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Lecture – 47
Pile Foundation: Under Compressive Load - VII

So, last class I have solved one numerical problem to obtain the load settlement behaviour of the pile through analytical approach.

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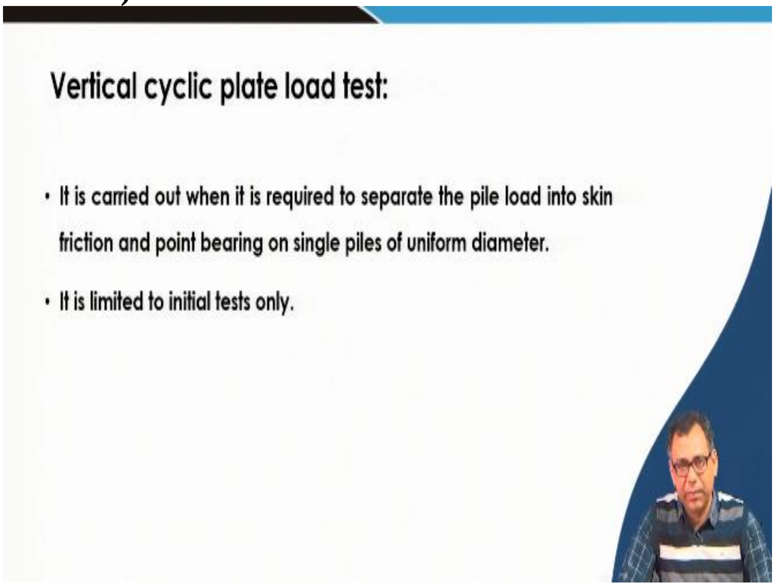

Now today in this lecture I will discuss that how we can determine the load carrying capacity of the pile based on other approaches. So, as I discussed that we conducted the plate load test and that plate load test was the static plate load test and where we increased the load in stages continuously. But there is another plate load test that I have discussed and that is the vertical cyclic plate load test where there will be loading, unloading and reloading.

So, the purpose of conducting that vertical cyclic plate load test is that, by conducting this plate load test, we can determine experimentally the tip resistance and the base resistance separately because the cyclic plate load test will give us the overall load carrying capacity of the pile. But by conducting vertical cyclic plate load test, we can separately determine the base resistance and the shaft resistance.

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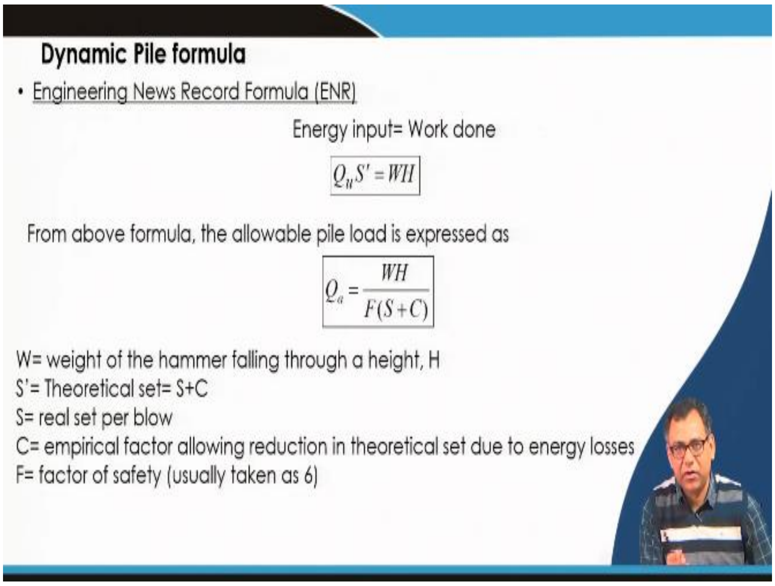

So, then we can use the dynamic pile formula by which also we can determine the load carrying capacity of the pile. So, there are several equations which are given. So, I am discussing two of them. So, the one is the engineering news record formula or ENR formula. And basically, here we are applying the hammer blow because it is done on driven piles and we have applied the hammer blow and then we apply the energy. And so that means the work done we have to equate with the input energy.

So that will be $W \times H$ because W is the weight of the hammer, H is the height of fall. So, that $W \times H$ will be equal to the load carrying capacity of the pile and the amount of the penetration or the deformation of the pile. So, both are equated. So, you have all these two equal values will give us that Q_a which is WH divided by the penetration and if we apply the factor of safety we will get the allowable load carrying capacity of the pile.

So, where W is the weight of the hammer, H is the height of fall and S' is the theoretical set which is $S + C$, S is the real set per blow that means generally some blows are and the penetration is recorded. So, we must determine the penetration for each blow. So, that is S that means the penetration per blow and C is the empirical factor. So, allowing the reduction in the theoretical set due to the energy loss and F is the factor of safety that means, if there is an energy loss that is taken care by the C which is an empirical factor. Generally, the factor of safety taken as 6 here.

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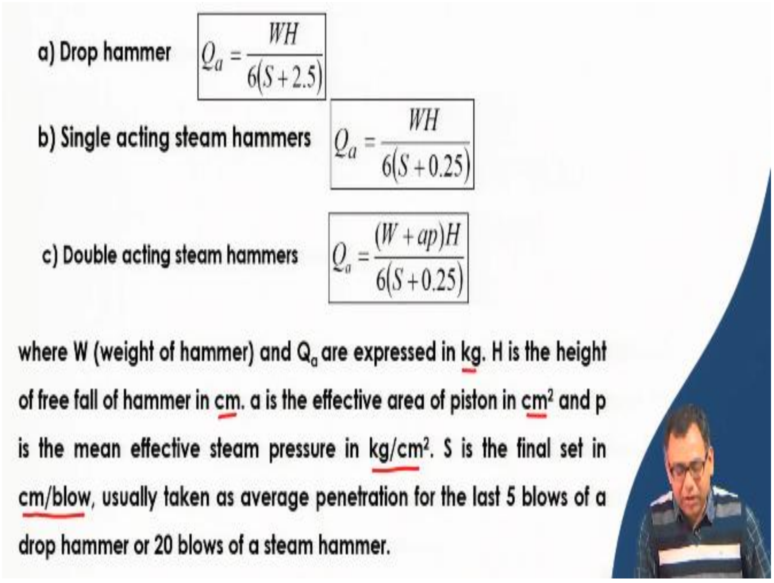

Now, this is the basic equation for different types of hammer. We can use this equation in different forms and that is for the drop hammer, single acting steam hammer, double acting steam hammer and these are the equations. But here we must use the proper unit. So, Q_a is in kg and H is in centimetre, remember that and here a is the effective area of the piston which is in cm^2, p is the mean effective stream pressure, which is in kg/cm^2, S is the final set in cm per blow. So, usually the average penetration for the last 5 blows of a drop hammer or 20 blows of steam hammer are taken as I have mentioned that and the average of the last few blows we must take. So, that means the average penetration for last 5 blows suppose like last 5 blows average penetration is 10 cm.

So, per blow penetration will be 2 cm or 20 mm, if the 5 blows penetration is 10 cm then it will be 2 cm per below or if it is 10 mm then it will be 2 mm per blow. So, this way we must calculate, so these ways we can determine the allowable load carrying capacity of the pile.

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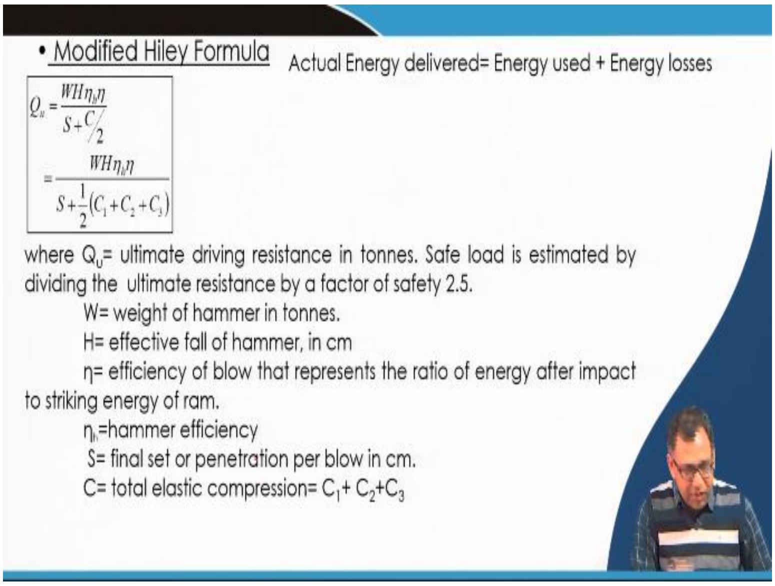

Similarly, there is a modified Hiley formula, where actual energy is equal to energy used and energy loss because previous also equation also energy lost is taken care by this empirical factor *C*. But here the total delivered is energy used plus the energy loss and based on that determine the ultimate load carrying capacity of the pile. So, again here *W* and *H* are the weight of the pile and the height of fall, respectively.

Then the factor of safety here we have to apply 2.5 and then η is the efficiency and that I will discuss how we can calculate the η, η_h is hammer efficiency and η is the efficiency of blows that represent the ratio of energy after impact of striking energy of ram. So, these two are the efficiency and *S* is the final set and *C* is the total elastic compression. So, elastic compression, so that is C_1, C_2, C_3. So, that means C_1, C_2, C_3, S is the final set and then η_h and η are the efficiency.

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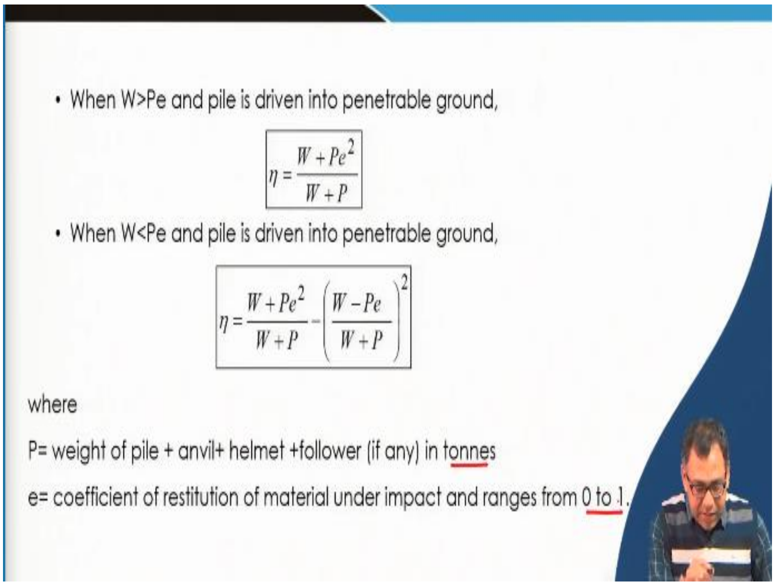

So, these ways we can determine the η, so this is if your P is the weight of the pile, I mean total weight of the pile including weight of the pile and helmet because we have to apply the helmet when you apply the follower, if any. So, including all this is the weight of the pile and this is in tonnes, e is the coefficient of restitution of material under impact and ranges from 0 to 1 we can take average value of 0.5. So now, if $W > P \times e$, then you have to use this equation and $W < P \times e$, then you have to use this equation.

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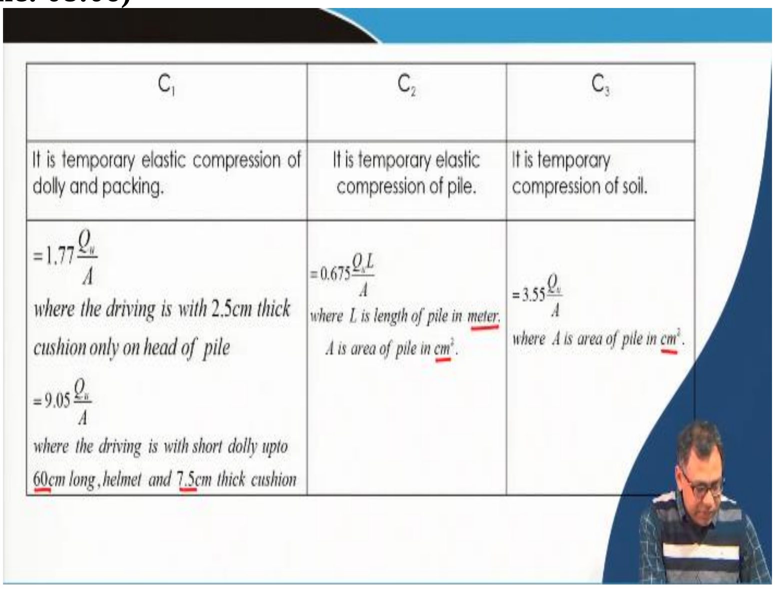

So, this way we can calculate the η and C_1, C_2, C_3 we can calculate by using these equations.

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Hammer type	η_h
Drop	1.0
Single acting	0.75-0.85
Double acting	0.85
Diesel	1.0

I am coming back but the η_h we can calculate from this table for drop hammer, single acting hammer, double acting hammer, diesel and this is the η_h value. The C_1 is that temporarily elastic compression of dolly and the packing, so the compression of the soil and the compression of the other components, so that summation is C. C_2 is the temporary elastic compression of the pile material. C_3 is that elastic compression or temporary compression of the soil and then this is the compression of dolly and the packing.

So, this way we can determine different compression of dolly and packing, if the cushion is on the pile head and which is 2.5 cm then we use this equation. And if the cushion is 7.5 cm, then you have to use this equation and then this is the equation for pile compression, this is the equation for the soil compression and so L is the length of the pile in m, area is in cm^2 because in all these empirical equations you have to use the proper unit.

So, this is cm^2, this is m, this is cm^2, so here also is cm this is cm. So, that you have to apply here. So, remember that when you apply there is a Q_u and we have to actually calculate the Q_u so both sides there will be Q_u. So, this will be a trial and error process by which we can determine the Q_u. So, then once you calculate the Q_u, then you apply the factor of safety of 2.5 and we will get the load carrying capacity of the pile.

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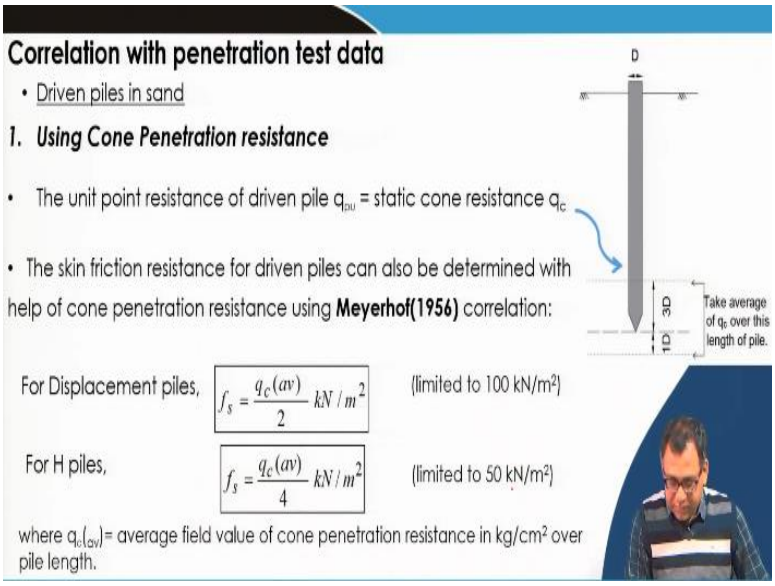

Then we can determine the load carrying capacity of the pile by using the penetration test data that mean by using cone penetration resistance. By cone penetration distance, if we take the average of 1*D* below the pile tip and 3*D* above the pile tip, total 4*D*, *D* is the diameter of the pile and the average cone resistance is Q_c that will give us the tip resistance of the driven pile in the average of 3*D* + 1*D*, 1*D* below the tip and 3*D* above the tip.

So, this average of 4*D* will give the static cone resistance and even though we have to do the static cone penetration test, so the average static cone penetration resistance Q_c will give you the driven pile tip resistance. Similarly, for displacement piles, what is displacement pile I have discussed? The driven piles are displacement piles where the soil is displaced laterally. So, for driven piles the frictional resistance will be average Q_c along the length of the pile divided by 2 in kN/m^2.

But it is limited to 100 kN/m^2. And for H pile this is $\frac{Q_c}{4}$ and limited to 50 kN/m^2. And remember that the average field value of cone penetration resistance is in kg/cm^2 over the pile length. So, this unit we have to use properly. So, because these are empirical equations so, that we have to use properly.

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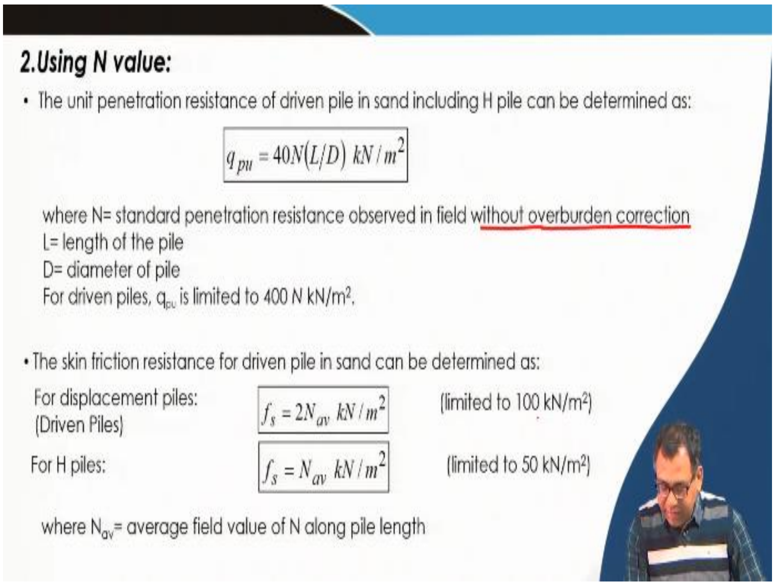

So, then by using N value also we can determine the tip resistance, so this N is the standard penetration value SPT value observed in field without overburden correction. I have mentioned in few cases we have to apply the overburden correction, so here overburden correction is not required and without overburden correction that N value. So, the unit penetration resistance is $40N\left(\frac{L}{D}\right)$, where, L is the length of the pile and D is the diameter of the pile. So, again this is limited to $400N$ kN/m^2.

Similarly, the skin friction value we can determine by using these two equations again for displacement or driven pile and for H pile. So, the average N value along the length of the pile is N_{avg}, so for the displacement pile it is limited to 100 kN/m^2 and for H pile is limited to 50 kN/m^2.

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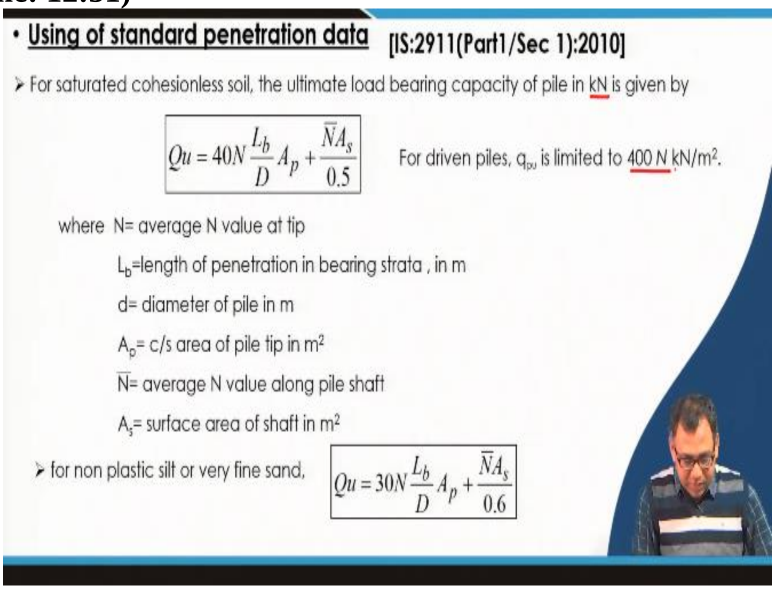

Similarly, IS code has also given equation by which we can determine the ultimate load carrying capacity of the pile by using a SPT value. So, here this *N* is the average *N* value at the tip and $\bar{N}$ is the average *N* value along the length of the pile or shaft of the pile, A_s is the surface area of the shaft and A_p is the base area of the pile. This equation is for cohesionless soil and this equation and for plastic silt or very fine sand we can use these two equations.

So, these Q_u is in kN and in these equations, first part is q_{pu} for driven pile and second part is for the friction resistance and that first part is limited to $400N$ kN/m^2. This way also we can determine the ultimate pile load carrying capacity.

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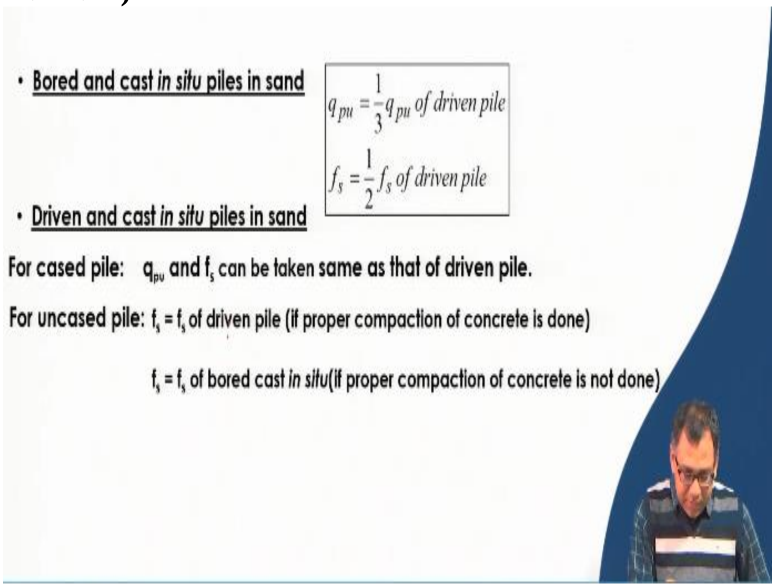

Similarly, for the bored pile because those equations are given for the driven piles. And so for the bored and cast-in-situ piles in sand that q_{pu} will be $\frac{1}{3} q_{pu}$ that we have determined by using the already discussed equations for driven pile and friction resistance will be half of the prescribed shaft resistance of the driven pile. But if it is a driven and cast-in-situ pile in sand, then if it is cased, then the q_{pu} and f_s are taken same.

And if it is uncased then f_s will be f_s for driven pile and f_s will be f_s of bored cast-in-situ pile. Here if the proper compaction of concrete is done the f_s will be equal to the f_s of the driven pile, if the proper compaction of the concrete is not done then we have to determine the bored cast in situ pile f_s that will be f_s in this case.

So, first one is a driven pile and the next one is the bored, if the compaction is not done properly then the bored pile, if the compaction is done properly then driven pile, so these are the equations.

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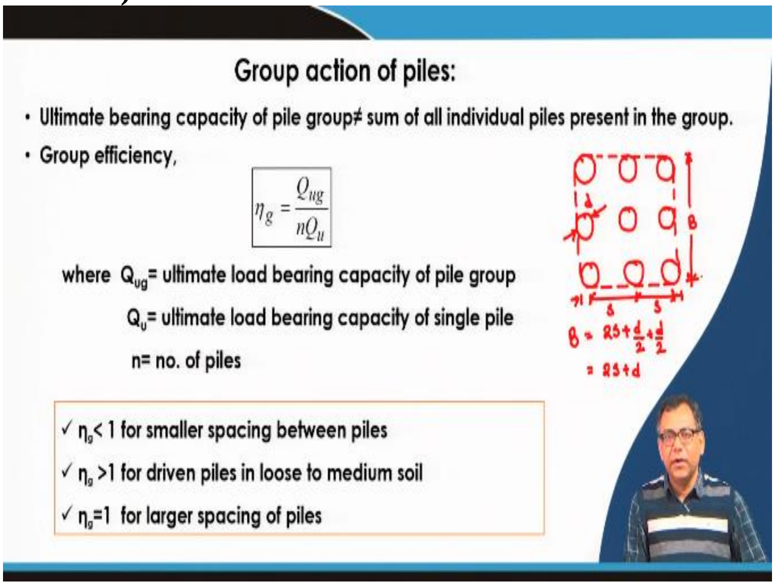

Then now I will go for the group action of the pile. So, suppose we have a pile group of 9 piles, so these ways we can determine the efficiency of the pile. So, first we have to determine the load carrying capacity of the pile group considering the block failure. Block type of failure means that total pile group will fail. So, considering that we will calculate the load carrying capacity of the pile group.

Then we will calculate the individual load carrying capacity of the pile and that we have to multiply with *n* where, *n* is the number of piles. Now, that if the spacing between the piles are very large then definitely the failure of the pile will be due to the individual pile failure because there will be less group interaction between pile to pile as the spacing is large. So, in such case the efficiency will be 1.

Now, if the spacing is very small then there will be an interaction between the pile to pile and your pile influence zone will also overlap with each other. So, the group load carrying capacity will reduce, so in that case the efficiency of the pile will be less than one. So, that means the if the spacing is large, then efficiency will be 1 because then the failure will be due to the failure of the single pile.

If this spacing is less than there will be group interaction and the efficiency will be less than one but there is a case when the efficiency can be more than one also. So, if the driven pile is used for loose to medium sand. So, in such case what will happen that due to during the driving up the pile, the loose sand the sand will get compacted, so its strength will increase. So, now, for the group pile as the pile will compact the soil and they will be increase the strength of the pile, so the group efficiency will increase.

So that increment will be more for the group because here the soil will be in the confined condition. So, when you apply the driven pile, so the soil surrounding the group and the soil within the group, both will be compacted. So, they will tend to increase the efficiency. So, that means in such case as a single pile that compaction effect will not be that significant. So, that mean the load carrying capacity of the pile for single pile × the number of piles will be less.

In case of group pile condition or block failure condition the total pile within the group or the total soil within the pile group will be compacted and there will be more compaction effect because of the surrounding piles and the soils within that zone. So, when the soil strength in that group pile condition will be more, so that means the density of the soil will increase due to the compaction, so that means our group efficiency will increase.

But generally, during design of the pile group we do not consider the efficiency more than one even if it is more than one, we will limit that value up to 1. So, now we will calculate the group efficiency as I mentioned that you have to calculate the pile load based on the single pile failure and then for group or the block failure and then you have to determine the efficiency or what would be the load carrying capacity of the pile?

So, we will calculate pile group capacity considering as block failure and as a single pile load carrying capacities then you have to multiply with the number of piles, so minimum of these two will be the load carrying capacity of the pile group.

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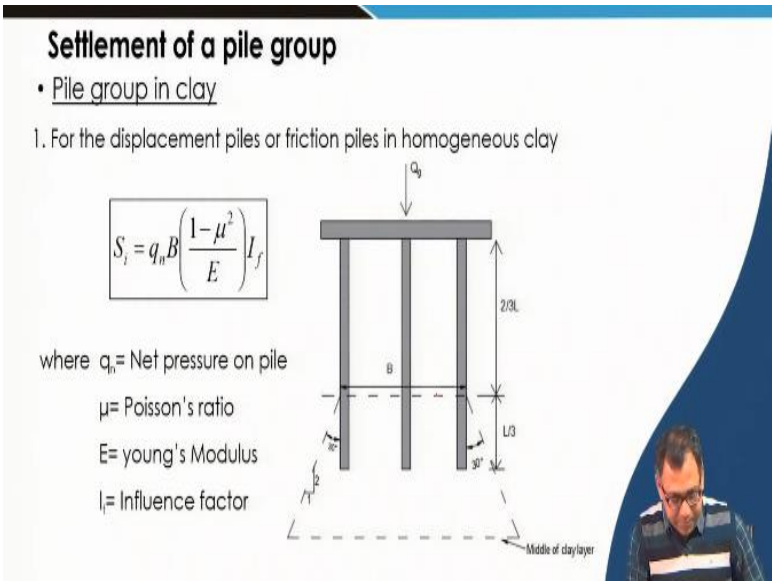

So, now the next one is the settlement of the pile group in clay because in the clay the settlement has a very serious effect and settlement we have to calculate in the clay soil because as we have discussed the settlement will have significant effect in your design if the soil is clay. Because in sand also will have the significant effect if the soil condition is not good, but most of the cases settlement we calculate for the clay soil because the clayey soil it will take consolidation settlement.

So, the settlement we have to calculate specifically for the clay soil, but for the loose soil also you have to calculate the settlement of the pile in sandy soil also, but clay soil the settlement is very crucial. So, now for this type of condition when the piles are installed in homogeneous clay then what we will do? We will consider all the piles are connected to the raft and that raft is placed at depth of the $\frac{2}{3}L$, where, L is the length of the pile.

Then we will calculate the settlement of that raft and I have already discussed how to calculate the settlement of the raft similar process we have to consider here but only that you have to place that raft at depth of $\frac{2}{3}L$ from the top of the pile. If it is homogeneous clay, then there will be 2 vertical : 1 horizontal distribution and then we will calculate the immediate settlement then you will calculate the consolidation settlement of the pile same as the raft design.

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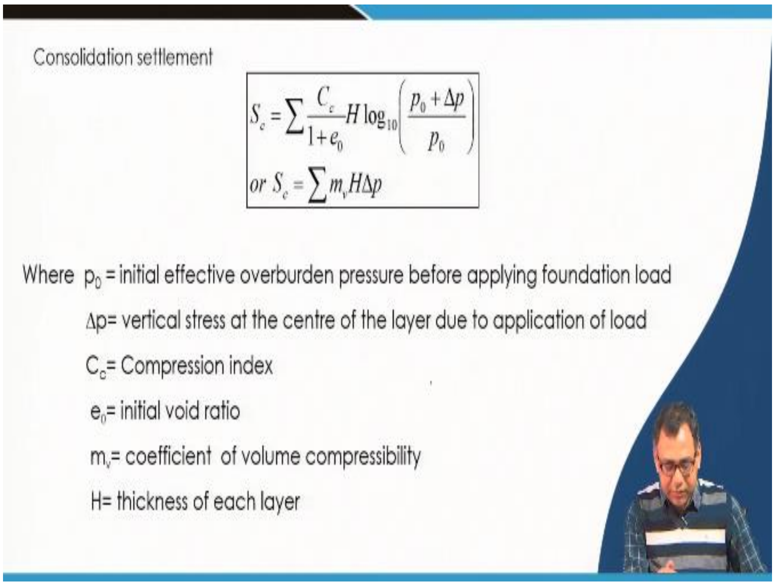

So, now, this is what considered is the settlement of the raft in case of shallow foundation.

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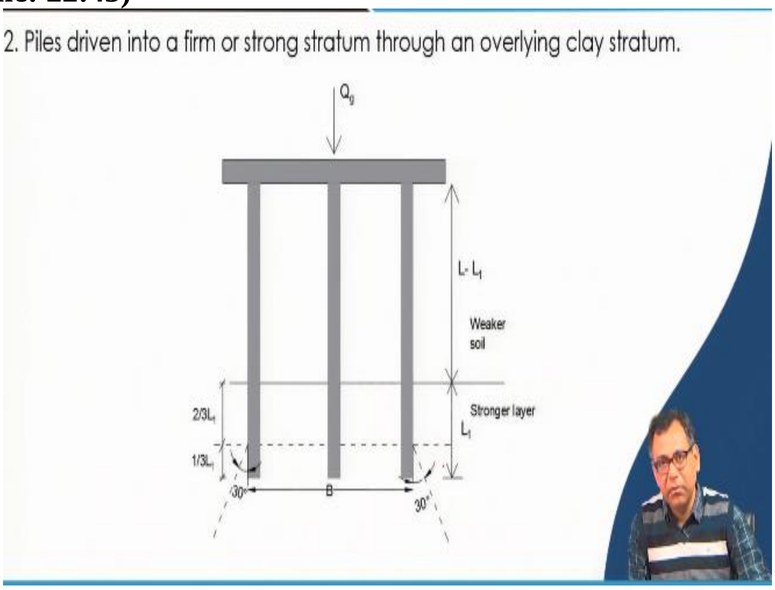

Now if the pile is resting in a stronger layer and the top layer is a weak layer then the raft we have to place at a depth of $\frac{2}{3}L_1$ from the top of the stronger layer and L_1 is the thickness of the stronger layer. So, suppose this is a weaker layer and this is a stronger layer, if the strength difference is not that much significant, then we will consider it as a homogeneous soil.

Because suppose one layer it is very soft clay for which C_u value is say, 30 or 25 kPa and the bottom layer which is a very stiff soil. Then definitely we will consider these conditions and, in that case, the raft has to be placed at a depth of $\frac{2}{3}L_1$ from the top of the bottom layer.

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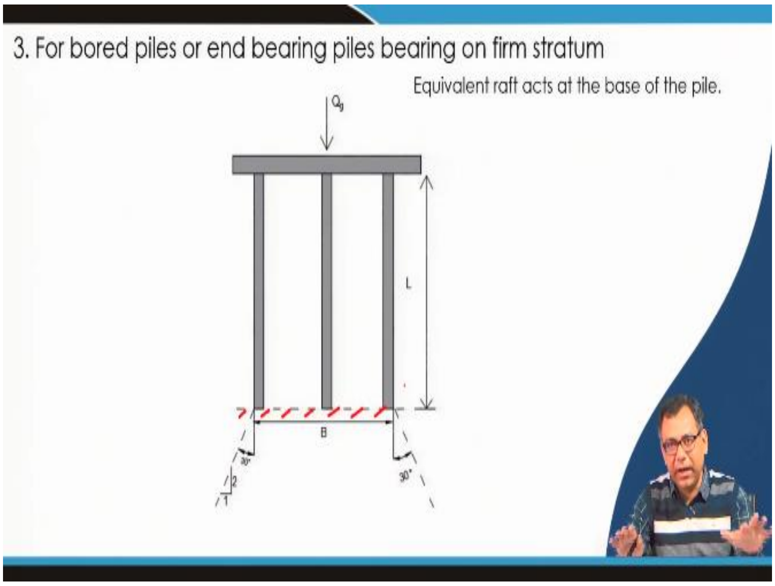

And another one is that the pile is resting on a strong stratum I mean this is a very strong stratum, where the pile is resting. So, in that case that raft we have to place at the base of the pile. So, this is a raft is placed at the base of the pile if the pile is resting on a very strong strata and then if the pile top layer is soft and the bottom layer is very stiff and the strength different is very significantly high. Then in that case, we have to place the raft at $\frac{2}{3}L_1$ from the top of the second layer which is the stronger layer.

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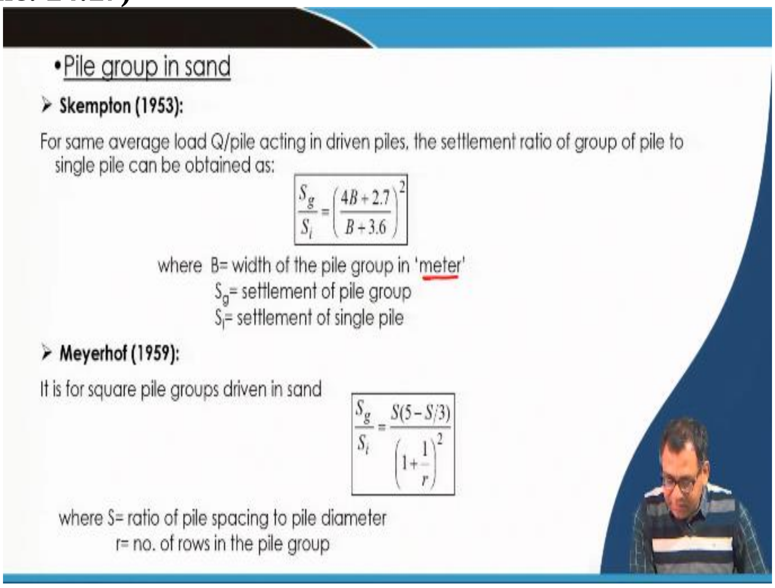

So, now pile group settlement also we can determine based on the single pile load test data suppose if I know the single pile settlement, then based on these equations we can determine the pile group settlement also. So, this is the settlement of the pile group, we can determine the settlement of single pile, S_i and B is the width of the pile group and this is the equation remember that we have to express B in meter.

Similarly, these also we can determine by using the approach or the equation proposed by Meyerhof this is the first one which was proposed by Skempton. What is the B value? B value is the width of the pile block in case of group pile, so that means if this is S, S is the spacing between the pile and d is the diameter of the pile and diameter of all the piles are same and spacing also same in both the directions.

So, that case B will be $2S + \frac{1}{2}d$ on this side and $\frac{1}{2}d$ on this side. So, this will be $\frac{1}{2}d + \frac{1}{2}d$, so that means $2S + d$, so that will be the B similarly, this side also this will be the B if it is a square pile. So, this way also we can determine the settlement of a pile.

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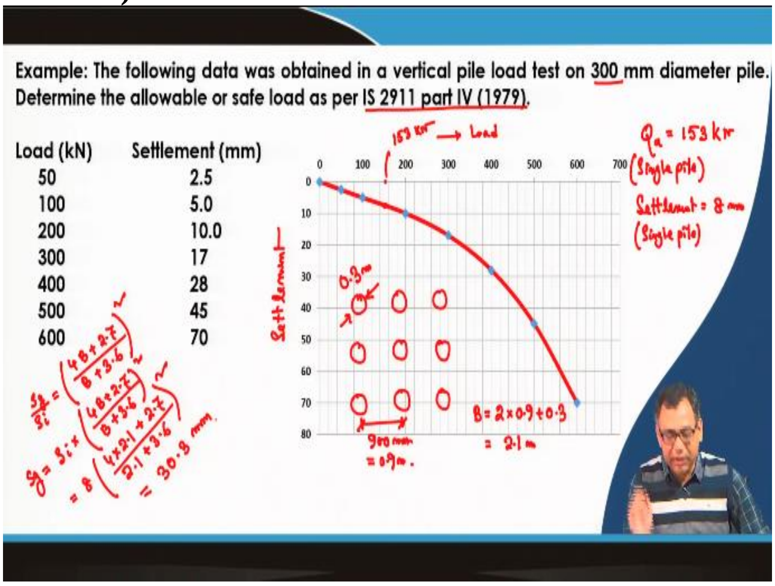

Now, I will solve one example problem, so the same load settlement plots are taken here that used to calculate the load carrying capacity of the single pile. So, that same load settlement curve I used here. So, this is the load settlement curve, so this is the load, and this is the settlement. So, in previous case the same problem, the Q_u for the single pile was 153 kN and that is the ultimate load carrying capacity of the single pile.

That was the allowable load carrying capacity because that is not the ultimate that is not allowable load carrying capacity of the pile. So, based on this IS code recommendation we have already determined the allowable load carrying capacity of the pile and that value was 153 kN. And then there is the same load settlement plot we have already used to determine the allowable load carrying capacity of the pile and that value was 153 kN.

So, now the settlement corresponding to 153 kN will be 8 mm it is 8 mm from the chart. So, this is 153 kN and corresponding settlement is 8 mm. So, that means, under the 153 kN load which is the allowable load carrying capacity of the pile the settlement is 8 mm and that settlement is for the single pile.

So, based on these strata, we can determine the settlement of the group pile by using Skempton equation or the Meyerhof equation. So, I am using Skempton equation. So, $\frac{S_g}{S_i} = \left(\frac{4B+2.7}{B+3.6}\right)^2$ and B is in meter and the pile configuration or group configuration is given here. So, it says square pile group where the spacing is 900 mm and diameter of the pile is 300 mm.

So, the diameter of the pile is 300 mm or 0.3 m, but here now it is a group pile. So, spacing is 900 mm or 0.9 m. So, here the B value will be as I mentioned that will be 2 × 0.9 + 0.3, so that will be 2.1 m. So, now that value if I put in this equation, this will be, so directly I can write the settlement of group that is equal to settlement of single pile × this value $\left(\frac{4B+2.7}{B+3.6}\right)^2$.

So, the settlement of the group is $8 \times \left(\frac{4\times2.1+2.7}{2.1+3.6}\right)^2$, so this value is 30.3 mm. So, the settlement of the pile group is 30.3 mm, when the settlement of the single pile is 8 mm. So, this way we can calculate the settlement of the pile group also. So, in the next class, I will show you our complete design of pile foundation in clay that means how to calculate the pile group load carrying capacity.

And then how to calculate the settlement of the pile in group and I will solve one numerical problem and then I will find that how considering settlement as well as the load carrying capacity we can design a pile group. Thank you.