Soil Structure Interaction
Prof. Kousik Deb
Department of Civil Engineering
Indian Institute of Technology-Kharagpur

Lecture-54
Soil Structure Interaction for Pile Foundation (Contd.)

In this lecture, I will discuss how to determine the settlement of a pile group using the interaction factor approach which is based on the elastic analysis. And then, I will discuss how to determine the settlement of a single pile too.

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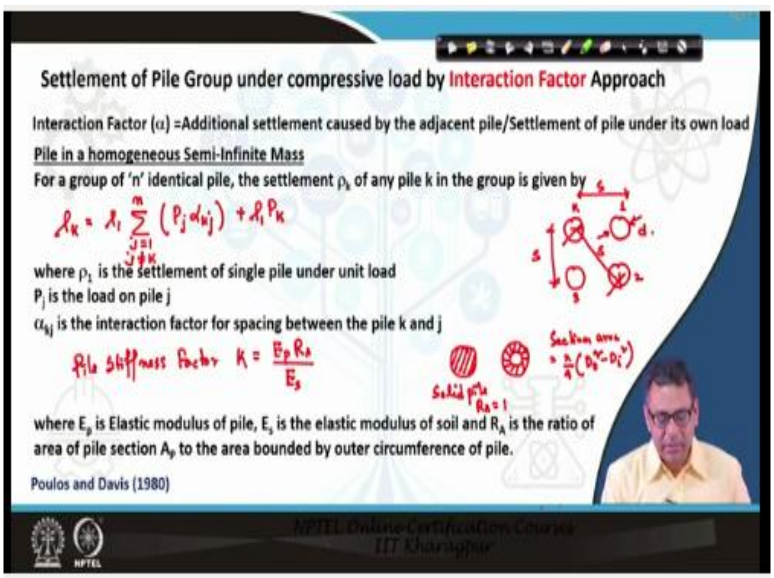

The interaction factor is a ratio between the additional settlement caused by the adjacent pile to the settlement of a pile under its own load. Consider a square pile group with n piles and the settlement of a pile in this group, say k^{th} pile should be determined. Now, when the pile group is loaded, the k^{th} pile settles due to its own weight and also the load coming onto it. Similarly, all the other piles in the group also settle. If there is an interaction between the piles, the settlement of one pile under the applied load will affect the settlement of other pile. The basic idea of the interaction factor approach is to capture this effect and calculate the settlement.

If n number of piles are in a homogeneous semi infinite mass as a group (i.e., they are floating piles), the formula for settlement of a pile (k^{th} pile) in the group is:

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

where, ρ_1 is the settlement of single pile under unit load

P_j is the load on j^{th} pile

α_{kj} is the interaction factor for spacing between the j^{th} and k^{th} piles

Here, if there is no interaction effect between two piles, then the α value in the above expression will be 0 (only for those two piles). That means there would be no additional settlement in the k^{th} pile due to the j^{th} pile.

For example, if a load of 200 kN is applied on the k^{th} pile, P_k is that 200 kN and ρ_1 may be considered as the settlement of that pile under 1 kN load. If the pile is subjected to 1 kN load really, then ρ_1 and $\rho_1 P_k$ are same. One thing to remember is that this is elastic analysis and so the soil behavior is considered to be elastic. So, the input parameters will be E and μ.

Remember that the interaction factor is a function of the spacing between the piles. So, the spacing between each pair of piles is to be calculated separately to decide the α value.

There is a need of one pile stiffness factor to cater for the cross section of the pile whether it is solid or hollow. The formula for this factor is:

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

where, E_s is the elastic modulus of the soil, R_A is the ratio of the area of the pile section A_p to the area bounded by the outer circumference of the pile. (for a solid pile, R_A will be 1, but for a hollow section, it will be less than 1).

If the pile has hollow cross section with an outer diameter D_o, then the area bounded by the outer circumference area of the pile will be $\left(\pi \times D_O^2 / 4\right)$. But, the area of the pile section would be $\left\lfloor \pi/4 \left(D_O^2 - D_i^2\right)\right\rfloor$ there by reducing the value of R_A less than 1. (D_i is the inner diameter of the hollow pile)

In the expression, P_k is the load which is coming onto the pile which can be calculated. ρ_1 can be determined from the pile load test or from the single pile elastic analysis, but how to obtain α?

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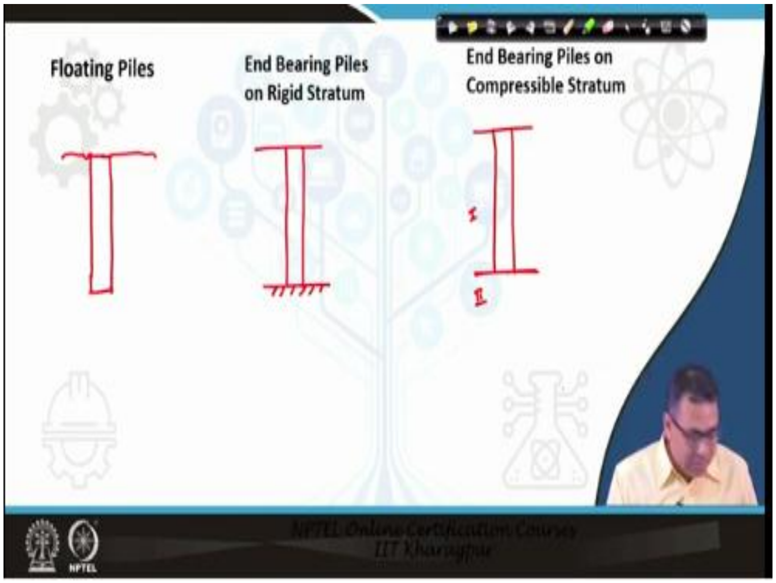

There are three different cases given for α: floating pile, end bearing piles on rigid stratum and end bearing piles on compressible stratum. Floating pile means that a pile is in a homogeneous soil and it is very deep. The pile referred to in the second case rests on a rigid stratum like hard rock and hence it cannot be compressed. But in the third case the pile, though is end bearing, rests on a compressible stratum.

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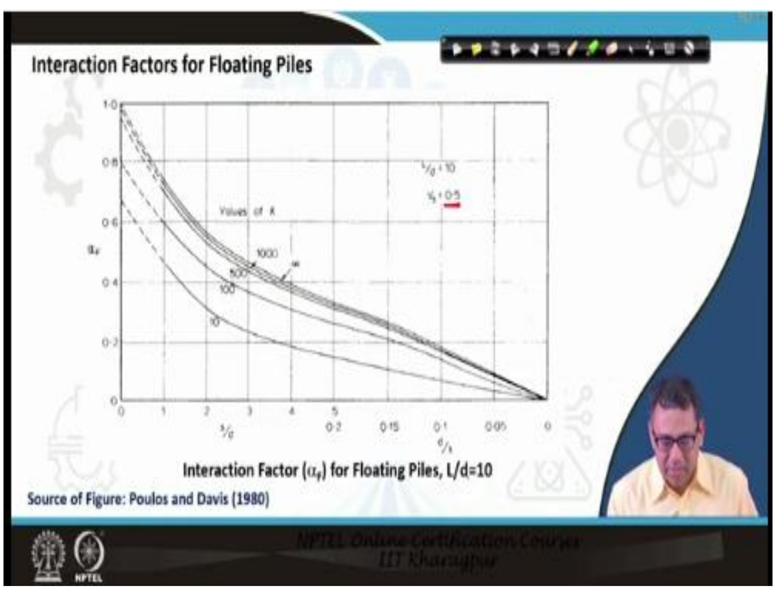

The above graph helps determining the α value depending upon the spacing, length, k-value and diameter of floating piles. This particular graph is for an L/d ratio of 10 and Poisson's ratio of 0.5. Since this graph is for the interaction factor of floating piles, it is termed α_f.

From the graph it can be noted that for a given L/d value, if the k value decreases, then the interaction factor value also decreases. So, to determine the interaction factor, the k value, S/d ratio and L/d ratio should be known.

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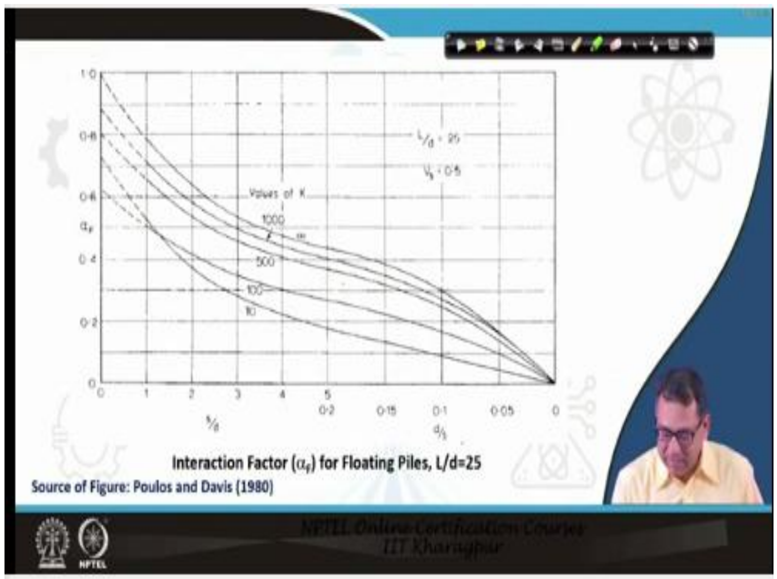

This is also a chart to determine the interaction factor of floating piles, but for an L/d ratio of 25.

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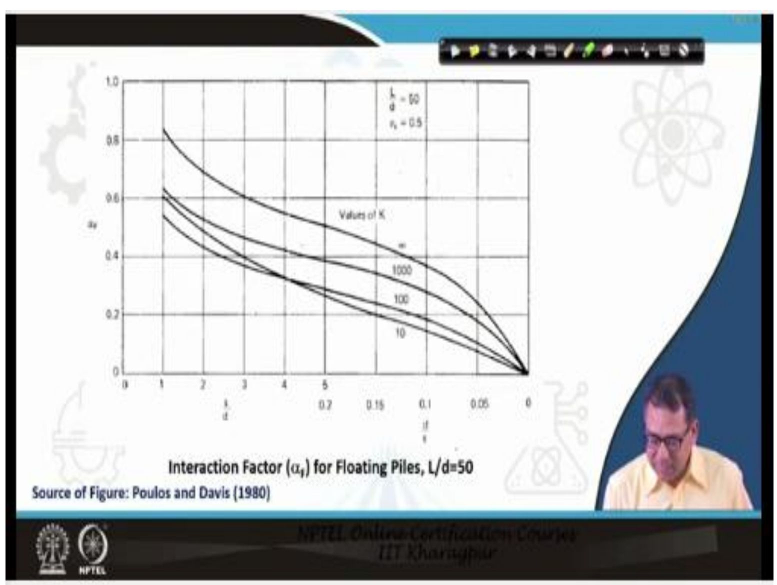

Similarly, the above chart is for an L/d ratio of 50.

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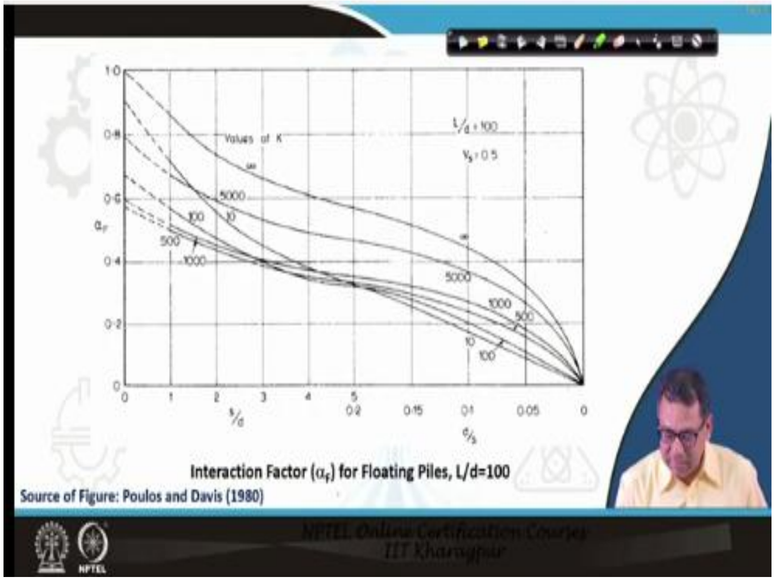

Similarly, the above chart is for an L/d ratio of 50. Note that all these charts are given for a Poisson's ratio of 0.5.

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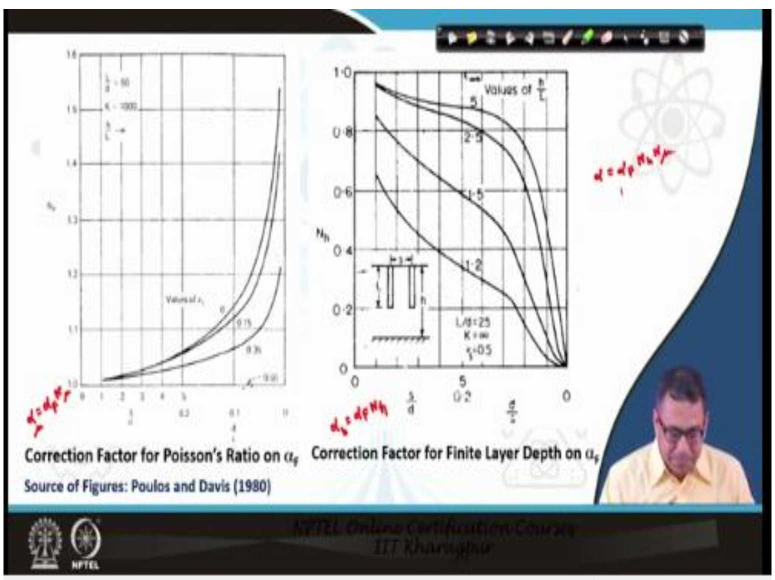

The μ value may not be always 0.5, but all these charts of interaction factor are developed for μ = 0.5 only. So, if μ is not 0.5, then a correction factor should be applied. That correction factor can be determined from the chart above. The α should be multiplied with this correction factor if the field soil has a different Poisson's ratio (other than 0.5). In the slide above, the chart on the left side gives this correction factor for Poisson's ratio (N_μ) in case of a floating pile in a soil stratum with infinite depth. But, if the layer in which the floating pile is resting has a finite depth, the interaction factor should again be corrected for the finite layer depth (N_h). So, if a floating pile rests in a soil layer of finite depth and the soil does not have a Poisson's ratio of 0.5, the interaction factor should be applied with two correction factors: $\alpha = \alpha_f \times N_h \times N_\mu$

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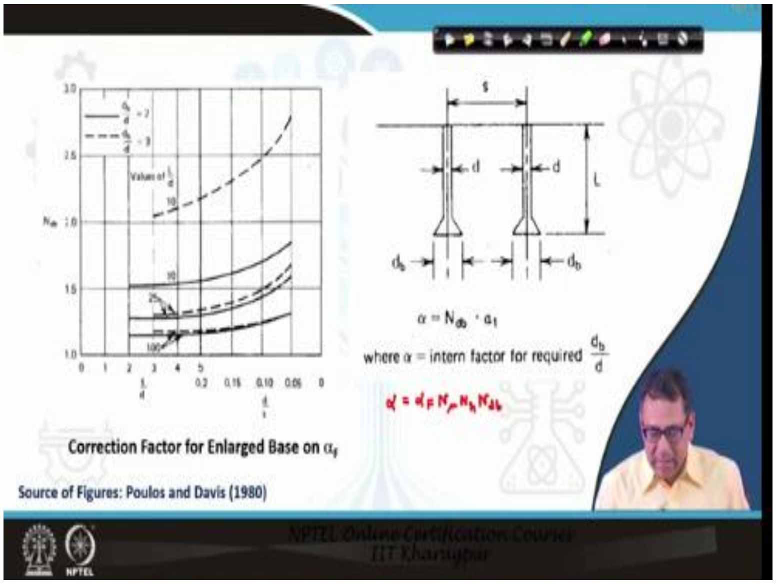

If the base of a floating pile is enlarged, another correction (N_b) should be applied to the interaction factor. The above chart gives this correction factor for d_b/d ratios of 2 and 3 (where d_b is the diameter of the enlarged base; d is the diameter of the pile shaft).

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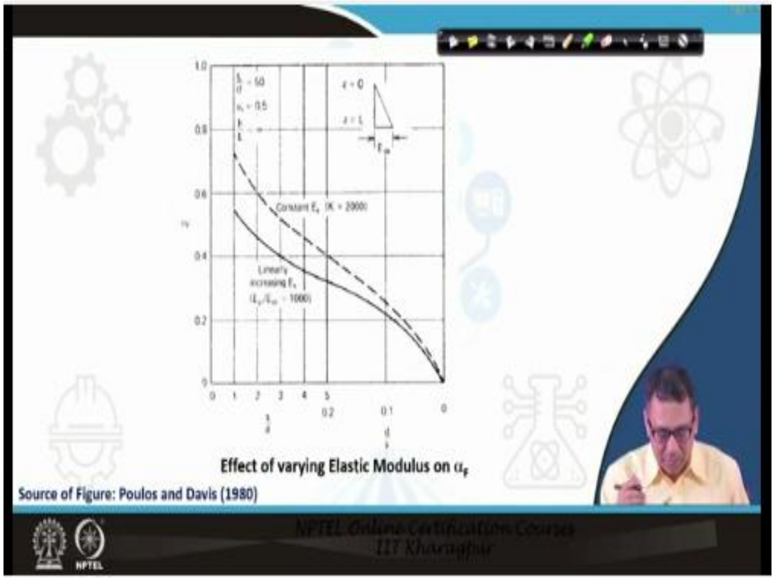

The charts discussed so far are developed considering constant elastic modulus along the depth of the pile. But most of the cases if we consider that pile elastic modulus increases with depth, there will be a 20% variation in the results. This chart gives the correction factor in case the soil's elastic modulus is increasing linearly with depth.

So for the interaction factor in floating pile groups, four correction factors are discussed: for Poisson's ratio, finite layer depth, enlarged base and for varying elastic modulus.

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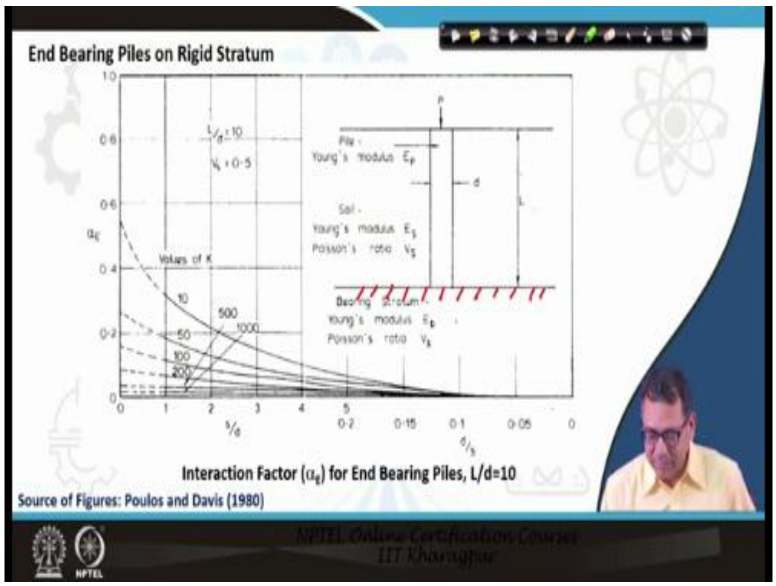

Similar charts are available for end bearing piles resting on a rigid stratum (the second case). As the interaction factor discussing now is for the end bearing piles, it is termed as α_E. The above chart shows the variation of α_E values with various spacing values for a soil of Poisson's ratio of 0.5, an L/d ratio of 10 and different k values.

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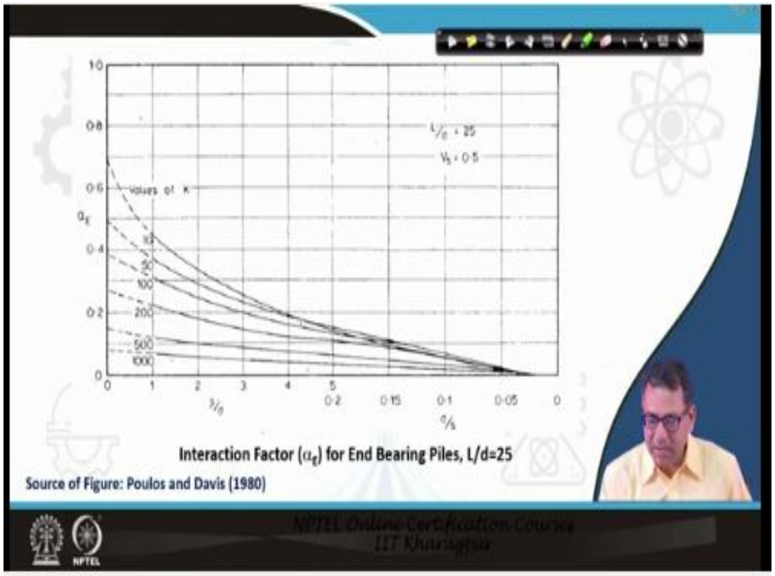

This chart is for an L/d ratio of 25 and a Poisson's ratio of 0.5.

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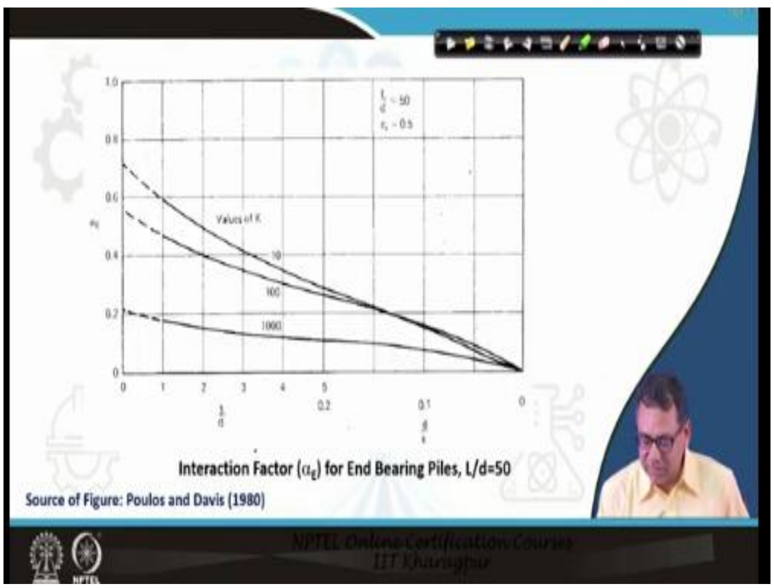

This chart is for an L/d ratio of 50 and a Poisson's ratio of 0.5.

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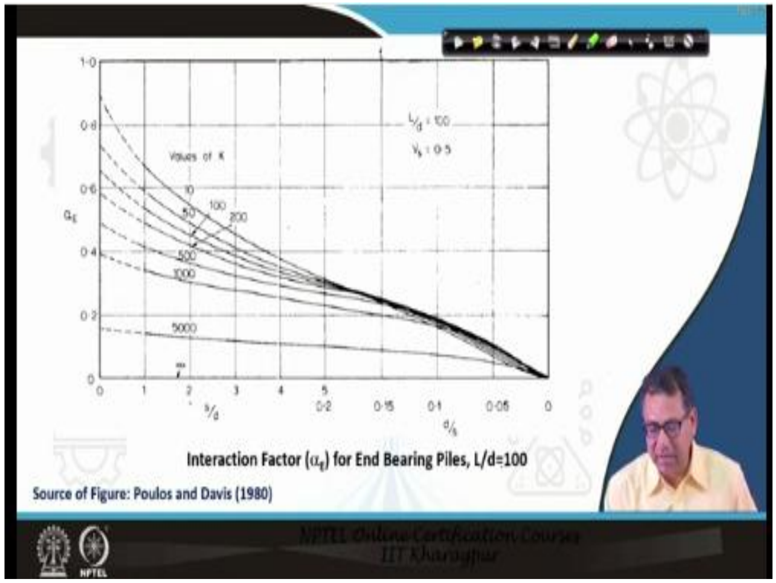

This chart is for an L/d ratio of 100 for 0.5 Poisson's ratio.

Even for the end bearing piles, further correction factor should be used if μ is not 0.5.

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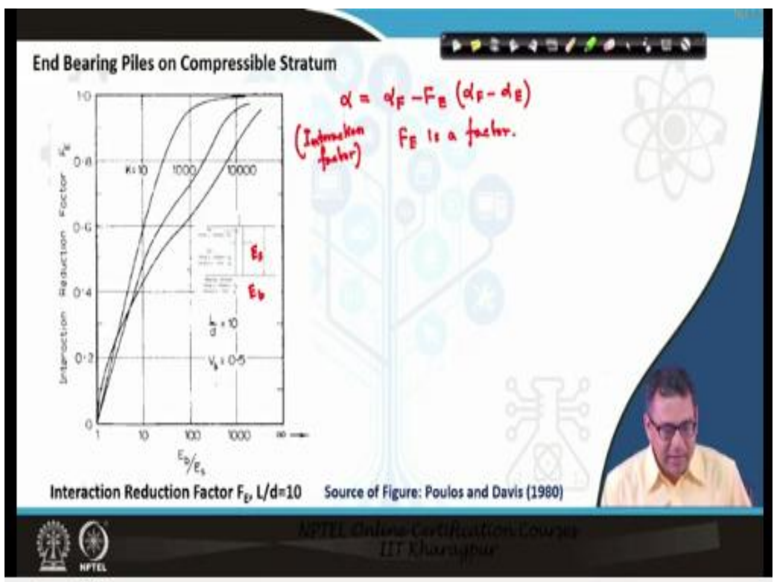

The third case is where the end bearing piles rest on a compressible stratum. The correction, in this case is named as the interaction reduction factor, F_E. The F_E value depends upon the L/d ratio and E_b/E_s ratio. E_b is the elastic modulus of the soil at the base of the pile and E_s is the elastic modulus of the soil where pile is passing. The above chart is given for an L/d ratio of 10 and a Poisson's ratio of 0.5. To apply this correction, there is a formula to be adopted:

$$\alpha = \alpha_F - F_E(\alpha_F - \alpha_E)$$

The α_F and α_E values should be read from the interaction factor charts of floating piles and end bearing piles respectively. The term α in the above expression is the corrected value of interaction factor.

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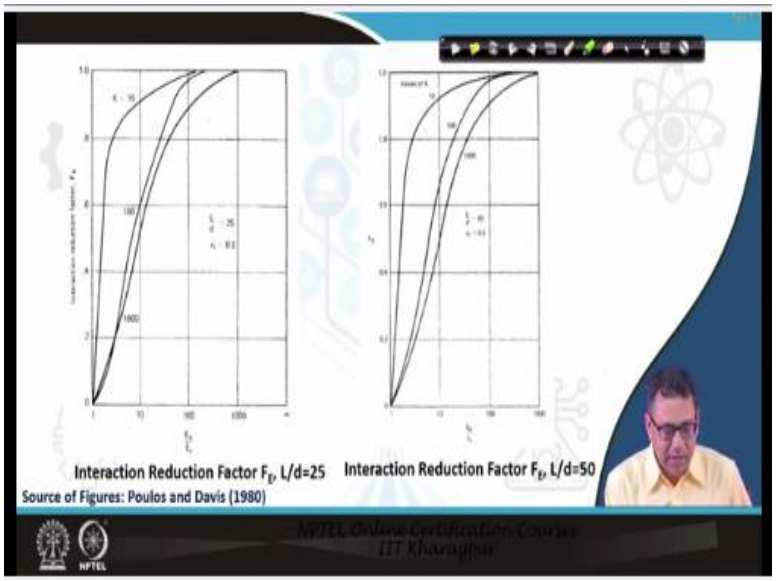

These charts are for L/d ratios of 25 (on the left) and 50 (on the right).

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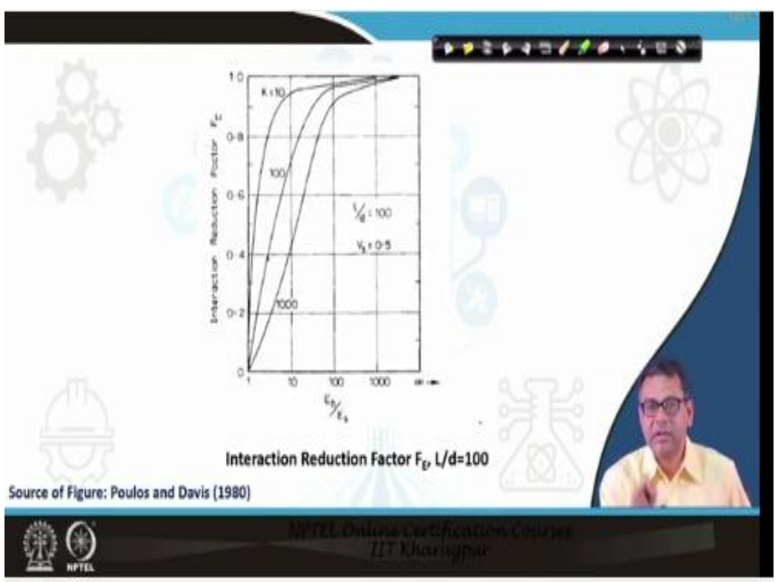

Similarly this chart is for an L/d ratio of 100.

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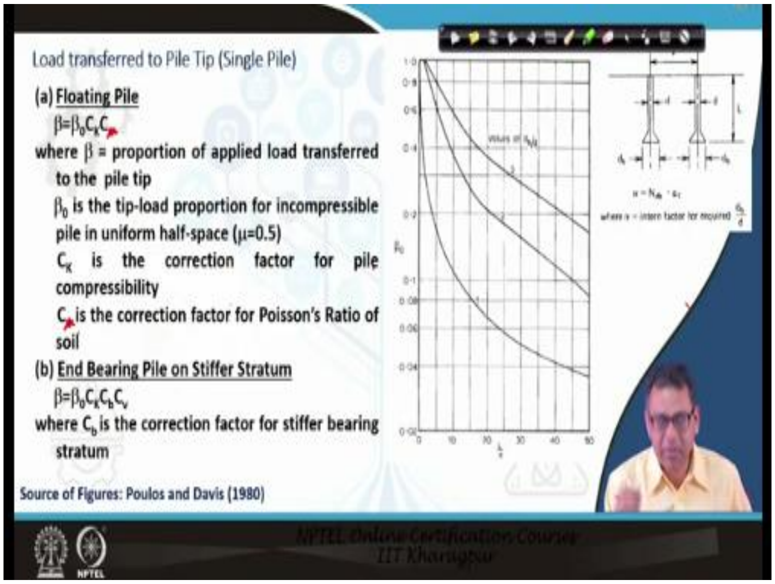

The next part is about the single pile settlement calculation. The settlement of a single pile depends on the load which will be transferred to the pile tip. Here also two cases will be considered: floating pile and end bearing pile on stiffer stratum. The load transferred to the pile tip in case of a single floating pile can be calculated by:

$$\beta = \beta_o C_k C_\mu$$

where, β is the proportion of applied load transferred to the pile tip, β_o is the tip-load proportion for incompressible pile in uniform half-space, C_k is the correction factor for pile compressibility and C_μ is the correction factor for Poisson's ratio of soil. β_o can be calculated from the chart shown in the above slide. This chart is given for the d_b/d ratios of 1, 2 and 3 (d_b is the diameter of the pile base and d is the diameter of the pile shaft).

β_o is also the proportion of load transferred to the pile tip similar to β, but the difference is that β_o is for a rigid floating pile resting in a soil of Poisson's ratio 0.5. If that is the case existing in the field, the C_k and C_μ values will be unit and β_o will be equal to β. This means that it is considered that the pile is incompressible and resting in a soil with very great depth of Poisson's ratio 0.5. If that is not the case, these corrections should be applied. Ck is applied if the pile is compressible and C_μ is applied if the Poisson's ratio of the soil is not 0.5.

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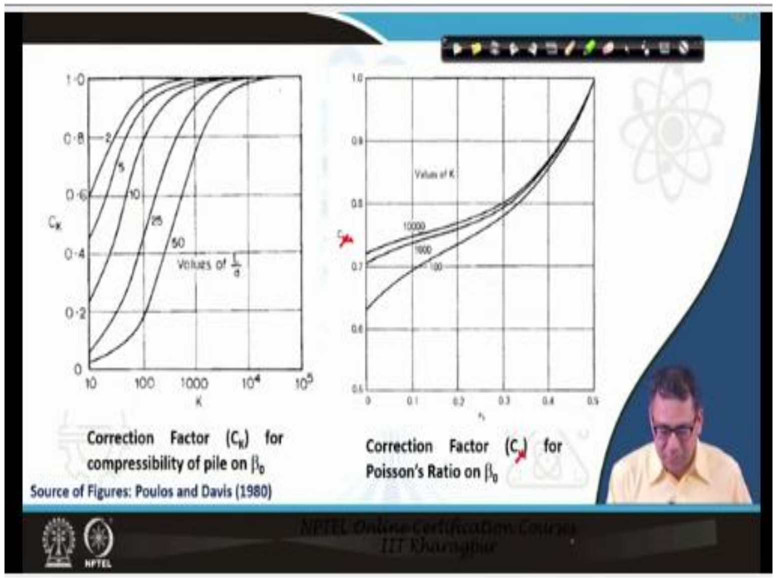

The C_k and C_μ values can be determined from the charts above. The chart for C_k depends upon the k value as this correction is related to the compression of pile. Similarly the chart for C_μ depends upon the μ value as this correction is related to the Poisson's ratio. If the correction factor, C_k is to be found out for a very high k value, it will be very near to one as a high k value refers to a rigid pile. Similarly C_μ will also be close to 1 if the Poisson's ratio is close to 0.5.

In the settlement determination of single piles, the other case is the end bearing piles. The formula for β in case of end bearing piles has an extra correction factor compared to that of the floating piles which is, C_b. C_b is the correction factor for stiffer bearing strata.

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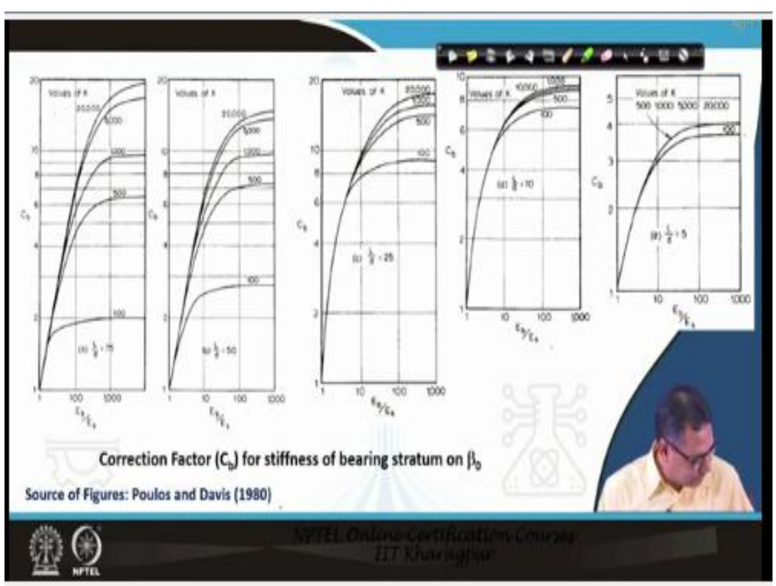

The values of C_b for various L/d ratio values are given in the charts above. These charts also show the variation of the factor with E_b/E_s ratio.

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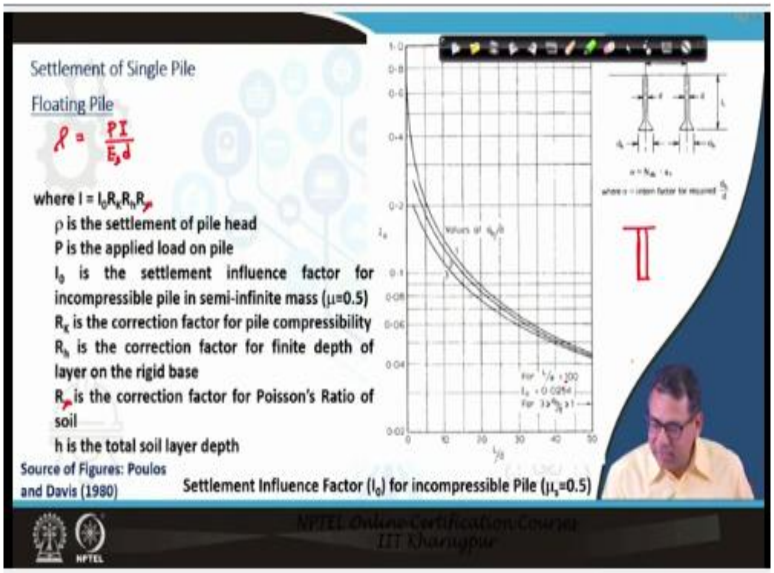

The settlement of a single floating pile can be given by:

$$\rho = \frac{PI}{E_s d}$$

where, $I = I_o R_h R_k R_\mu$; ρ is the settlement of the pile head, P is the load applied on the pile, I_o is the settlement influence factor for incompressible pile in semi-infinite mass (μ = 0.5), R_k is the correction factor for pile compressibility, R_h is the correction factor for finite depth of layer on the rigid base and R_μ is the correction factor for Poisson's ratio of soil.

If the pile has some compressibility, the correction factor R_k should be applied and if the pile has a finite depth then the correction factor R_h should be applied and if the Poisson's ratio is less than 0.5 then the correction factor R_μ should be applied, h is the total soil layer depth. The I_o values can be determined from the chart in the above slide. This chart is given for L/d values ranging from 0 to 50 and is valid only if $3 \geq {}^{d_b}\!/_{d} \geq 1$.

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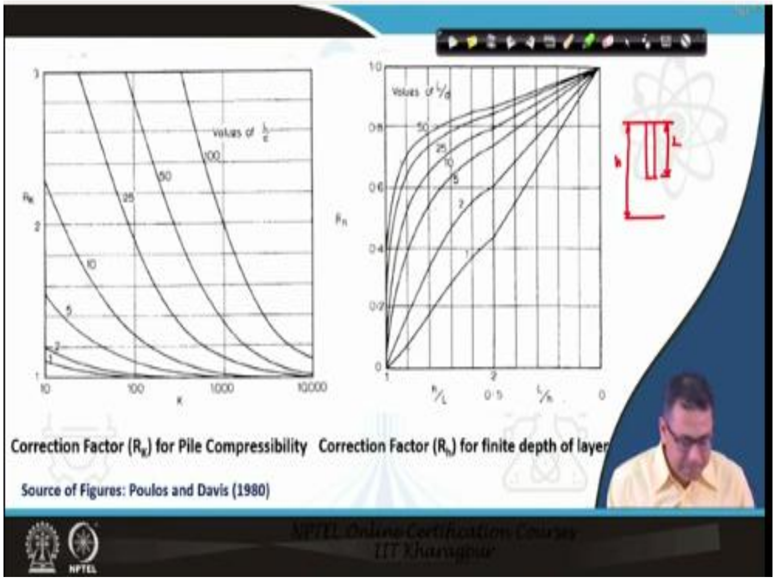

These are the charts for the correction factors, R_k (on the left for the pile compressibility) and R_h (on the right for finite depth of layer). The R_k value is given for different L/d values varying with the k value of pile. The R_h correction is given for different L/d ratios varying with the h/L or L/h ratio. For an infinite layer, the height of the layer is ∞ and hence the L/h value will be 0 for that case. In the chart, it can be seen that for an L/h value of 0, the R_h value is 1. This implies that for a pile in infinite beam there will be no height correction (or R_h = 1).

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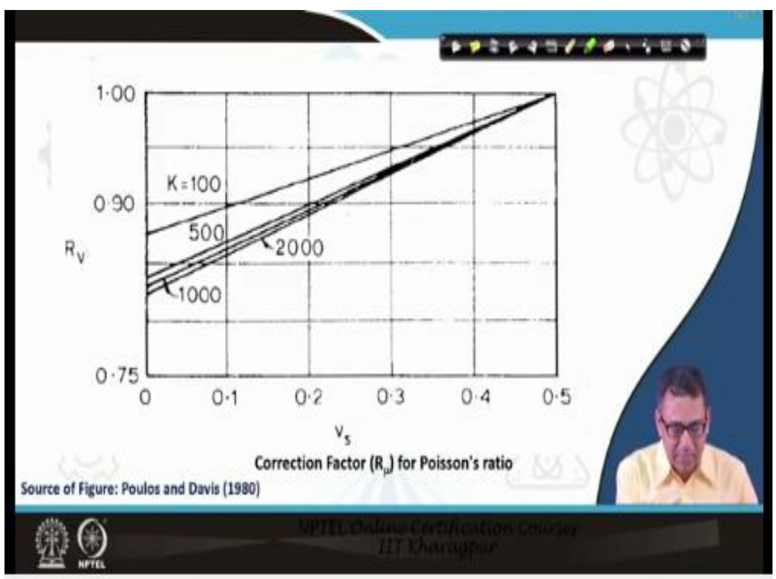

Similarly this chart is for the R_μ correction factor for various k values varying along with μ.

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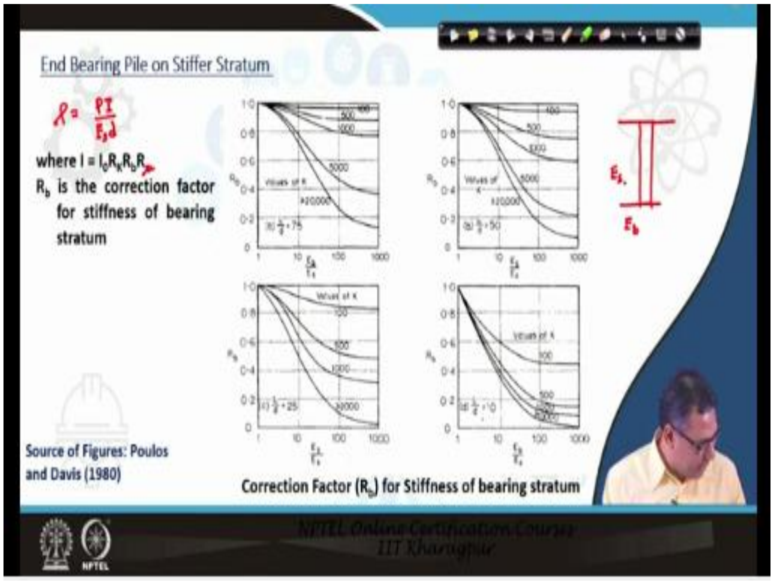

The next case is the end bearing piles resting on stiffer stratum. The settlement expression for this is the same as that of the floating piles:

$$\rho = \frac{PI}{E_s d}$$

The only difference is in the I value because here, $I = I_o R_k R_\mu R_b$ (Rb is the correction factor for stiffness of the stiffer bearing stratum). The Rb value varies with the E_b/E_s ratio, k value and also the L/d ratio which is shown through the charts above. As this formula is developed for the end bearing pile, the correction for the finite layer height, R_h is not required here.

So, that means, there will be the formation of the this strata also. So, that means here this correction factor Rb correction factor for the stiffness of the bearing strata is also incorporated. That means that was not there in the floating pile because there is that is the stiffness of bearing strata was not present. So here that correction factor is we have to include but the finite depth correction factor is not required here.

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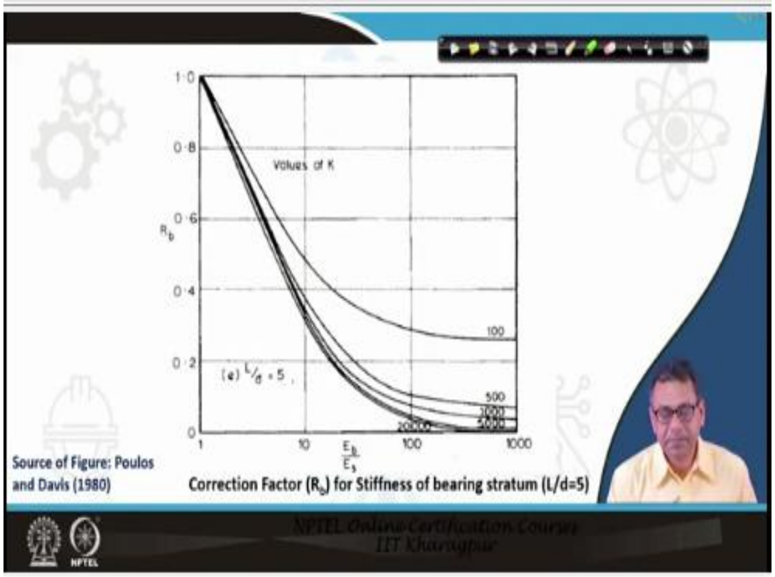

This is the chart for R_b when the L/d ratio is 5.

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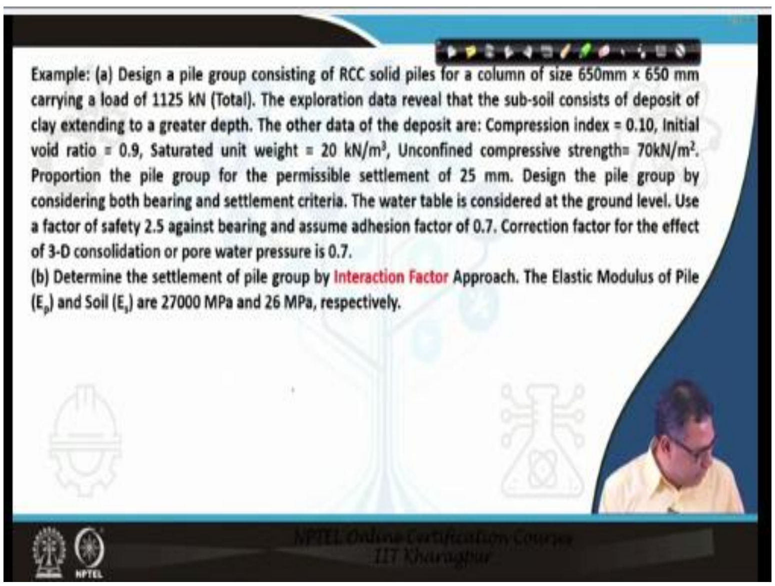

These are the charts that can be used to determine the single pile settlement. The interaction factor charts can be used to determine the group pile settlement.

In the next class, I will solve one design problem and I will show how to use these charts and to calculate the settlement of a group pile. Thank you.