Soil Structure Interaction
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Lecture-53
Soil Structure Interaction For Pile Foundation (Contd.)

In my previous lecture I discussed about the pile foundation and the 3 types of piles under different loading conditions (compressive load, lateral load and uplift).

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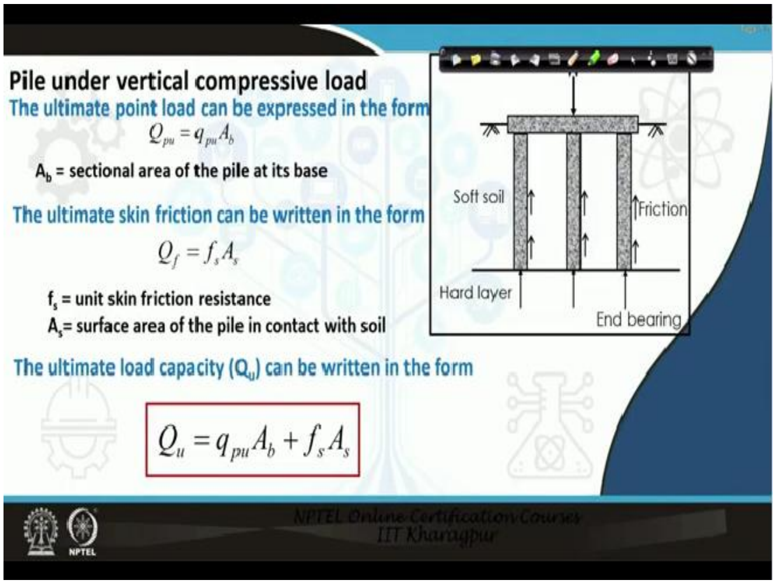

Then I discussed about the pile under compressive load where the load capacity will be obtained from both depth resistance and frictional resistance.

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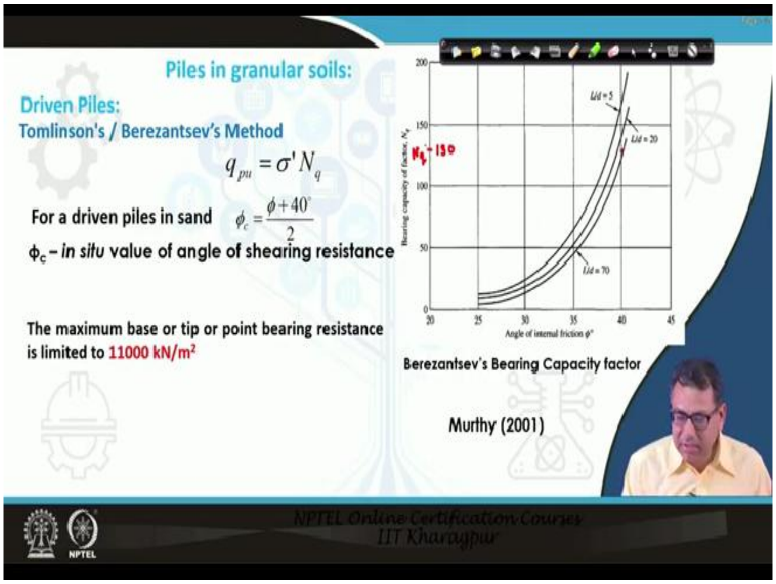

The correlation formula for the tip resistance in driven piles in granular was also given. The limiting value of the tip resistance was given as 11,000 kN/m^2.

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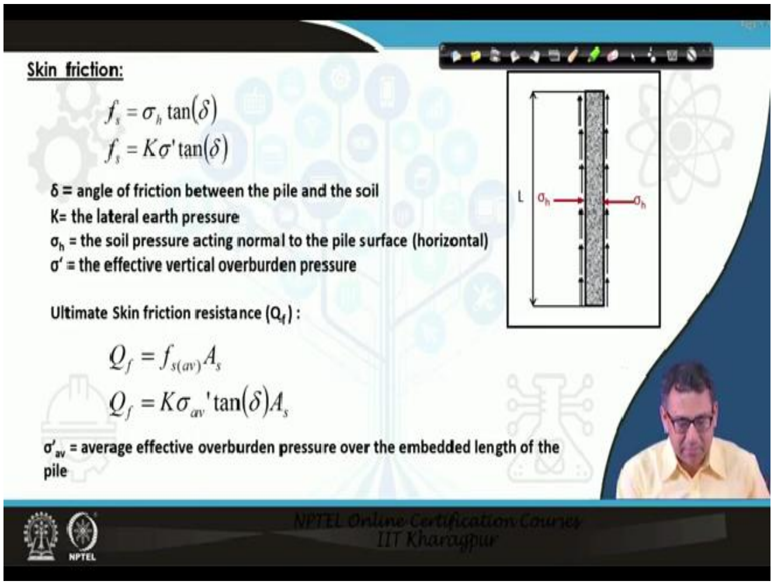

Then the expressions to determine the skin fiction were discussed.

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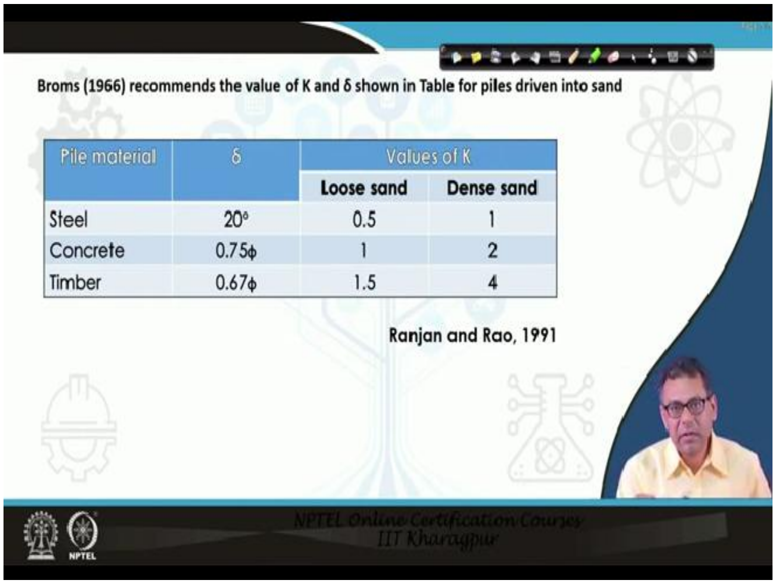

The values of δ and k for various materials and combinations were also given.

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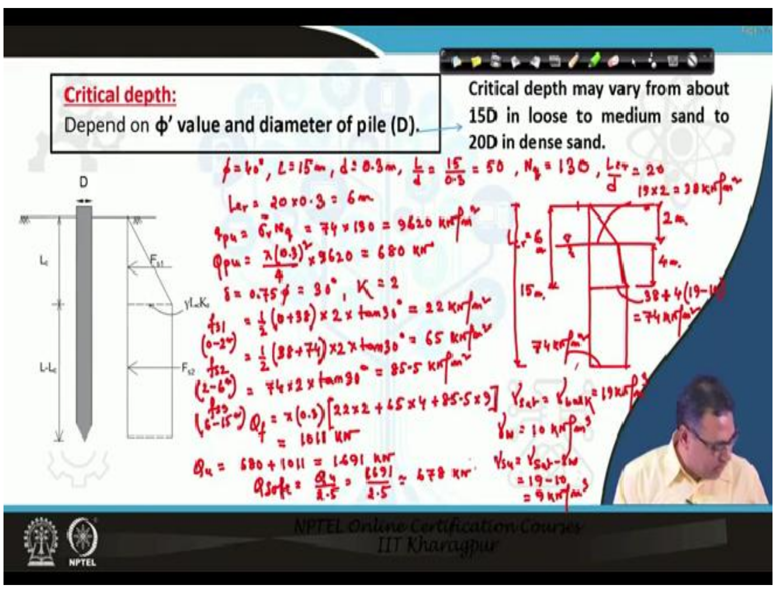

The concept of critical depth implies that the distribution of the lateral earth pressure will not keep increasing linearly always, but will have a limit. Instead, it increases up to a depth and then becomes constant. This depth, at which the earth pressure becomes constant and does not increase further, is called the critical depth. Let us see an example where this critical depth concept can be used to determine the load carrying capacity of a single pile. The procedure will be the same for group piles also.

In the example problem, the condition is that a single pile of length, L = 15 m and diameter, d = 0.3 m rests in a homogeneous soil with $\varphi = 40^o$. Water table is at a depth of 2 m from the ground surface. The saturated and bulk unit weight of the soil is 19 kN/m^3.

So, the L/d value will be: $\frac{L}{d} = \frac{15}{0.3} = 50$. From the table, for a φ value of 40^o and L/d value of 50, the N_q value will be 130. Now, introduce the critical depth concept. For piles in granular soils, the critical depth would be 15d if the soil is a loose sand and 20d if the soil is a dense sand. Here, as the φ value is 40^o, it is a dense sand and hence critical depth, L_{cr} will be 20d.

$$\Rightarrow L_{cr} = 20 \times d = 20 \times 0.3 = 6m$$

As the critical depth is 6 m, the earth pressure increases up to that depth only and beyond 6 m, it will be the same value as that of at 6 m. So, earth pressure should be calculated only up to 6 m. Out of the 6 m, 2 m of soil is in unsaturated condition and the remaining 4 m soil is in saturated condition as water table is at 2 m depth. The vertical stress at 6 m depth and beyond is:

$$\Rightarrow \sigma_v = (19 \times 2) + [(19 - 10) \times 4] = 74 kN/m^2$$

Since the unit weight of water is 10 kN/m^3 and the soil under water table exerts overburden stress corresponding to its submerged unit weight only.

The formula to calculate tip resistance of a pile is:

$$q_{pu} = \bar{\sigma}_v N_q = 74 \times 130 = 9620 kN/m^2$$

The above value is just the resistance per m^2 area of pile tip. The actual load this pile can carry with its end bearing strength is:

$$\Rightarrow Q_{pu} = \frac{\pi (0.3)^2}{4} \times 9620 = 680 kN$$

Now, to calculate the frictional resistance of the pile, δ and k values are needed.

$$\delta = 0.75\varphi = 30^o;\ k = 2 \text{ (Since, it is dense sand)}$$

The earth pressure diagram can be divided into three parts: 0 to 2 m, 2 to 4 m and 4 to 6 m. To calculate the frictional resistance of the entire shaft, average acting on the shaft should be calculated.

$$\underbrace{f_{s1}}_{(0-2m)} = \frac{1}{2}(0 + 38) \times 2 \times \tan(30^o) = 22 kN/m^2$$

$$\underbrace{f_{s2}}_{(2-6m)} = \frac{1}{2}(38+74)\times 2\times \tan(30^o) = 65kN/m^2$$

$$\underbrace{f_{s3}}_{(6-15m)} = 74\times 2\times \tan(30^o) = 85.5kN/m^2$$

So, the total frictional resistance of the pile is:

$$Q_f = (\pi\times 0.3)[22\times 2 + 65\times 4 + 85.5\times 9] = 1011kN$$

The ultimate load capacity of the pile is:

$$Q_u = 680 + 1011 = 1691kN$$

So, the safe load carrying capacity of the pile is:

$$Q_{safe} = \frac{Q_u}{F.S} = \frac{1691}{2.5} = 678kN$$

The load carrying capacity of a single pile in sand can be calculated in this way using the critical depth concept.

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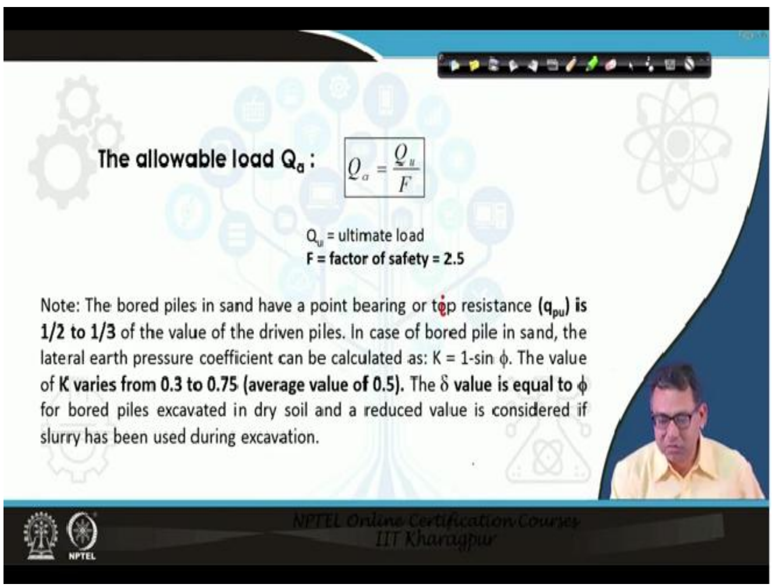

The formula for $Q_{allowable}$ or Q_{safe} is Q_u divided by F and the factor safety is 2.5 for piles.

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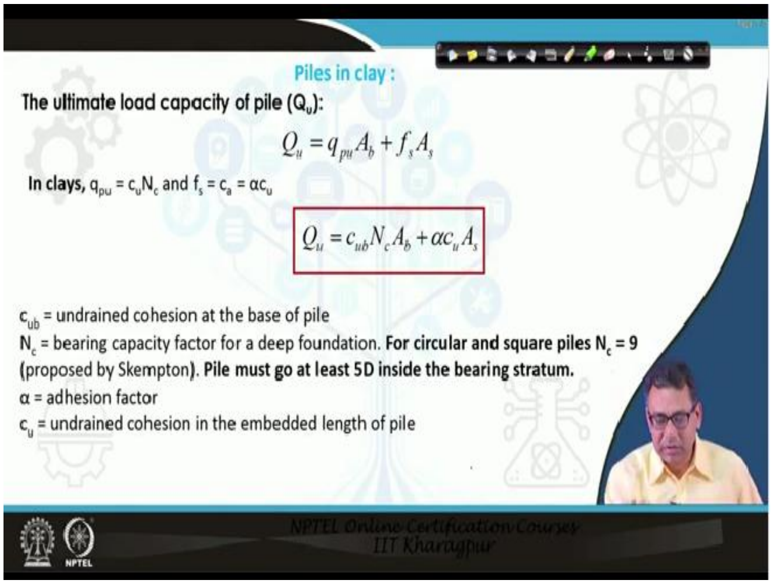

Similarly the ultimate load capacity of the pile in clay soil can be calculated using the formulae shown above.

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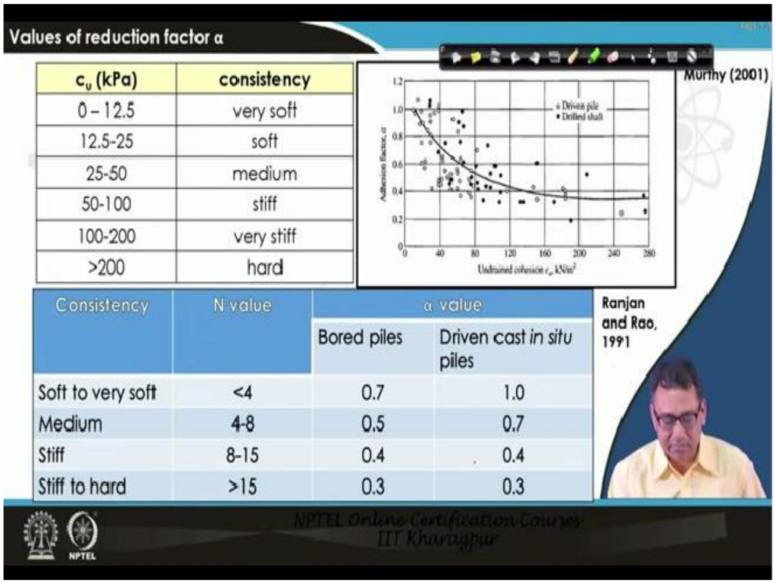

To determine the load carrying capacity of piles in clay, the adhesion factor, α need to be found out which is given in a tabular form above. The α value depend upon the type of installation of pile i.e., bored or driven.

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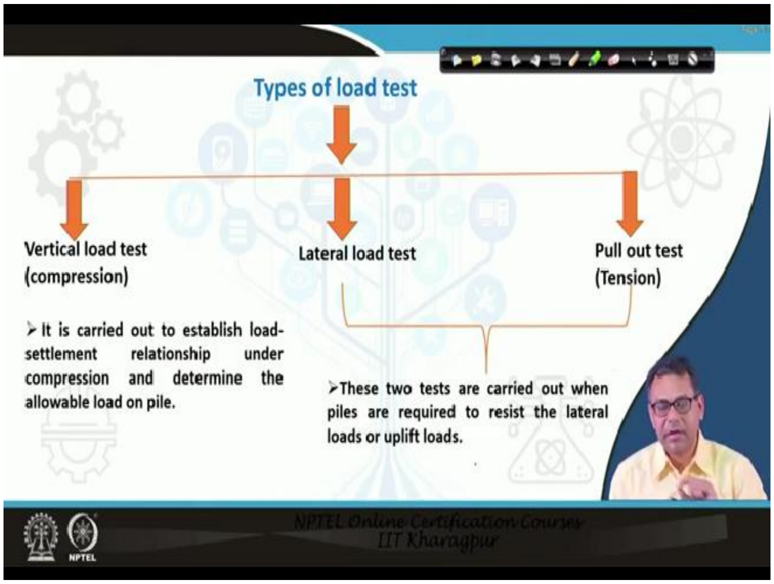

The pile load capacity can also be determined by the pile load test which is similar to the plate load test for shallow foundations. The pile load test can be of 3 types: pile under vertical load, pile under lateral load and pile under pull out. From the test results, a load vs displacement curve can be plotted and from there the ultimate or the allowable load carrying capacity of the pile can be determined. The settlement of single piles and pile groups can also be determined from the test results.

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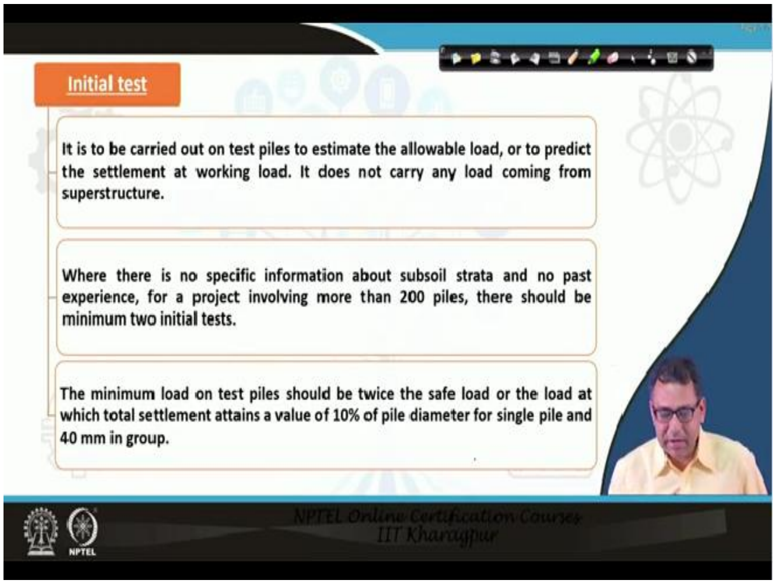

The test can be done on two types of piles and the test too consists of two parts. One is initial test that is carried on the piles to estimate the allowable load or to predict the settlement at working load. It does not carry any load coming from the superstructure. That means these are not the real piles upon which the structure is built, but are test piles. So, if there is no specific information is available, then for a project involving more than 20 piles, 2 piles will be chosen for the initial test. The minimum load on the test pile should be twice the safe load or the load at which settlement attains a value of 10% of pile diameter for single pile and 40 millimeter for group pile. So, before the initial test, the soil properties for the site should be known and the safe load carrying capacity for a pile should be determined. This procedure for determination is already explained before. So, the load applied on the test pile for initial test will be determined through this way from the expression.

As these piles are only test piles and will not be used in the construction later on, the loading can be done up to failure too. But the minimum is up to twice the safe load or a settlement of 10% of the pile diameter for single pile and 40 millimeter for group pile.

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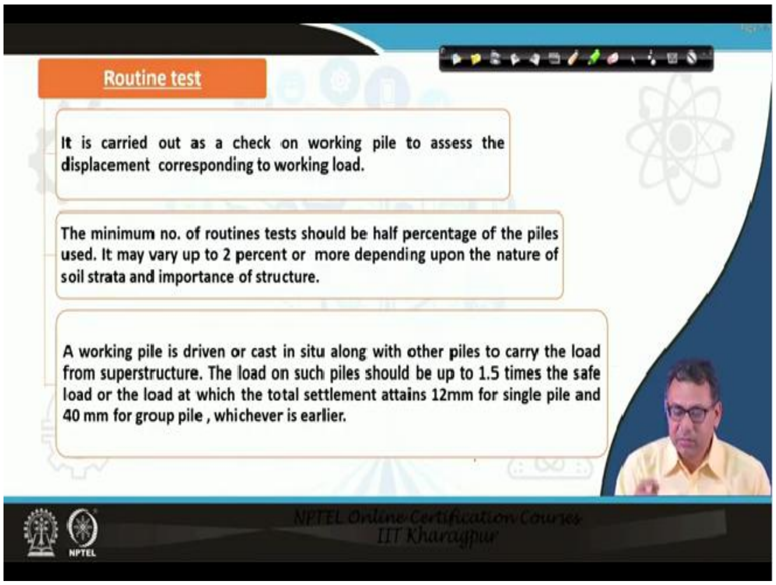

After the initial test is done, the routine test will be performed to check the working piles and to assess the displacement corresponding to working load. In this case, the test will be done on the working piles or the real piles upon which the structure will be built. So, the loading upon them should be such that it should be below failure and hence the load is restricted to 1.5 times the safe load or the load at which settlement is 12 mm for single pile and 40 mm for group piles.

Remember that in initial test, the requirement of 2 times the safe load is minimum i.e., the load should be more than twice the safe load. But here, the maximum load is 1.5 times the safe load. 2% of the actual piles should be used for the routine test.

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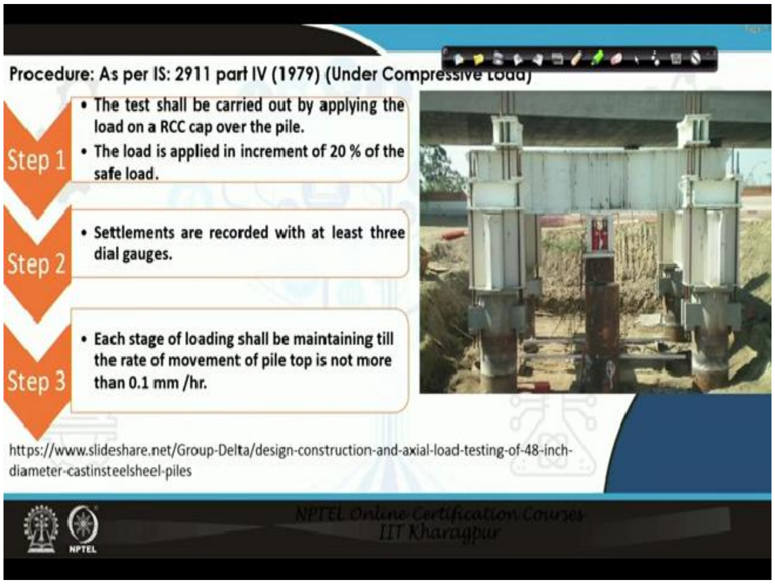

The test setup is shown in the above picture. The test should be carried out by applying an RCC cap over the pile. The load should be applied in increments of 20% of the safe load (the safe load will be determined by using the expression already discussed). As the loading progresses, the settlements are recorded with at least 3 dial gauges and the average value will be taken the settlement of the pile for a particular load. Each stage of loading should be applied till the rate of movement of the pile top is not more than 0.1 mm/hr.

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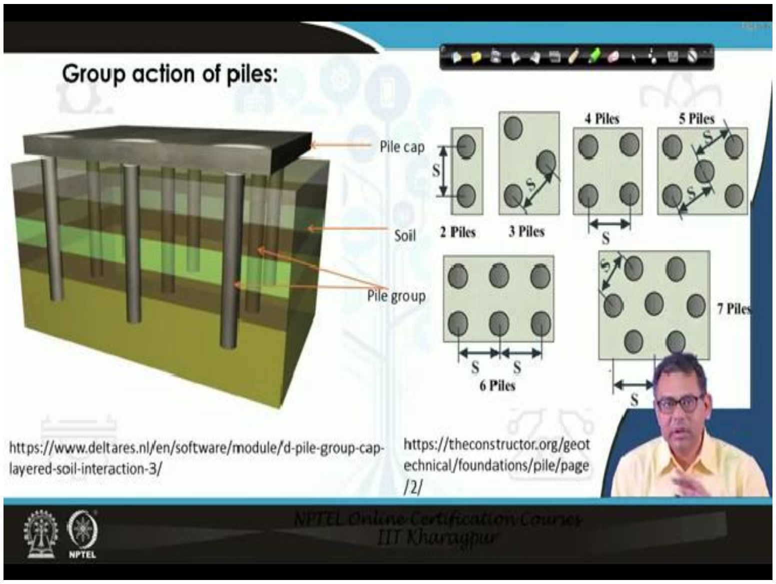

Now let us discuss about the group action of the piles which is very important because usage of a single pile alone is very rare. Most of the cases piles are used as a group. So the group interaction should be studied well, along with the 'how' to calculate the group capacity of the pile and how to calculate the group settlement of the pile. Different pile groups are shown in the above slide (groups with 2,3,4,5,6,7 piles) and for a pile group, a pile cap is always placed on the top of the piles.

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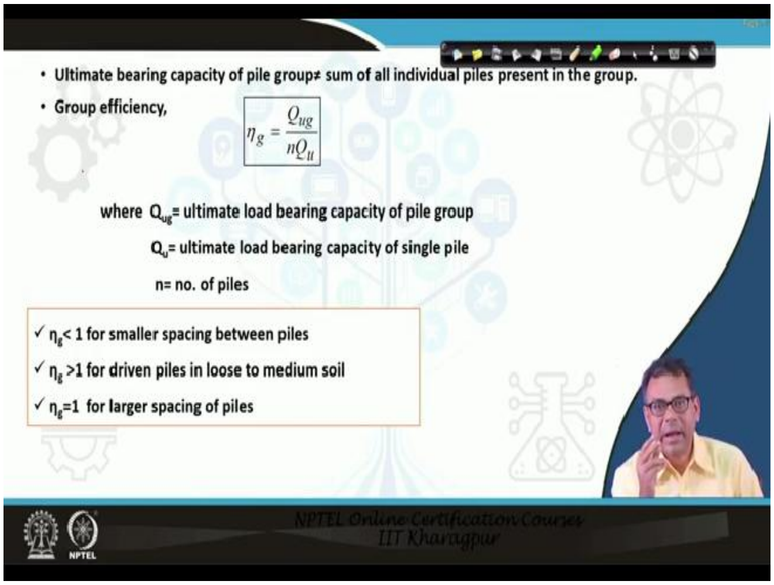

The ultimate bearing capacity of a pile group may always not be equal to the sum of individual bearing capacities of all piles in the group. The group efficiency can be calculated as the ratio of the group capacity to the individual capacity of the pile times the number of piles.

$$\eta_g = \frac{Q_{ug}}{nQ_u}$$

If the spacing between the piles is very large then every pile acts as an individual pile. So, there will be very less interaction between the piles and hence in that case, group capacity will be equal to n times the individual capacity of the pile. So, group efficiency will be 100%. But if the spacing is very less, there will be an interaction between the piles and so the capacity will reduce because the stress zones overlap for the piles. So, in that case the group capacity will be less than the capacity of individual pile times the number of piles or simply, less than 1. This is the reason why the group efficiency is less than 1 for a pile group with smaller spacing between the piles.

For larger spacing between the piles it usually is 1, but sometimes is can even be greater than 1. Suppose there is a loose soil and in that loose soil if a pile is driven, it compacts the soil and hence the group capacity increases. This increase is due to the relatively high compacted soil the pile group rests in, when compared to that of a single pile.

This means that the strength of the soil after the installation of the pile group, will increase. So, in that case the group capacity will be greater than the capacity of individual pile times the number of piles. This is theoretically possible, but practically the group capacity or the group efficiency will not be considered greater than 1.

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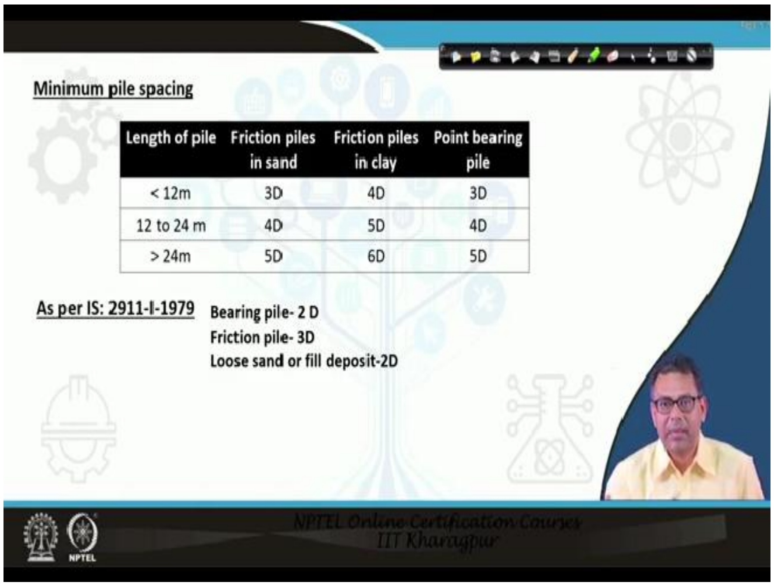

Above are some recommendations for the spacing to be maintained in a pile group and if these are followed, most of the cases the group efficiency will be 1. The ideal spacing between the piles in groups depend upon the pile length, type of pile and type of soil. The above recommendations considered all these factors to suggest the values.

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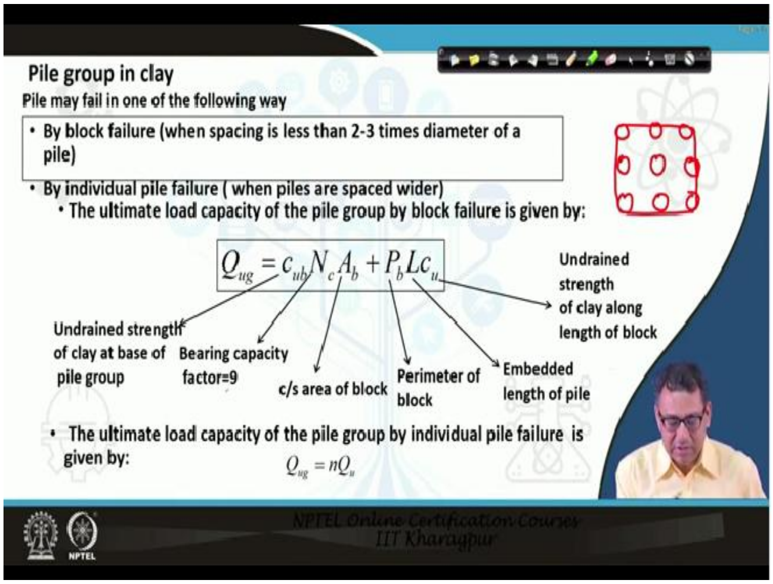

The formula to determine the group capacity of pile groups is shown above. To determine the pile group capacity, it should be considered as a block. Even if failure occurs, it is assumed that it occurs as a block. So, the area and perimeter components used in the formula for pile group refer to the complete block, but not an individual pile. An example of a block for a 3 × 3 pile group is shown in a small figure above. Except this change, the formula and procedure are all same for a single pile and a pile group. The N_c value will be 9 in case of pile groups too.

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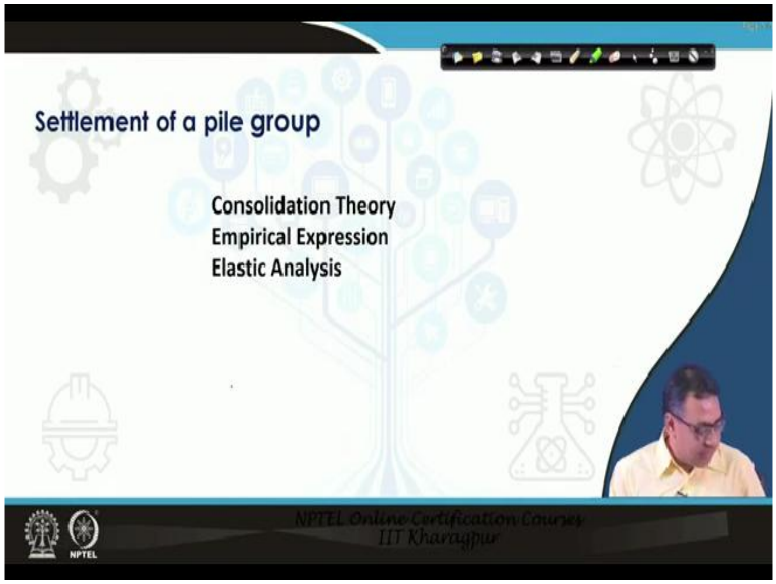

The settlement of a pile group can be determined by consolidation theory (seen in shallow foundation), empirical expressions and if the consolidation properties are not available, elastic analysis can also be used. All these three approaches to determine the pile group settlement will be discussed.

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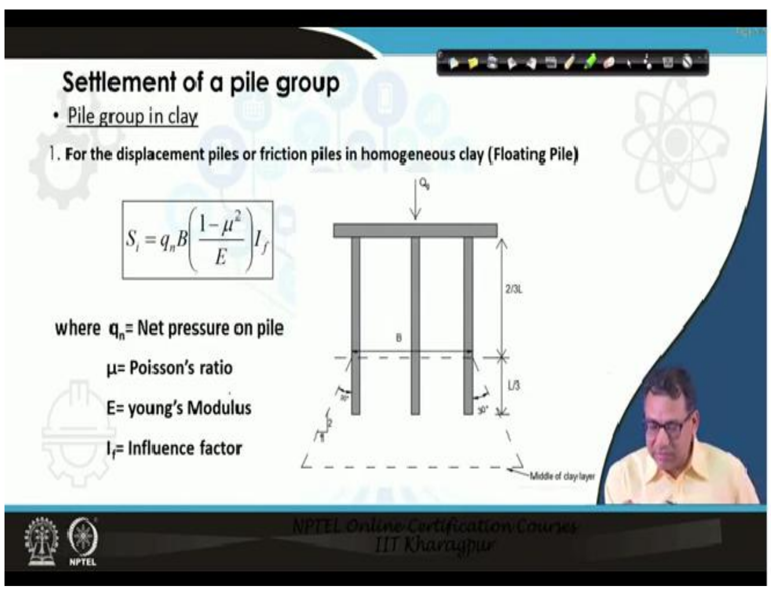

Consider a group of floating piles in a clayey soil. If a pile and its influence zone fall under a single, homogeneous soil layer, that pile can be called as a floating pile. (Floating piles do not rest on harder strata). So, if a pile group consists of floating piles, they should be first considered as a block and the stress distribution (in 1:2 ratio) from the piles to the soil is assumed to start from 2/3rds the pile length. It is like considering that a raft is present at a depth of 2/3L from the ground surface from where the stress starts dissipating in 1:2 ratio.

There are 2 components for the settlement: one is the immediate settlement, another is the consolidation settlement. The immediate settlement or elastic settlement can be calculated by using the expression shown above which is same as that of used for the raft foundation.

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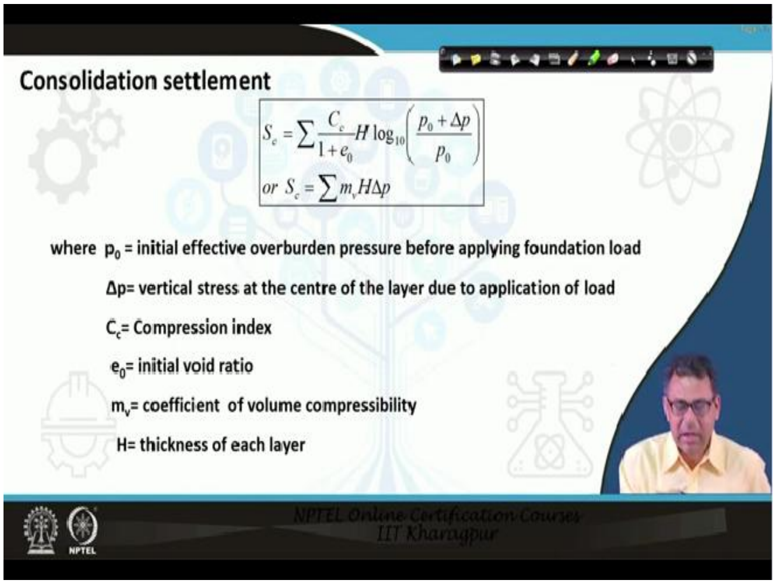

The consolidation expression also, is the same as that of a raft foundation which is shown in this slide (above). This has already been discussed during the shallow foundation design.

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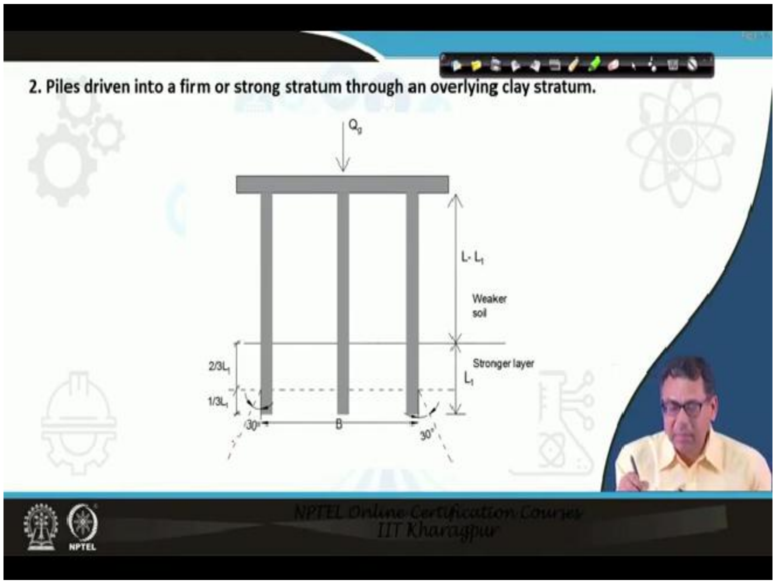

Let us see the second case in pile groups where the pile group is placed in a stronger layer at its end but passing through a weaker layer. That means that the soil profile is such that the upper layer is weaker and the lower layer is stronger. A certain part of the pile, say, of length L_1 is embedded in the harder layer. Now, the stress distribution starts from a depth of $2/3L_1$ from the level where the harder layer starts.

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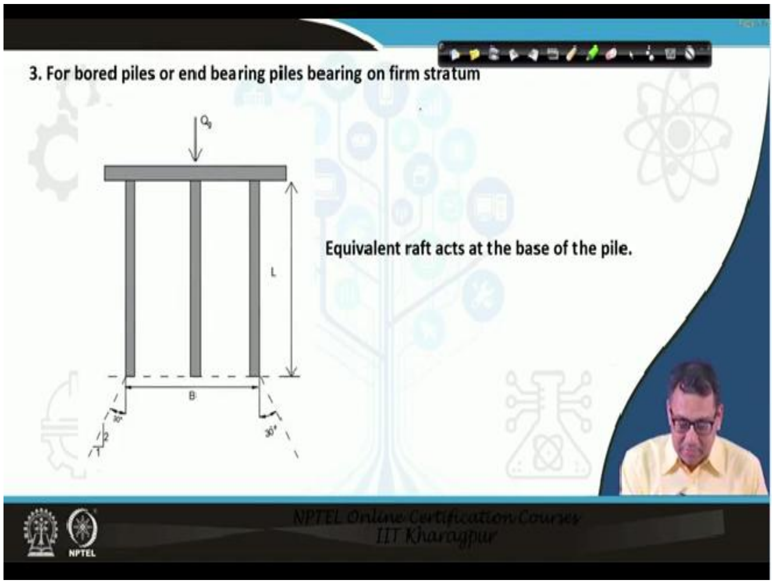

The third case is that if the pile rests on a very firm stratum of the rigid soil, then the stress distribution will be from the base of the pile. In this case, it is like the raft is placed at the base of the pile group. This is called the equivalent raft approach and it act from the base of the pile here.

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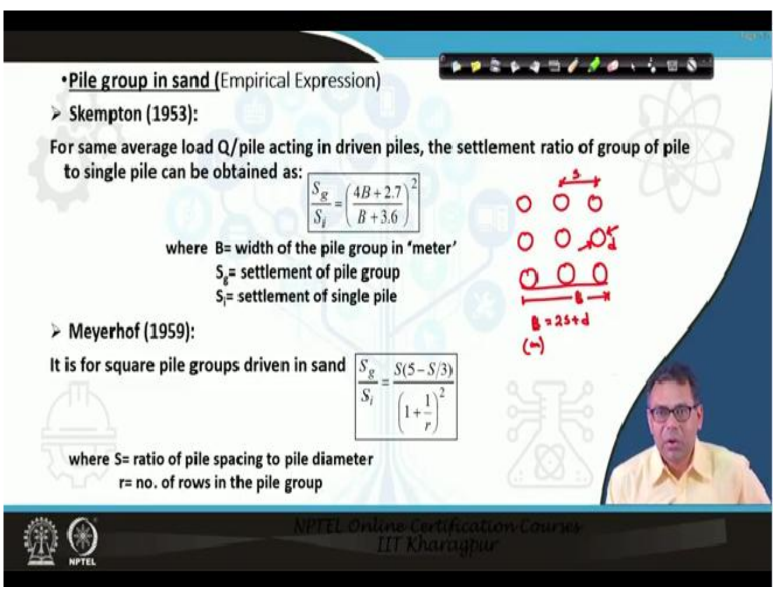

The empirical expressions are formulated from a pile load test, where if the test is done one load, the settlement of the pile can be determined for any particular load. If the total load coming onto the pile group is known and it is assumed that all the piles are taking the same amount of load or equal amount of load, the settlement of group can be determined using these expressions.

For a 3 × 3 pile group, the side of the block can be calculated by making use of the pile spacing and diameter. There are three piles and two spaces in one side of the block. So, 2s is the centre to centre distance between the two peripheral piles of the group. But the side of the block is from edge to edge and so, the side of the block is 2s +2r (r is the radius of the pile) which can be written as 2s + d. Once the B value is known, the S_i value, settlement of individual pile for a particular load should be known to calculate the group settlement.

The first expression in the slide above, was given by Skempton and the second one by Meyerhof. In the second expression, S refers to the ratio of pile spacing to pile diameter and r is the number of rows in the pile group. For a 3 × 3 pile group, the r value is 3.

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The next concept is the settlement of the pile group based on elastic analysis approach. In the elastic analysis, the pile is divided into a number of uniformly loaded elements and the solution is obtained by using displacement compatibility between pile and adjacent soil. The displacement of the pile can be determined by considering compressibility of the pile under axial load and the displacement of the soil is obtain by Mindlin's equation.

The detailed explanation about this can be found in the book of "pile foundation analysis and design" by Poulos H. Davis. It is beneficial to refer this book along with the lectures. Now let us look into the approach about how to determine the settlement of a pile group and also single pile.

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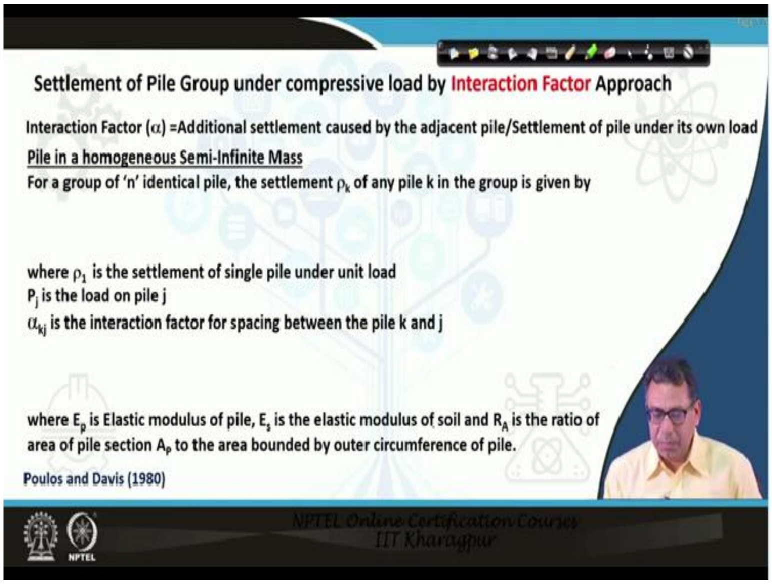

The method that is about to be discussed, with which the pile group settlement under compressive load can be determined, is called the interaction approach. In the consolidation settlement approach, the pile group is considered as a block and then is considered as an equivalent raft to determine the settlement. But there is an interaction between the piles which is not considered.

Here the settlement of a particular pile is assumed to be affected by other piles in the group. So, the interaction factor approach considers the interaction among all the piles to determine the settlement of the piles as a group.

In the next class, I will first discuss this interaction factor approach and to determine the settlement of a particular pile in a pile group based on that. Then, I will solve a problem where I will show the consolidation theory approach as well as the interaction factor approach to determine the settlement of a pile group. Thank you.