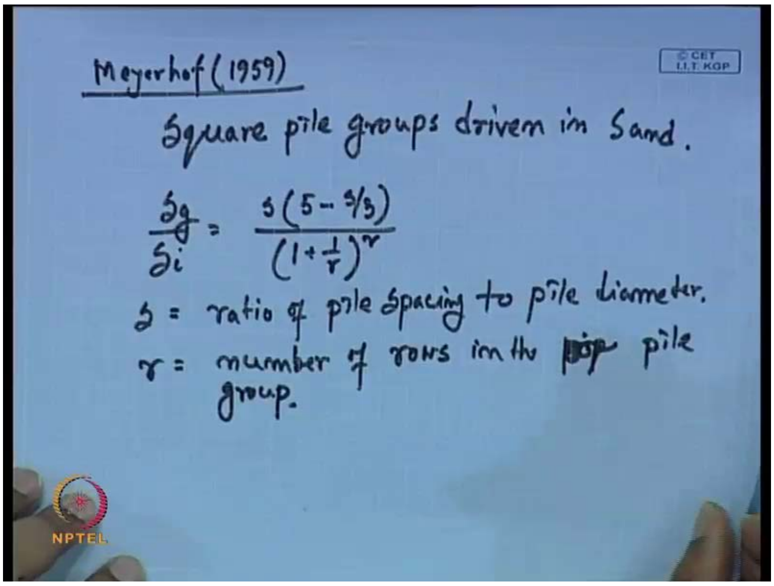

Now, second expression is given by the Meyerhof 1959. It is for the square driven pile in sand, sand. This is again S g divided by S i is S 5 minus S by 3 divided by 1 plus 1 by r to the power square, where S is equal to ratio of pile spacing to pile diameter, so that means, this is spacing versus diameter ratio, and r is the number of pile or row in the pile group. So, r is the number of rows in a pile group, and S is the ratio of piles spacing in the pile diameter. So, this is the, we can say, that if I replace this S by, this is the small r or, this is the, S is the ratio or the pile spacing in the pile diameter. So, these are the different expression by which we can determine the settlement of the pile group in sand.

So, next one, now, till now I have discussed about the ultimate load carrying capacity of the single pile group pile, then for the under reamed pile, then the settlement calculation, the next, this chapter I will explain the negative skin friction of the pile, then how to calculate the negative skin friction of the pile. Negative skin friction we are talking about, now the load carrying capacity of the pile, and the pile, and then we are talking about the friction resistance that we are getting from the surrounding soil of the pile. Then here the resistance that we are getting the, if the pile load is acting downwards, the resistance will act in the upward. So that means, that will give us the resistance of the load, against the load. But the negative skin friction, it will act in same direction of the load, so that means, here, we will not get any resistance, it will act as a load on the pile.

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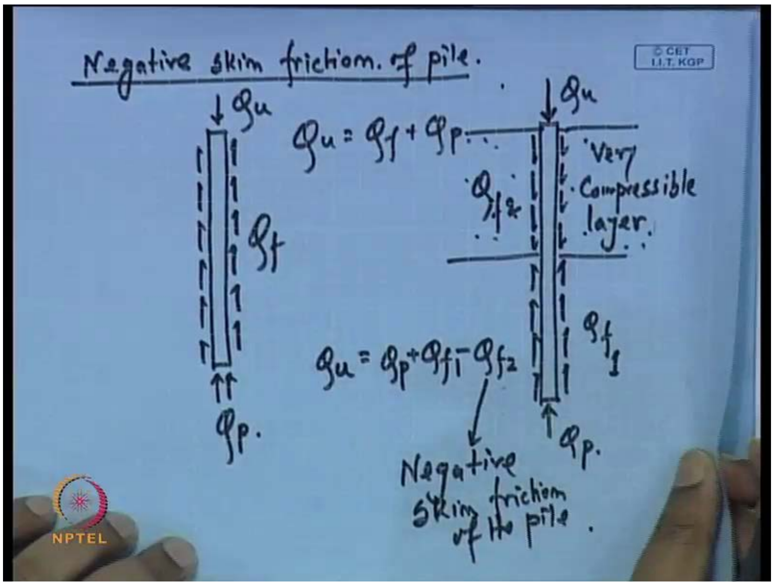

So, in, suppose in, this is the, if I go for the negative skin friction, suppose we see here, this is the pile, normally, if you will apply the load, this is the Q, apply that load Q u here. So, here we will get the tip resistance, and here the friction resistance that will act in the upward direction, because the pile will settle in the downward direction, and the resistance that will act in the upward direction.

So, that means, the, this is the friction part Q f, and this is the tip, tip resistance. So, the, our Q u will be Q f plus Q p, this is that additional pile load carrying capacity calculation. Now if, one pile is this one, and this is a load is Q u is applied, and suppose upto this level from here to here, this is very compressible layer is existing, so that means, this is the very compressible layer. So, what will happen that, here the, that means, the if the pile is moving downward direction, so the resistance were getting in the upward direction. But here, due to very compressible nature of this pile, suppose this portion is filling soil is there, which is very loose. So, during this installation of the pile this, there, so when you will apply the load, now that this soil, the settlement of this soil, this compressible layer is more compared to the settlement of this pile.

So, what will happen? If I consider the relative displacement between the, this soil and this pile, then compared to this, as this settlement of this soil layer is more compared to the settlement of this pile. So, as if the relative settlement, the soil will settle more, pile will settle less. So, the friction resistance that we are getting, it will not act in the upward direction, it will act in the downward direction. Because with respect to soil and this pile, as if the pile is moving in upward direction, because the soil settlement is more compared to the pile settlement. So, the relative displacement, we will consider, as if in this region compared to this soil, the pile is moving in the upward direction, because of this high settlement, of this compressible layer. So, here, in, this layer is as usual soil layer. So, here you will get the resistance that will act in the upward direction, and this is as usual the tip resistance. So, here we will get the resistance in the upward direction. But here we will get the resistance in the downward direction, as compared to this two soil, soil layer and the pile, the pile is moving in the down, upward direction. So, we will get the resistance in the downward direction.

So, now if the resistance of this part is Q f, for this resistance Q t is the tip resistance, and this is for the Q f 1 is the resistance we are getting from the resistance, this is the negative, negative skin friction is Q f 2. So this one, this friction, now it will not give any resistance, it will act as a load in the pile, because it is acting in the downward direction.

So, we can calculate, this Q u will be Q p plus Q f 1 minus Q f 2; that means, we are losing some resistance or load from, due to this negative skin friction. So, this Q u f 2 is called the negative skin friction of the pile. So, now, we will calculate. So, we know how to calculate Q p for different soil that we have already explained, how to calculate Q f 1 that is the friction resistance here Q f, then how to calculate Q f 2 that we will discuss in this section. Suppose, this section, this L 1, and from this L 1, how to calculate the negative skin friction, in single pile.

So, first we will go for the negative skin friction for the single pile. This is for the, first we will go for the single pile, to calculate this negative skin friction. So, then first case, we will go for this cohesion soil or cohesive soil. So, this one is the cohesive soil, where we are considering that phi is 0.

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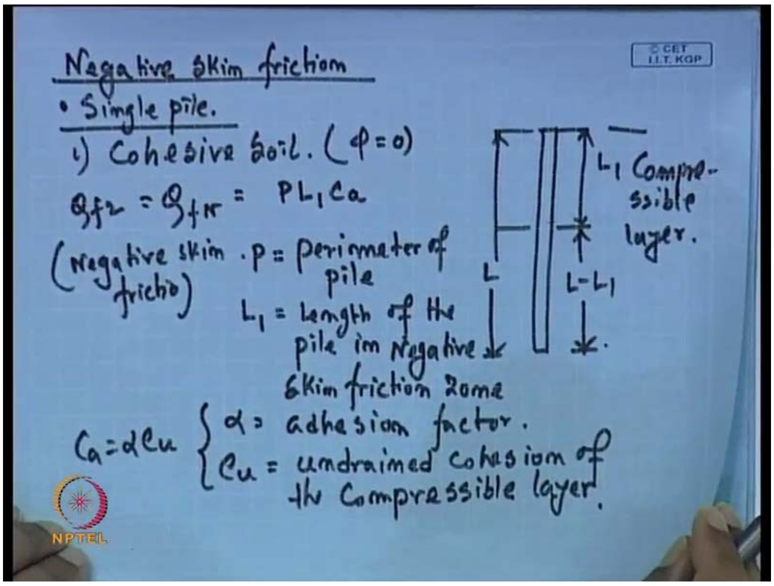

So, this, suppose negative skin friction is Q f N, N is the negative skin friction. So, this is negative skin friction. So, this is, we can write, suppose this is the pile, upto this layer, upto this length, say L 1, there is a negative skin friction zone, and this is as usual the pile tip, as usual resistance we are getting. So, this is, this length is L minus L 1. So, this negative skin friction will get, this is the perimeter and L 1 and C a, where P is the perimeter of the pile, L 1 is the length of the pile in negative skin friction zone, alpha is the adhesion factor, and C u so that means, this C a is basically alpha into C u. So, here C a is the adhesion, and C u is the undrained cohesion of the compressible layer.

So, for, this one is compressible layer. So, up to this L 1, it is compressible layer, so that means, this is the negative skin friction, we are talking about negative skin friction, or initially as we have mentioned that is Q f 2. So, that is the negative skin friction we are calculating, this is the perimeter of the pile, within this compressible layer. This is the perimeter of the pile. So, this is the perimeter of the pile, and then L 1 is the length, and this is the adhesion the, for this layer, alpha is the adhesion factor, and C u is the undrained cohesion of this compressible layer. So, that friction resistance we are getting that is the negative skin friction. So, this one, we have to add with Q u, or that total resistance, we have to subtract this portion from the other part. So, this is the, for the cohesion cohesive soil.

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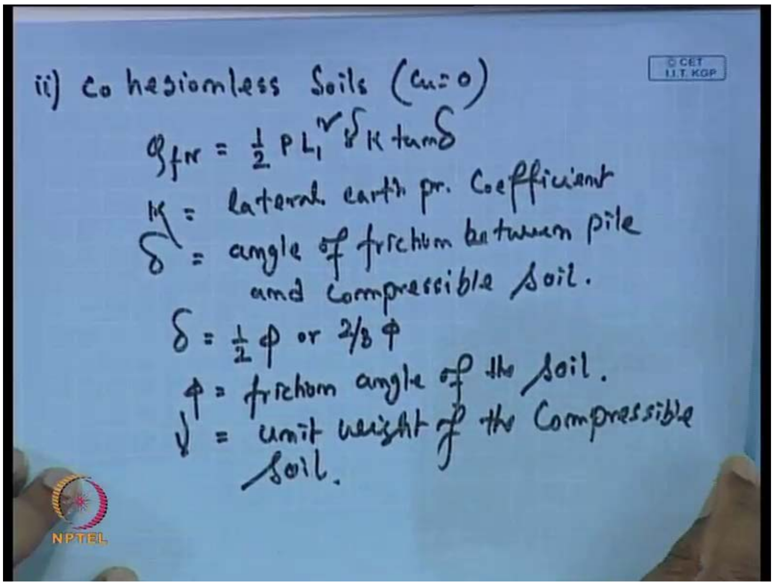

Now for the second one, is the cohesionless soil, or C u equal to 0. So, in that case, Q f N will be half into P is the perimeter, L 1 square into gamma into K into tan delta, this expression is same as the calculation of friction resistance for the cohesionless soil. So, where K is same as lateral earth pressure coefficient, delta is the angle of friction between pile and that compressible soil. Now generally, delta is taken half phi or two third of phi, where phi is the friction angle, between the, of the soil, of the soil, and P is the perimeter as of this pile, as I mentioned, L 1 is the length of that compressible layer, and gamma is the unit weight of the compressible soil, of the soil. So, this is the expression is same as…

So, this one is the negative skin friction, that will act downward not upward, so this will not give any resistance, this will act in the downward direction. So, now, the next one we will calculate, this is for the single pile. So, we will give for the group pile, or negative skin friction in pile group. So, next one is in the pile group.

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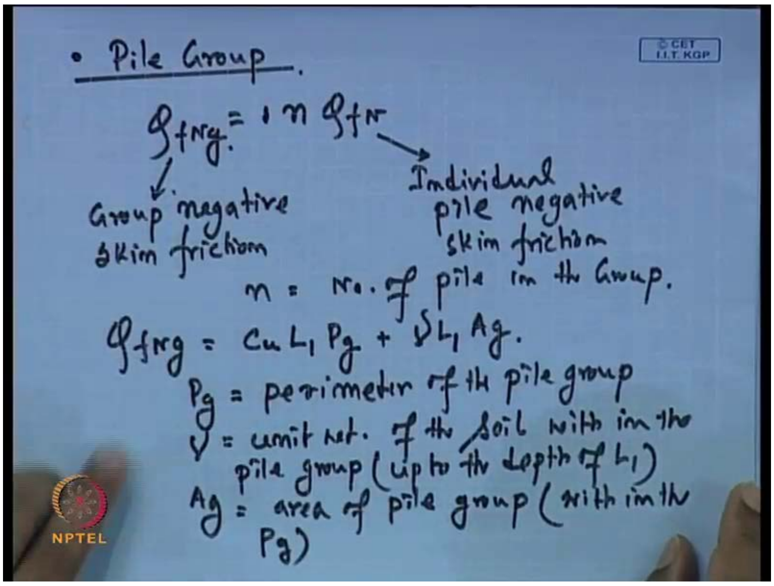

So, again this negative skin friction f N in the pile group, that will be equal to N into friction f N, so this is we can write group. So, this is the, for the group negative skin friction, this is for the individual pile, pile negative skin friction, and n is the number of pile in the group. So, same as this group friction, negative skin friction we can calculate, this is the C u L 1, this is the P g of the group plus L into L 1 into A g. So, this is C u for the undrained cohesion. So, here, P g is the perimeter of the pile group, then gamma is the unit weight of the soil within the pile group up to the depth of L 1, and A g is the area of pile group that is within, within the perimeter P g, or within the P g.

So, that means, this group friction, if it is friction we can calculate, this is the, if I consider the group as a block, then this is the perimeter of that pile group, then this is the length of this compressible layer into C u; and then because here we will not consider any adhesion factor because adhesion factor is basically is equal to 1, because this is the interaction between the soil and soil, because this we are considering as a group like the pile foundation in the group.

And then this is the, A g is the area of the pile group within the perimeter P g, and L 1 is the length of the compressible layer, and the gamma is the unit weight of the soil within the pile. So, this will give us the negative skin friction of the pile in group. So, then we have to calculate the factor of safety.

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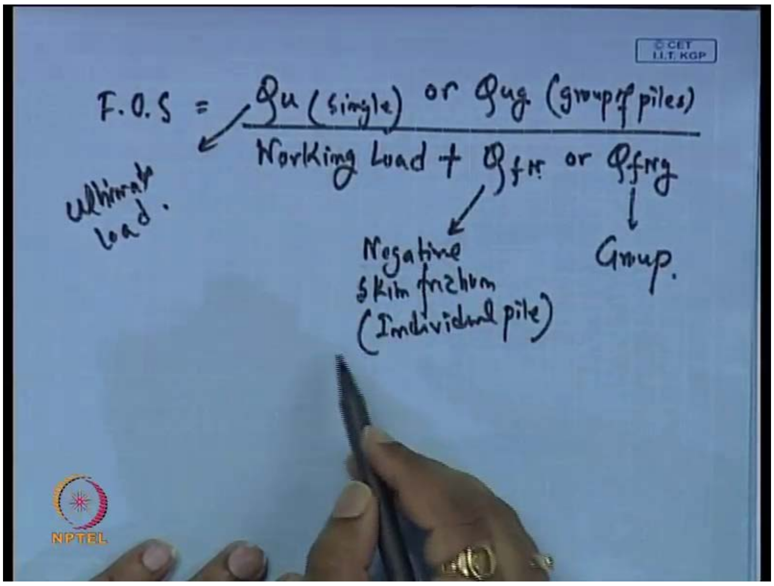

Now, factor of safety is the ultimate load carrying capacity of the pile in single, this is the single, single pile, or Q u g, or group of pile, divided by the working load, plus the negative skin friction, that is Q f N or Q f N g. So, this is for negative skin friction, friction, this is for the individual pile, and this is for the group. So, if this is the single pile factor of safety, and if we want to calculate, then this will be Q u divided by working load plus Q f N, this is the ultimate load, or this is we can say, this is the ultimate load; and if we are talking about the group pile, then this will be Q u g group pile ultimate load divided by working load plus Q f N g, and it is skin friction in group.

So, in this, where you have to calculate the factor, factor of safety; now if this, then this is again if it is a single pile failure, or the block failure, that we have to consider based on that we have to decide which one we will choose, either Q u, or Q u g, or Q f N. or Q f N g, because the same concept we have to use, when we, that thing we have discussed for the pile group. So, these are the, this way we have to incorporate the negative skin friction effect into our pile load carrying capacity design, now when you calculate the load carrying capacity.

So, this part, up to this we have discussed about the load carrying capacity of the pile, under compressive load; and then settlement calculation based on that. Now in the next section, or the next class, I will discuss about the load carrying capacity, or the tension pile, or that means, the uplift capacity of the pile. Thank you.