Soil Structure Interaction
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Lecture-55
Soil Structure Interaction for Pile Foundation (Contd.)

In this class I will first solve one design problem to show the procedure to design a pile group and to determine the settlement of the pile group using consolidation theory approach and the interaction factor approach.

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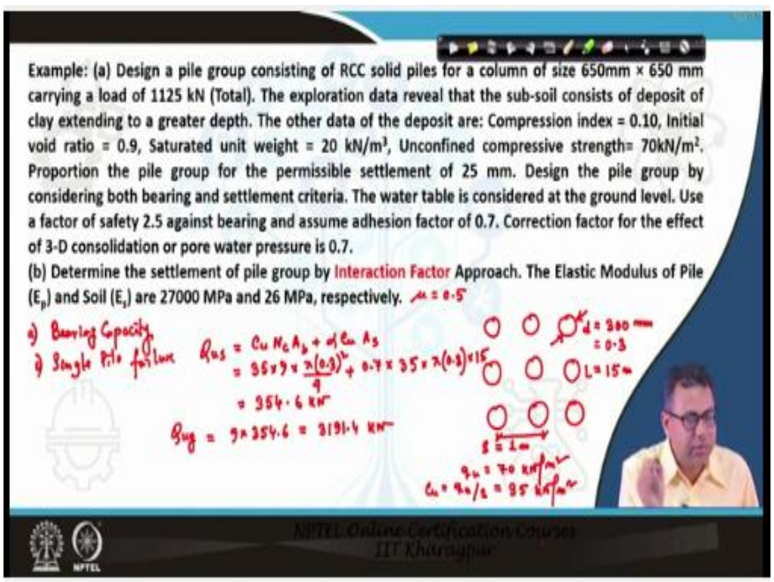

The problem is to design a pile group consisting of RCC solid piles of size 650 mm × 650 mm carrying a total load of 1125 kN. The exploration data revealed that the sub-soil consists of deposit of clay extending to a great depth (floating pile). The compression index is 0.1, initial void ratio is 0.3, saturated unit weight is 20 kN/m^3, unconfined compressible strength is 70 kN/m^2. Proportion the pile group for a permissible settlement of 25 mm and design the pile group by considering both bearing and settlement criteria. Water table is considered at the ground level, use the factor safety 2.5 against bearing. Assume the adhesion factor, α = 0.7, correction factor for the effect of 3D consolidation or pore pressure is 0.7. So, the correction factor is same as the raft foundation design.

If the consolidation data is available, the settlement for the pile group can be calculated from that data. But if that data is not available, the settlement should be determined through the interaction factor approach. The elastic modulus of pile is 27000 MPa and elastic modulus of the soil is 26 MPa. The Poisson's ratio of the soil can be considered as 0.5 because it is clay and also for μ = 0.5, few corrections can be avoided.

First the bearing capacity will be calculated and then the settlement. As the pile group should be designed, some arbitrary values should be assumed for the pile diameter and the spacing between them. So assume that there are 9 piles in a 3 × 3 square group arrangement. The diameter of the pile is say 300 mm and it is uniform (shaft diameter and base diameter are same). As per IS code the minimum spacing between piles in clay is say 3 times of d and so it will be 900 mm. Consider 1 m spacing for the first trial.

The bearing capacity based on the single pile failure will be calculated first. So the bearing capacity expression for Q_{us} will be:

$$Q_{us} = c_u N_c A_b + \alpha C_u A_s$$

$$\Rightarrow Q_{us} = 35 \times 9 \times \frac{\pi(0.3)^2}{4} + 0.7 \times 35 \times [\pi \times (0.3) \times 15] = 354.6 kN$$

$$Q_{us} = 9 \times 354.6 = 3191.4 \; kN$$

where, $c_u = q_u/2$, N_c value is 9 for piles, A_b is the area of the end bearing offered by the pile which is nothing but the cross sectional area of the pile ($\pi \times 0.3^2/4$), α is given 0.7 and A_s is the the area along which the skin friction acts = ($\pi d \times L$).

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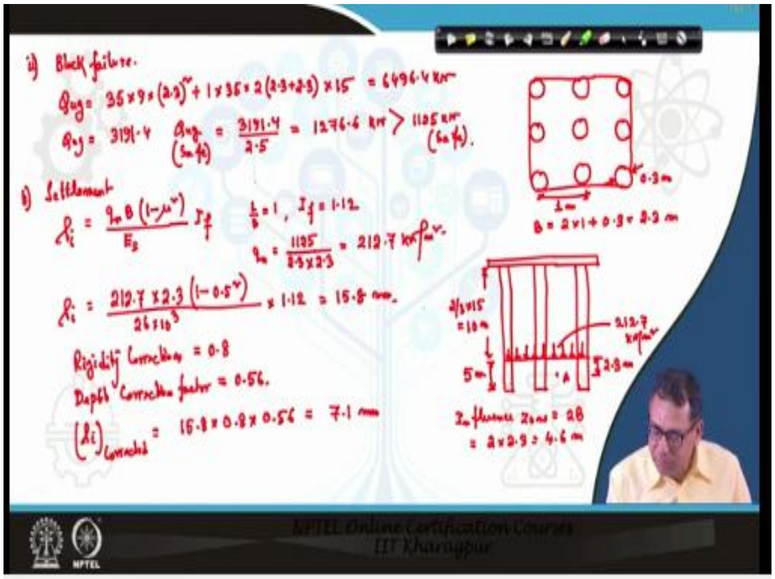

The next case in the bearing capacity is that the pile group may fail by block failure. The size of the block, B will be:

$$B = 2s + d = 2 \times 1 + 0.3 = 2.3 \text{ m}$$

The bearing capacity considering block failure (Q_{ug}) will be:

$$\Rightarrow Q_{ug} = 35 \times 9 \times (2.3)^2 + 1 \times 35 \times \left[2 \times (2.3 + 2.3)\right] \times 15 = 6496 kN$$

$$\therefore Q_{ug} = 3191.4 kN$$

Though there are two values of group bearing capacity obtained, the least value should be considered as the group bearing capacity to be on the safe side. The safe bearing capacity will be:

$$Q_{g(safe)} = \frac{3191.4}{2.5} = 1276.6 kN > 1125 kN$$

The safe bearing capacity of the pile group for the assumed arrangement is higher than the load coming onto it and hence the design is safe considering the bearing criterion.

Here, the group efficiency turned out to be greater than 1. This means that the spacing given is greater than the optimum spacing. Optimal spacing is the spacing where the group efficiency will be 1.

Now the settlement criterion should be considered. Let us first calculate the immediate settlement. As the piles here are floating piles, the stress distribution starts from $2/3^{rd}$ length of the piles (the equivalent raft will be at that length). As the pile length is 15 m, the imaginary raft from which the load dispersion starts will be at 10 m (2/3 × 15) from the ground surface. The depth of influence zone is 2B and as the block width is 2.3 m, the influence zone depth is 4.6 m from the raft. So, q_n should be calculated at a depth of 2.3 m (point A) from the raft. The expression for immediate settlement is:

$$\rho_i = \frac{q_n B(1-\mu^2)}{E_s} I_f$$

L =B = 2.3; I_f =1.12, q_n = (1125/2.3^2) =212.7 kN/m^2

$$\rho_i = \frac{212.7 \times 2.3 \times (1-0.5^2)}{26 \times 10^3} \times 1.12 = 15.8mm$$

The depth correction factor is calculated from the Fox's chart.

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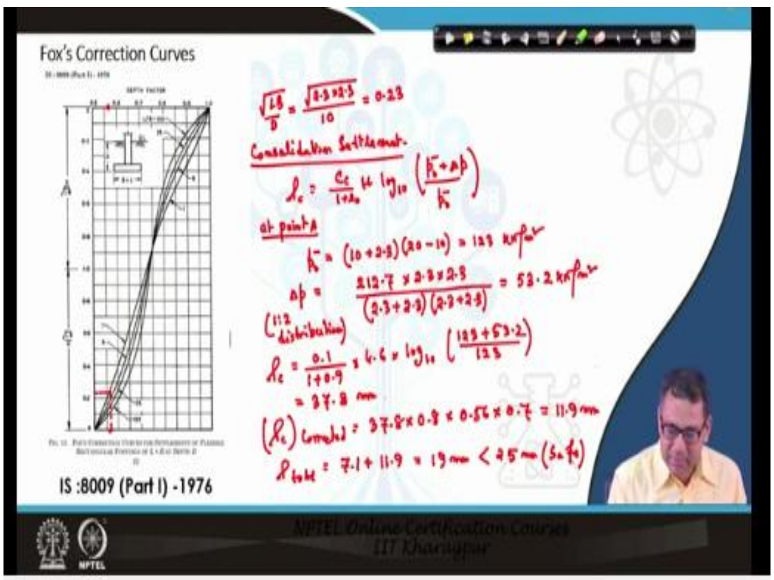

$$\frac{\sqrt{LB}}{D} = \frac{\sqrt{2.3 \times 2.3}}{10} = 0.23$$

As the pile group is in a square shape, L = B and the depth of the raft from ground surface is 10 m. So for a value of 0.23, the depth correction factor from the chart is 0.56.

Rigidity correction factor = 0.8, Depth correction factor = 0.56

$$\therefore (\rho_i)_{corrected} = 15.8 \times 0.8 \times 0.56 = 7.1mm$$

So the corrected value of immediate settlement is 7.1 mm.

The consolidation settlement should be calculated at the point A as it is the centre of the soil subjected to stress from the pile group. The expression for consolidation settlement is:

$$\rho_c = \frac{C_c}{1+e_\circ} H \log_{10}\left(\frac{\bar{p}_\circ + \Delta p}{\bar{p}_\circ}\right)$$

$$\text{At point A, } \bar{p}_\circ = (10+2.3)(20-10) = 123 kN/m^2$$

$$\Delta p = \frac{212.7 \times 2.3 \times 2.3}{(2.3+2.3)(2.3+2.3)} = 53.2 kN/m^2$$

$$\Rightarrow \rho_c = \frac{0.1}{1+0.9} \times 4.6 \times \log_{10}\left(\frac{123+53.2}{123}\right) = 37.8mm$$

Rigidity correction factor = 0.8

Depth correction factor = 0.56

Pore pressure correction factor = 0.7

$$\therefore (\rho_c)_{corrected} = 37.8 \times 0.8 \times 0.56 \times 0.7 = 11.9mm$$

So the total settlement of the pile group is:

$$\rho_{total} = 7.1 + 11.9 = 19mm < 25mm \text{(safe)}$$

The total settlement of the pile group is less than the permissible value, 25 mm and hence the design is safe with respect to the settlement criterion also.

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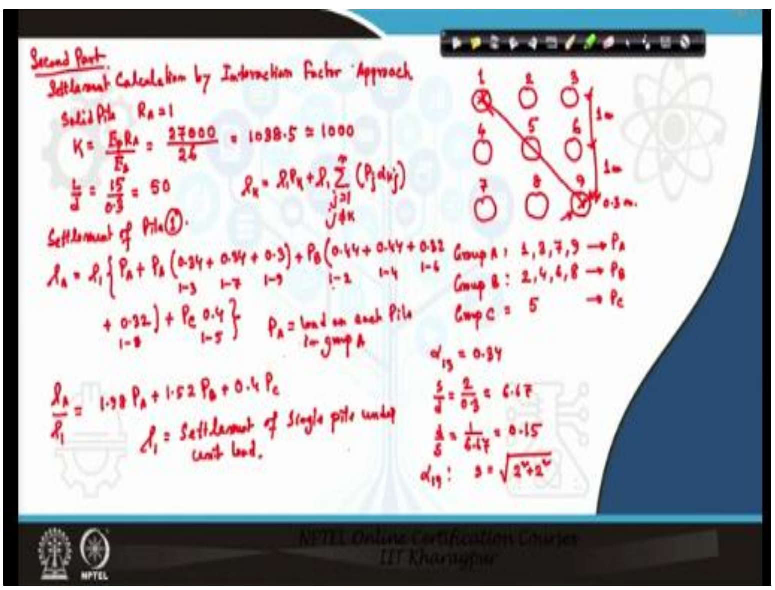

Now the second part of the problem will be solved using the elastic analysis approach. The 9 piles in the group are drawn and marked in the above figure. Among these 9 piles, the piles 1, 3, 7 and 9 will behave identically, in terms of the interaction because their spacing to the other piles are identical as these are the corner piles and hence are being grouped under group A. Similarly, the piles, 2, 4, 6 and 8 can be grouped under the same group, B. The center pile, 5 will be in another group alone as there is no other pile similar to this pile in the group.

Let us get started with the calculations now. The k value should be determined first and the expression for that is:

$$k = \frac{E_p R_A}{E_s}$$

The R_A value for a solid pile is 1 and the E_p, E_s values are given already.

$$\Rightarrow k = \frac{27000 \times 1}{26} = 1038.5 \approx 1000$$

The L/d ratio of the pile is 50 (= 15/0.3). Now let us calculate the settlement of pile-1. As this pile is grouped under A, all other piles in this group (3, 7 and 9) also have the same settlement and hence the settlement is indicated as ρ_A. The general settlement expression is:

$$\rho_k = \rho_1 P_k + \rho_1 \sum_{\substack{j=1 \\ j \neq k}}^{n} \left(P_j \alpha_{ij} \right)$$

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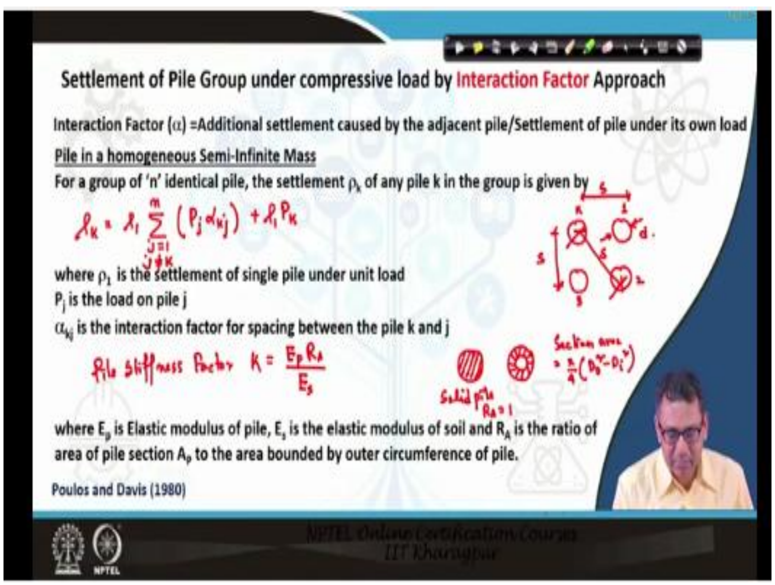

The piles which are positioned similarly and are expected to behave similarly are grouped under one group. As the external load acts on the pile cap, it will be shared by all the piles. But this sharing is considered to be similar for piles under one group. For example, all the piles in group A carry the same load and so the piles in group B too. If the load carried by pile 1 is termed as P_1 and the load by pile 2 as P_2, then in this case: $P_1 = P_3 = P_7 = P_9 = P_A$. The load carried by each pile of group A is termed as P_A and similarly the load carried by each pile of group B is termed as P_B. So the settlement for all piles in a group would also be the same and hence the settlement of pile 1 which is to be calculated is considered as ρ_A:

$$\rho_A = \rho_1\{P_A + P_A(\alpha_{1-3} + \alpha_{1-7} + \alpha_{1-9}) + P_B(\alpha_{1-2} + \alpha_{1-4} + \alpha_{1-6}) + P_C\alpha_{1-5}\}$$

So these interaction factors should be calculated first. The calculation of this interaction factor will be showed and all other interaction factors can be calculated in the same way. To calculate the interaction factor between 1 and 3 piles, the spacing or centre to centre distance (s) between them should be calculated first. The spacing between 1 and 3 is 2 m as the pile spacing is 1 m and there are two such spacings between 1 and 3. As the diameter of the pile is 0.3 m, s/d = 2/0.3 = 6.76.

But in the chart, the limit for s/d value is 5 and if it exceeds 5, the interaction factor value should be read from the d/s value. So, here the d/s value is = 0.3/2 = 0.15. Now as it is a floating pile the chart for floating pile should only be used.

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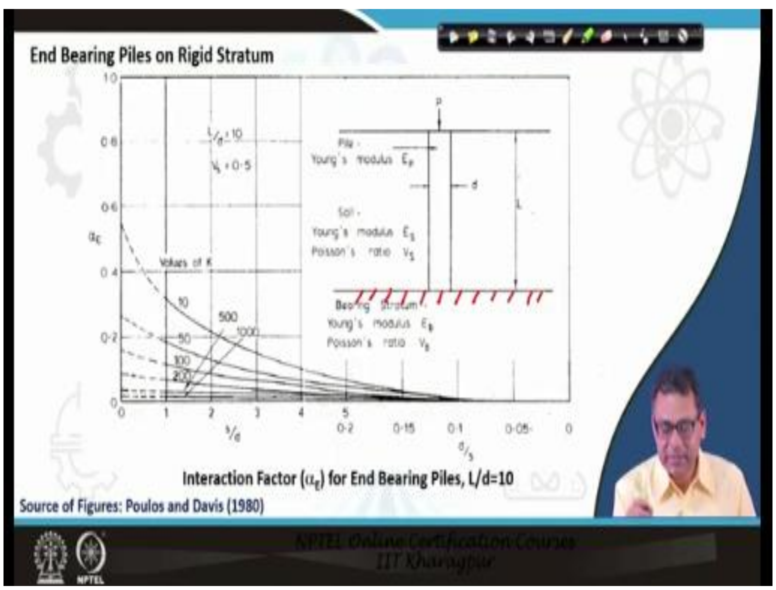

The above is the chart for end bearing pile and so cannot be used.

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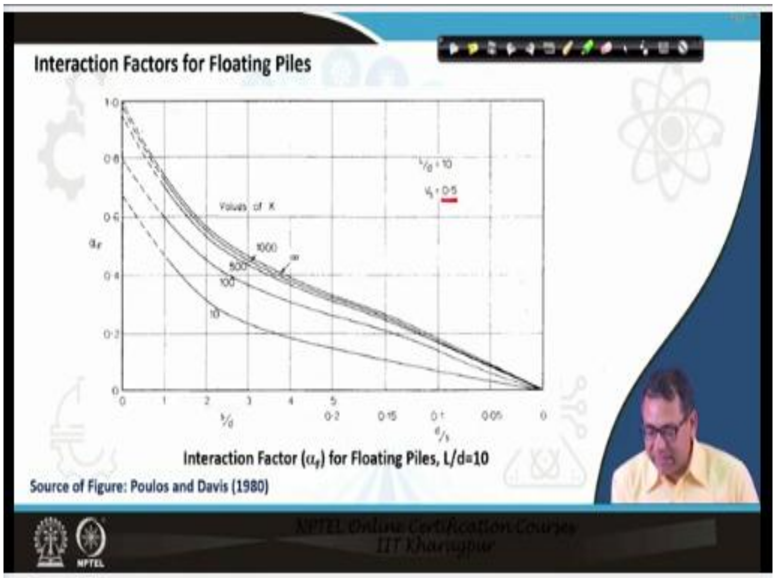

This is the floating pile chart, but this is for L/d = 10, but the L/d for this case is 50. So, we cannot use this chart.

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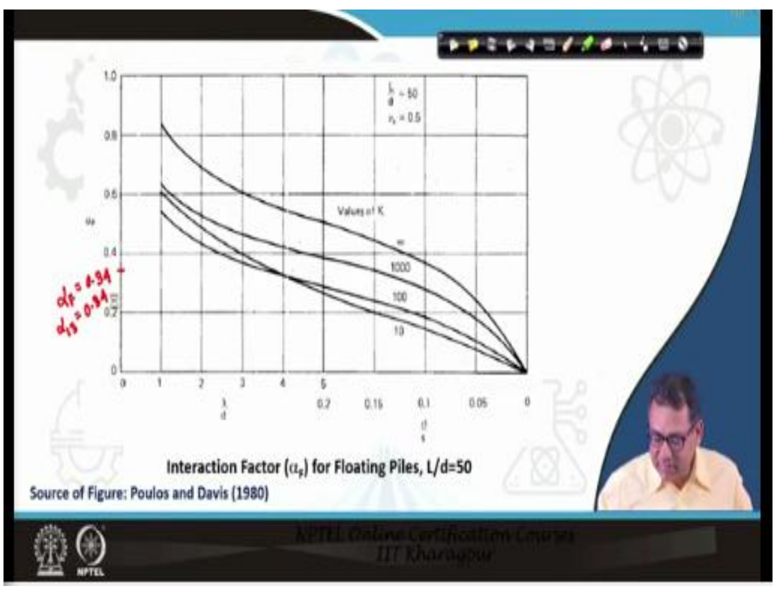

This is the chart that can be used for floating piles with L/d = 50. For a d/s value of 0.15 and for a k value 1000, the interaction factor value will be approximately 0.34. So, $\alpha_f = \alpha_{13} = 0.34$.

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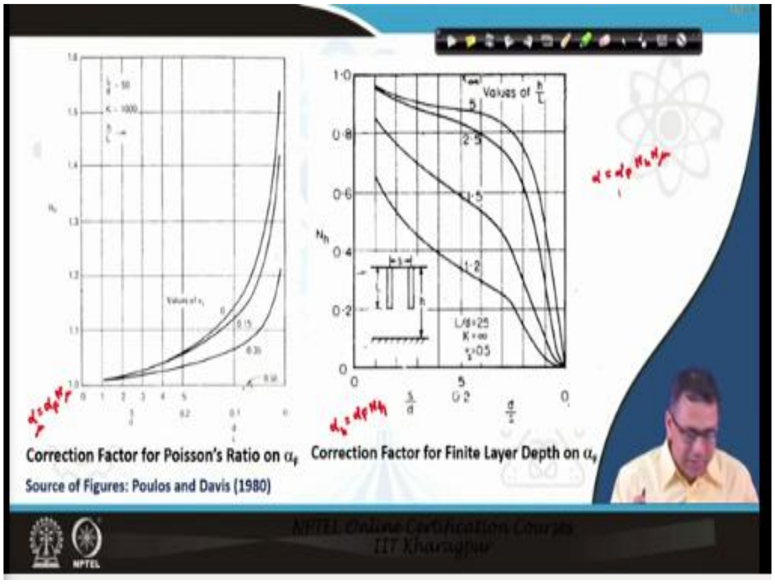

Remember that only because the case described in the problem is of infinite depth, the finite layer correction is not required. But if in any question, the depth of the layer is mentioned to be of some finite value, the chart for that (chart on right in above slide) should be used. Also, the Poisson's ratio of the soil was considered to be 0.5 and so the correction for Poisson's ratio (chart on left in the above slide) is also not required.

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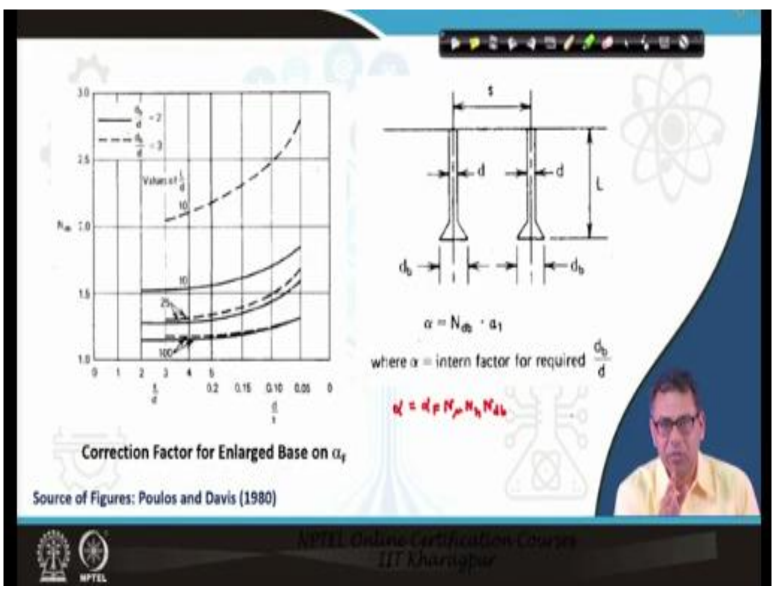

If the pile has uniform diameter through put its length (no enlarged base), the above correction is also not required. The above correction should only be used if the pile has an enlarged base. (*All these corrections are not valid in the present case, but I am showing you when to use these* *corrections*.) Whatever corrections are valid for the described conditions should be determined and multiplied with the α_f value found from the interaction factor chart.

So the interaction factor for the 1 and 3 piles, α_{13} is 0.34. Similarly, the factor for piles 1 and 7 will also have the same value as the spacing between 1 & 3 and 1 & 7 is the same (so, α_{17} = 0.34). But for the piles 1 and 9, the case is a little different. The spacing between the piles 1 and 9 will be $\sqrt{2^2+2^2}$ as the line joining the centers of both the piles (1 & 9) act as a hypotenuse for an isosceles right angled triangle of side 2. Once the spacing is determined the rest of the procedure is similar to that of used for piles 1 & 3.

Now the interaction factors for the second group, group B should be calculated. The piles 2, 4, 6 and 8 come under group B. The spacing between 1 & 2 piles is 1 m and the s/d ratio is 3.33 giving an α_f value of 0.44. The α_f value will be the same for the piles 1 & 2 and 1 & 4 because of the similarity of spacing in both the cases. Now the spacing between the piles 1 & 6 will be $\sqrt{2^2+1^2}$ as the vertical spacing between 1 & 6 is 1 m and the horizontal spacing between them is 2 m. For this spacing and 0.3 m diameter, the α_f value will be 0.32 (from the chart). The α_f value considering piles 1 & 8 will also be the same (0.32) as the spacing between the piles 1 & 6 and 1 & 8 is the same. Similarly the interaction factor between 1 & 5 piles can also be determined. Substituting all the determined interaction factor values:

$$\rho_A = \rho_1\left\{P_A + P_A\left(\underbrace{0.34}_{1-3}+\underbrace{0.34}_{1-7}+\underbrace{0.3}_{1-9}\right)+P_B\left(\underbrace{0.44}_{1-2}+\underbrace{0.44}_{1-4}+\underbrace{0.32}_{1-6}+\underbrace{0.32}_{1-8}\right)+P_C\left(\underbrace{0.4}_{1-5}\right)\right\}$$

$$\Rightarrow \frac{\rho_A}{\rho_1} = 1.98P_A + 1.52P_B + 0.4P_C \rightarrow (1)$$

Here, ρ_1 is the settlement of single pile under unit load. The procedure to determine ρ_1 will also be discussed.

In the next class I will determine the settlement of other piles. If the value, ρ_A is determined, it means that the settlement of piles 1, 3, 7 and 9 is determined as the settlement of all piles in group A is the same. Similarly, in the next class I will determine the settlement of all the piles by finding out ρ_B and ρ_C. Then I will determine the settlement of the pile group itself. Thank you.