Advanced Foundation Engineering
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Lecture - 44
Pile Foundation: Under Compressive Load - IV

So, last class I have discussed that how theoretically we can generate load settlement curve for pile. And in that approach we divided the pile into number of segments and then for each segment we determine or calculate the settlement at the centre by assume a tip deformation. And then we will get that P_u, ultimate load carrying capacity of the pile and that settlement of the pile at the top based on one particular assumed tip deformation.

So, now if we change the tip deformation value then you will get different P_u and δ. So, this way you have to repeat this process for different Δy_P values and then you will get the load versus settlement value for different tip deformation. So, under different tip deformation we will get a deformation of the pile top and the load. So that you have to plot and you will get the load versus deformation curve.

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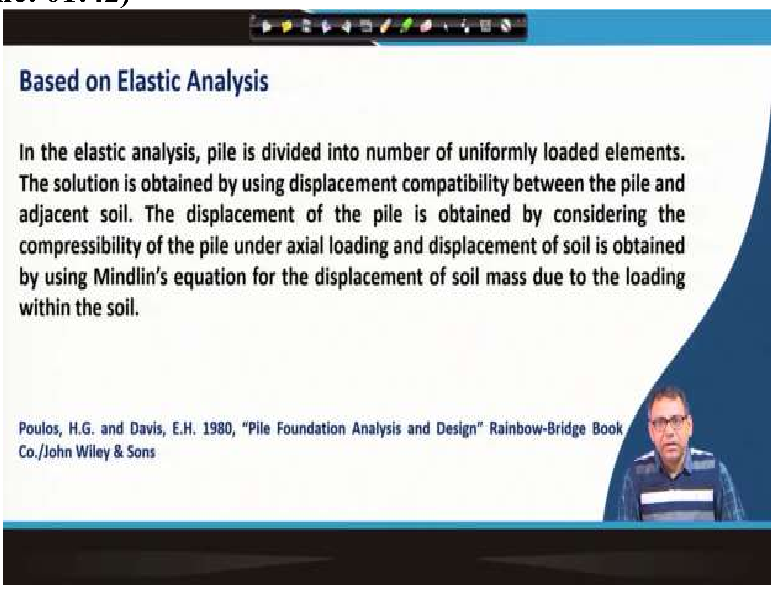

Now next today I will discuss another approach which is the elastic analysis so based on elastic analysis also you can generate the load deformation curve theoretically. So, elastic analysis is what? In elastic analysis also pile is divided into number of uniformly loaded elements the solution is obtained by using displacement compatibility between the pile and the adjacent soil.

The displacement of the pile is obtained considering the compressibility of the pile under axial load. And the displacement of the soil is obtained by using Mindlin equation for the displacement of soil mass due to loading within the soil. So, if you get the detailed solution procedure of this process then you can go through this book or given the reference. So, this pile foundation analysis and design by Poulos and Davis you will get the detailed solution procedure.

So, I will not discuss that solution procedure I will discuss how I can apply that approach to determine the load settlement curve so detailed solution procedure is available here. So, in this method so what is that? That we can determine how much load is transferred to the pile tip when we apply a load on the pile top. So that value or that expression is given for floating pile.

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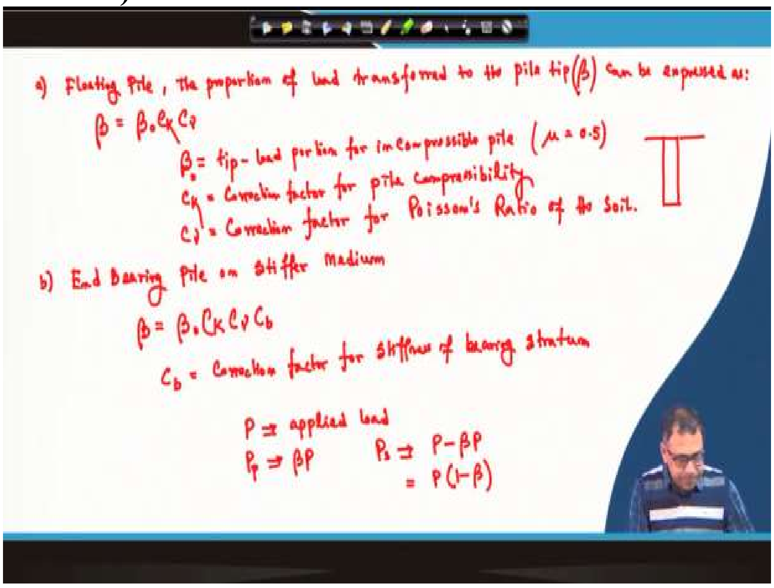

Floating pile means pile is not resting on a rigid stratum it is only a uniform soil where for the floating pile the proportion of load transferred to the pile tip, β can be expressed as $\beta_0 C_K C_\nu$. So, what is β_0? β_0 so, where the β_0 is equal to the tip-load portion for incompressible pile when the Poisson's ratio ν is 0.5. So, that means that if the pile is incompressible and the soil Poisson ratio is 0.5 then we can use $\beta = \beta_0$.

But if the pile is not incompressible and the ν is not 0.5 then you have to apply two correction factors. So, those two correction factors are C_K and C_ν. So, C_K is equal to correction factor for pile compressibility and C_ν is the correction factor for Poisson's ratio of the soil.

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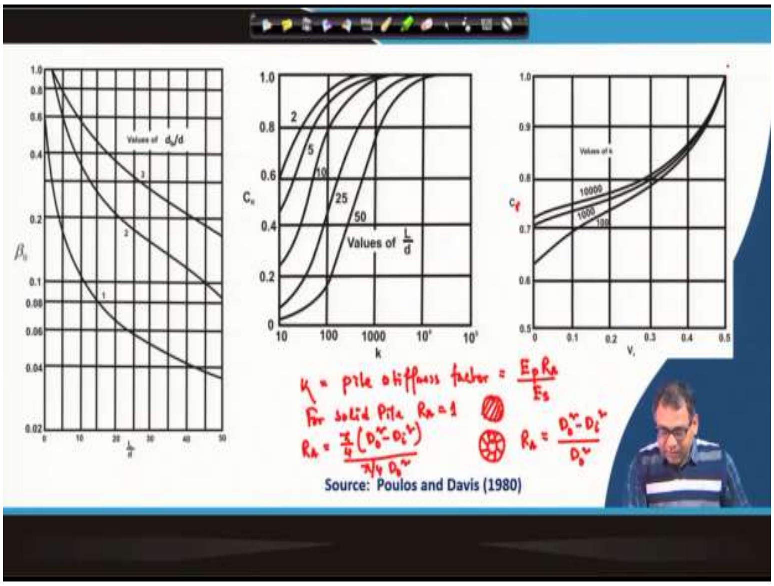

So, how I will get this β_0, C_K, and C_ν so, this β_0, I will get from these values these charts. So, this is $\frac{L}{d}$ different length by diameter. This is the β_0 value and this d_b is the diameter of the base. Suppose, if uniform diameter, then $\frac{d_b}{d}$ will be 1, but if the base has enlarged diameter compared to the shaft, then we have to calculate $\frac{d_b}{d}$ accordingly otherwise, if the shaft diameter and the base diameter is same, $\frac{d_b}{d}$ will be 1.

Then I will get C_K from this chart and where K is called the pile stiffness factor which we can calculate from $\frac{E_P R_A}{E_S}$, where, E_P is the elastic modulus of the pile and E_S is the elastic modulus of the soil. Now, for solid pile, $R_A = 1$ and for the hollow pile, $R_A = \frac{\frac{\pi}{4}(D_O^2 - D_i^2)}{\frac{\pi}{4} D_O^2}$. So, for the hollow pile this will be $\frac{(D_O^2 - D_i^2)}{D_O^2}$.

So, outer diameter of the pile is equal to D_o and inner diameter of the pile is equal to D_i. So, for the solid pile $R_A = 1$ and for the hollow pile, so, this is equal to that effective area divided by the area covered by outer surface of the pile. So, your effective area is this one which is the hatch portion and divided by the outer surface of the pile which is D_O^2. So, this is the R_A value you will get.

So, for a very stiff pile where the stiffness is very high you can see that the correction factor is 1. So that means if the pile is incompressible or very stiff then the correction factor is 1. And if the Poisson's ratio of soil is 0.5 and the pile is very stiff then $\beta = \beta_0$ otherwise we have to apply these. Similarly, you can see that if Poisson's ratio is different from 0.5, we have to apply these corrections.

So, this is for different K values and I have discussed how to calculate it. So, this is for the floating pile similarly for the end bearing pile on stiffer material or stiffer medium then the $\beta = \beta_0, C_K$ then C_ν and C_b. So, these C_K and C_ν are same as we have discussed for the floating pile but now C_b is introduced. What is C_b? C_b is the correction factor for stiffness of bearing stratum.

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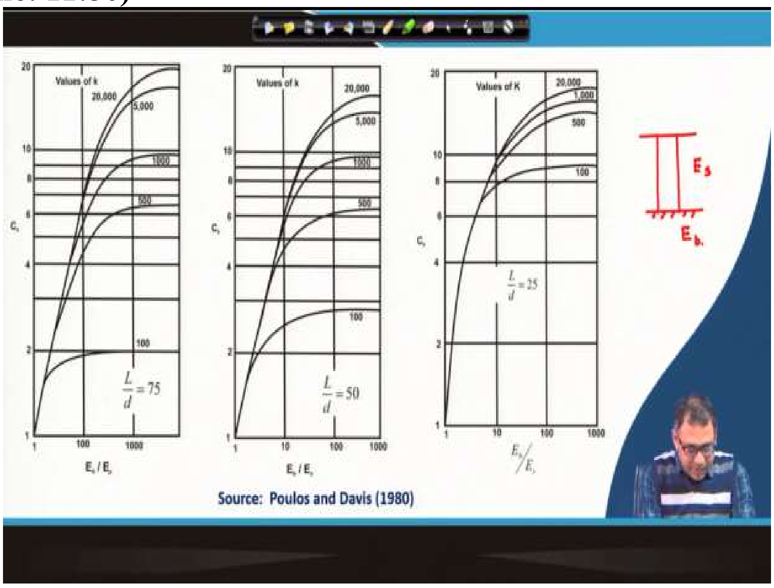

So, how I will get this C_b value? So, C_b value I will get by using these expressions. So that means here the pile is on the bearing stratum or a stiff stratum boundary where this is the E_s and this is the E_b or the base soil where the pile is resting. And previous case the floating pile means this is the pile which is in a uniform soil. And that soil is extended up to a deeper depth that is for the floating pile. And here it is resting on a stiffer medium or stiffer stratum. So, now this is $\frac{E_b}{E_s}$ for different $\frac{L}{d}$ ratio. This $\frac{L}{d}$ ratio is 75, 50, 25.

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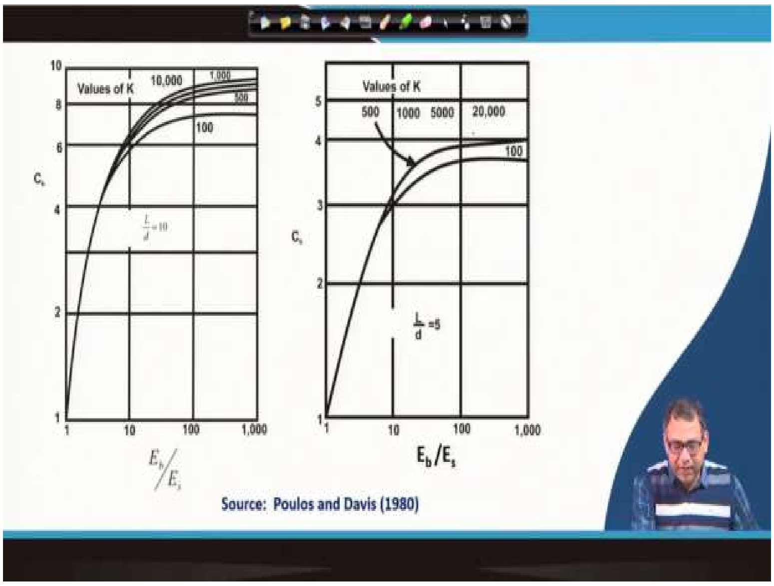

Then this is 10, this is 5 and this is different K value. K value I have already discussed then if I know that $\frac{E_b}{E_s}$ and $\frac{L}{d}$ ratio and the K value then I will get the correction factor. So, this way I will get the correction factor for different $\frac{L}{d}$ ratios from 75 to 5. So, this way I can calculate that how much portion of the load is transferred to the tip of the pile when we apply a load on the pile.

So that means some portion of the load is taken by the friction and some portion by the pile tip. So, this beta is the portion of the load transferred to the tip. So, the if the P is the applied load, then the $P_P = \beta \times P$ because that portion of the load is transferred to the tip and then the P_s is the frictional and that will be equal to $P - \beta P$. So that will be equal to $P(1-\beta)$. If $\beta = 0$ then all stresses are taken by the friction

If $\beta = 1$ that means all the stresses are taken by the pile tip. So, this way we can determine how much load is transferred to the tip and how much load is taken by the friction of the pile. Now I will calculate the settlement of a single pile by using this approach. So, now we know that how much load is transferred to the tip and how much load is taken by the pile friction.

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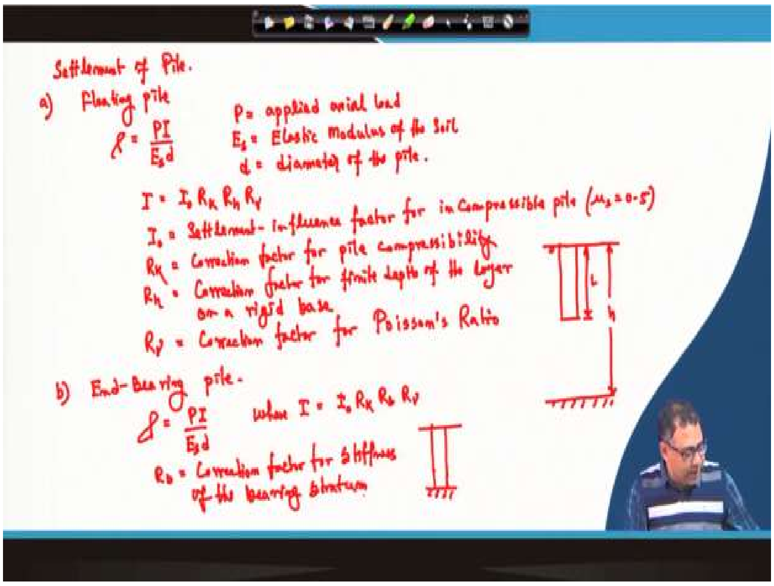

Then now we can calculate the settlement of pile. So, again for floating pile that settlement, $\rho = \frac{PI}{E_s d}$. So, P is the applied axial load then E_s is the elastic modulus of the soil, d is the diameter of the pile and $I = I_0 R_K R_h R_\nu$. Now, what is I_0? This I_0 is equal to settlement factor for incompressible pile when $\nu_s = 0.5$. So, that means the settlement influence factor for incompressible pile.

So, correction factor for incompressible pile is R_K is 1 then for $\nu = 0.5$, R_ν will be 1 and R_h is another factor which is due to the finite depth of layer on a rigid base. So, previous floating pile we have assumed depth of layer is infinite, but if the depth of layer is finite. Suppose your pile is like this, this is the pile and there is a finite depth of the layer it is floating pile but this is the L and this h is the thickness of the layer then also we have to apply the correction factor because these I is for infinite depth or the thickness of the layer.

If it is a finite then you have to apply the correction factor. So, these three correction factors one is for the compressibility of the pile, one is for Poisson's ratio of the soil and another is for finite thickness of the layer. So, again the R_K is the correction factor for pile compressibility, R_h is the correction factor for finite depth of the layer or finite thickness of the layer on a rigid base and R_ν is the correction factor for Poisson's ratio like this one. Here also correction factor for these three cases we have to apply the same correction factor. Now how we will calculate this correction factor?

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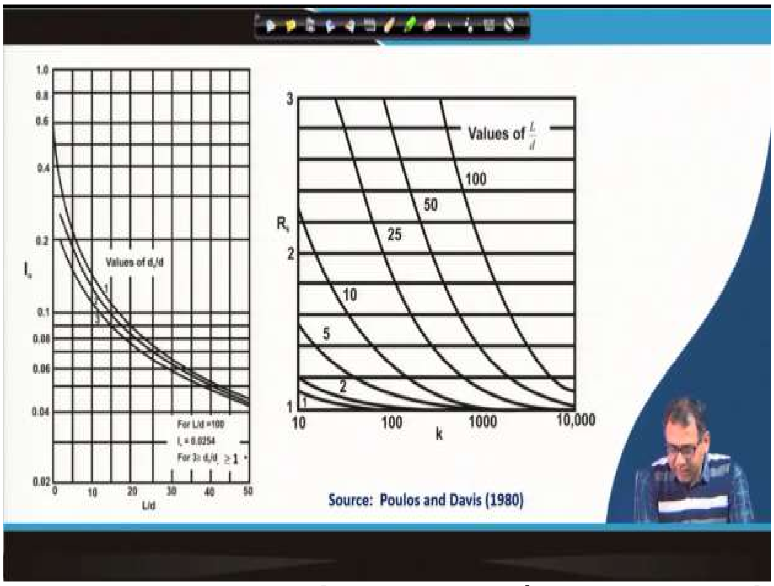

So, this is I_0 and we will get for different $\frac{L}{d}$ and again for $\frac{d_b}{b}$, I_0 value and if $\frac{L}{d}$ is greater than or equal to 50 then I_0 will be equal to this value, but this is valid for $\frac{d_b}{b} = 1, 2, 3$ then correction factor, this is for R_K chart for different $\frac{L}{d}$ and the K values.

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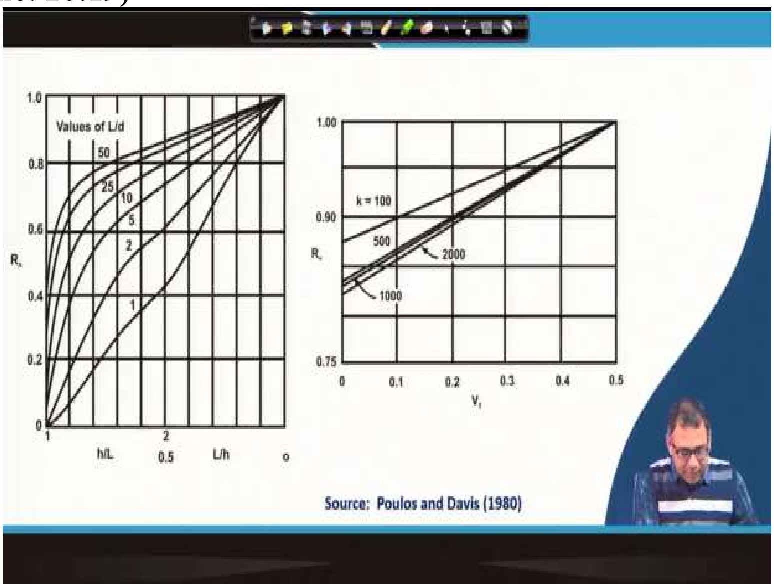

Then this is for the R_h chart different $\frac{h}{L}$ values and this is for Poisson's ratio of the soil, ν_s chart. This is for different Poisson's ratio 0.0 to 0.5 for different K values and then we will get these correction factors from this chart or this chart. Now, similarly, for the end bearing pile again the similar expression we can write $\frac{PI}{E_s d}$ where $= I_0 R_K R_b R_\nu$. So, R_K, R_ν are same as the R_K, R_ν discussed for the floating pile.

But here R_h will not act here because in this case it is resting on the rigid stratum. So, there is no question of R_h but R_b is introduced which will incorporate the effect of stiffness of the base soil where the pile is resting so that means here R_b is correction factor for stiffness of the bearing stratum.

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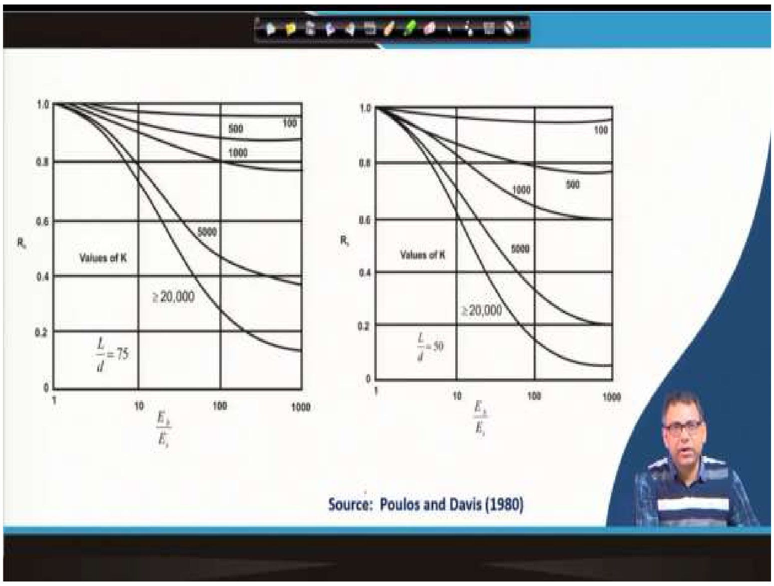

So, now I can calculate the R_b so, this is the chart where I can calculate the R_b. So, again for different $\frac{L}{d}$ values of 75, 50, 25, 10 and 5.

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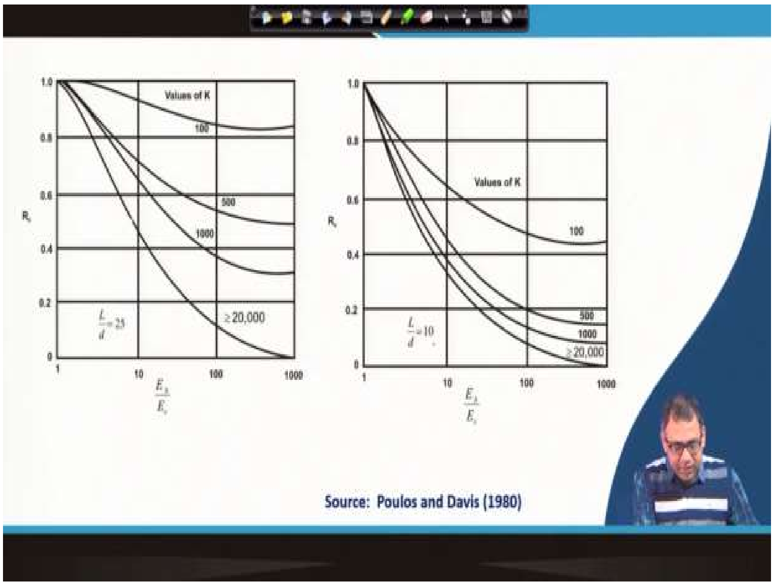

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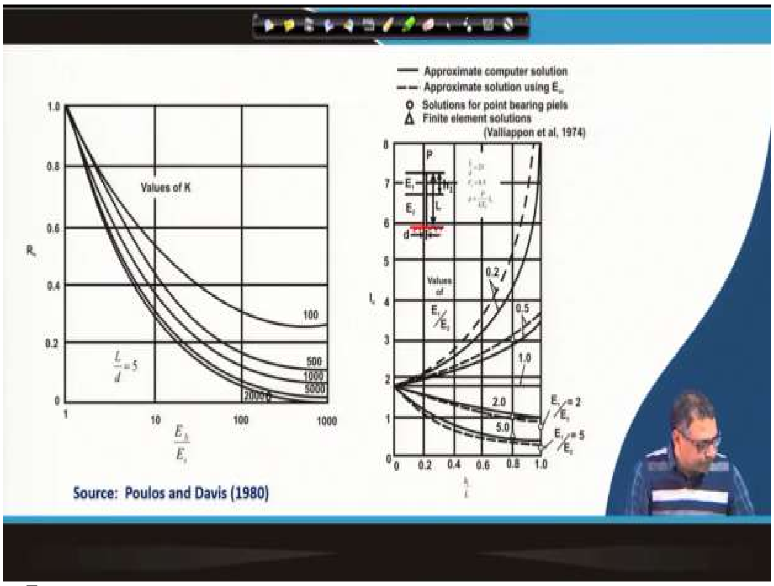

And for different $\frac{E_b}{E_s}$ values and for different K we will get the R_b value. So, these are the correction factors, we will get. Now these charts will give you that how we can calculate I_0 for different layers of soil. If you have a layered soil for layer 1 and layer 2, the layer 1 thickness is h_1 and the total thickness is L. So, layer 2 thickness will be $L - h_1$you will get I_0 for different values of $\frac{E_1}{E_2}$.

So, E_1 is the elastic modulus of the layer 1, E_2 is the elastic modulus of layer 2 and these 2, 5, 1, 0.2, 0.5, 1, 2, 5 we can get the value of I_0. Now, what is the difference between dotted line and the firm line? The firm line is the approximate computer solution and dotted line if you take the average E value and then that if you take the weighted average E value and then you follow the same process that we have done for the uniform soil because here it is the layered soil and previous cases are for uniform soil.

So, in layered soil also, you take the weighted average value and apply the concept of the uniform soil then also you will get more or less close result. But the firm line is taking different E value into the analysis and not the weighted average that is given the firm line and the dotted line is for the solution for taking the average E value and using the concept of uniform soil.

So, you use the firm line to determine the I_0 for layered soil and that is for h_1 is the thickness of the first layer and L is the total thickness of the layered soil and d is that diameter of the pile. So, this is the pile which is on the rigid strata. Then L is the total length of the pile where E_2 is your elastic modulus for the second layer and E_1 is the elastic modulus of the first layer.

This way also you can determine the I_0 for layered soil and after that you have to apply the corrections as we are doing for the uniform soil. So, one option you use different E_1, E_2 values and then calculate the I_0 and another option you take the weighted average and use the I_0 value for using the uniform soil concept. So, if you do not have this chart for layered soil, you can use the average value and use your uniform soil concept otherwise, you have this chart you can use this chart for taking different E_1 and E_2s value and then you will get I_0.

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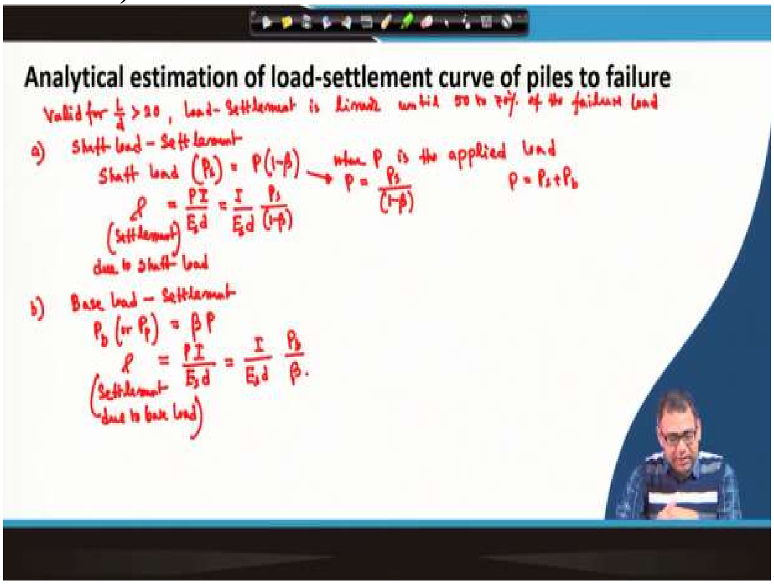

So, next part is how I can use these analyses and I can estimate the load settlement curve for pile up to the failure. So, this analysis is valid for $\frac{L}{d} > 20$ and load settlement is linear until 50% to 70% of the failure load. So, that means the load settlement behavior is linear up to 50% to 70% of the failure load, after that is nonlinear. So, but actual load settlement behavior is nonlinear but here we will represent that load settlement curve by linear lines.

So, first I will discuss about the determination of the shaft load versus settlement behavior. What is this? Settlement so as I have discussed the shaft load P_s is how much? That is equal to $P(1-\beta)$ because β is portion of the load which is transferred to the tip. So, the shaft load will be $P(1-\beta)$ where P is the applied load. So, because we have already discussed the settlement will be equal to $\frac{PI}{E_s d}$ that is the settlement or here in place of P we are writing the P_s.

Because we want to determine the settlement due to the shaft load only. So, that will be the P_s or settlement due to shaft load. So, that will be $\frac{P(1-\beta)I}{E_s d}$. Now, how we can calculate the I that I have discussed that you have to calculate I_0 and based on that you have to calculate the other factors and then you have to multiply those factors and finally you will get the I value.

So, now, the second part is the settlement due to base load. So, the base load P_p or P_b that is equal to $\beta \times P$. So, the settlement we will get the settlement due to the base load will be equal to $\frac{I}{E_s d}\frac{P_b}{\beta}$ because here this is $\frac{P_b}{\beta}$ which I can write for P so this line I have to slightly modify actually this is the total load and that we have to represent by P.

So, these will be $P = \frac{P_s}{(1-\beta)}$ so this is P because that equation is given the settlement is $\frac{PI}{E_s d}$ so this P we are replacing with $\frac{P_s}{(1-\beta)}$. Here also this is $\frac{PI}{E_s d}$ so that P we are replacing with $\frac{P_b}{\beta}$ so these will be $\frac{P_b}{\beta}$. So that means we are using the actual equation that is the settlement is equal to $\frac{PI}{E_s d}$. Now this P is that total applied load now this P has two parts one is the P_s another one is the P_b so that means, $P = P_s + P_b$.

So, now this is P is replaced in terms of P_s in case of shaft and in case of base the P is replaced in terms of P_b. So, here P is replaced by $\frac{P_s}{(1-\beta)}$ and here P is replaced by $\frac{P_b}{\beta}$. So, in this way we can determine what would be the settlement in terms of shaft load and another settlement in terms of the base load. So, in the next class based on these equations I will show you how we can determine the load settlement curve theoretically, thank you.