Soil Structure Interaction
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Lecture-58
Soil Structure Interaction for Pile Foundation (Contd.)

In the last class I discussed the procedure to calculate the settlement of a pile group in layered soil. I determined the R_s value from the table and applied 2 corrections for finite layer and Poisson's ratio. The corrected R_s value was found to be 3.02.

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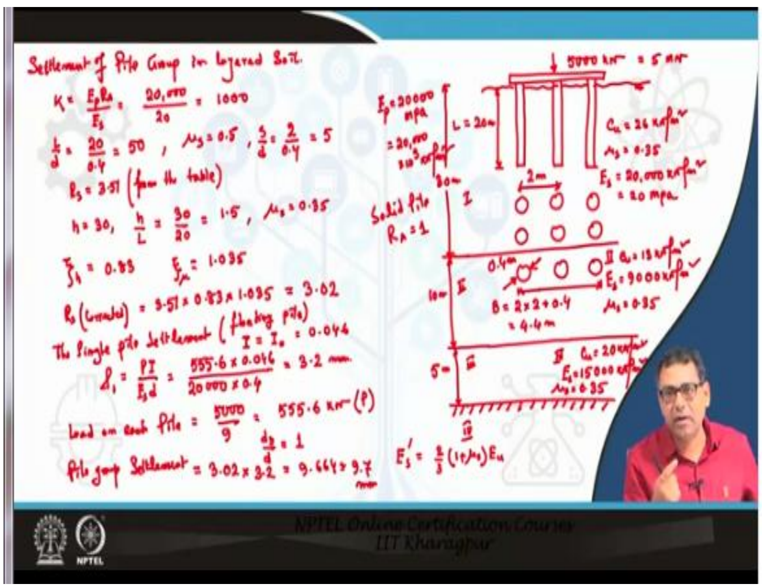

Now that the R_s value is known, the single pile settlement should be known to calculate the group settlement of the piles. The floating single pile settlement resting in a finite depth of the layer should be calculated now.

$$\rho_1 = \frac{PI}{E_s d}$$

The load coming on to each pile, P = 5000/9 = 555.6 kN and I = I_o = 0.046 (from the chart below), the elastic modulus of the soil, E_s = 20000 kPa and pile diameter, d = 0.4 m

$$\Rightarrow \rho_1 = \frac{555.6 \times 0.046}{20000 \times 0.4} = 3.2mm$$

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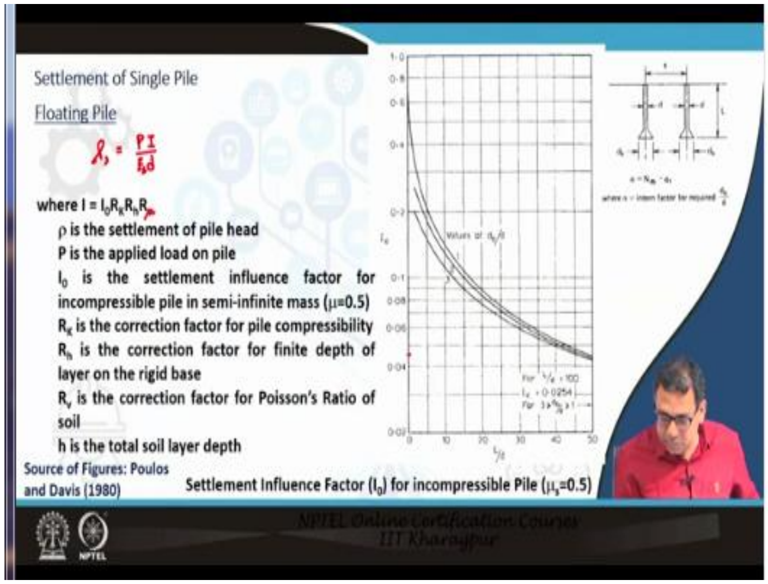

So the single pile settlement is calculated to be 3.2 mm. So the pile group settlement will be:

$$\therefore \text{Pile group settlement} = R_s \times \text{Single pile settlement} = 3.02 \times 3.2 = 9.664 \approx 9.7 \text{ mm}$$

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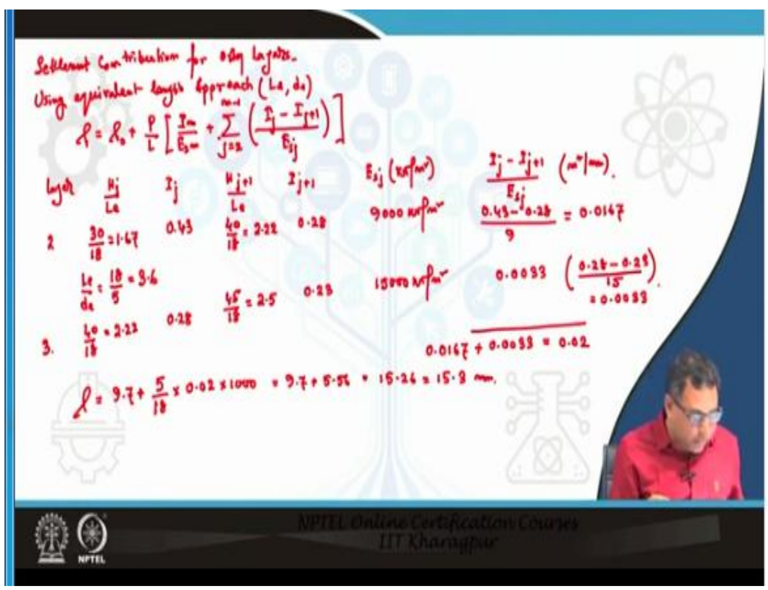

The settlement calculated is only for the first layer. Now the settlement of other layers should be calculated. For this, the equivalent length concept or the equivalent diameter concept can be used but first let us adopt the equivalent length approach.

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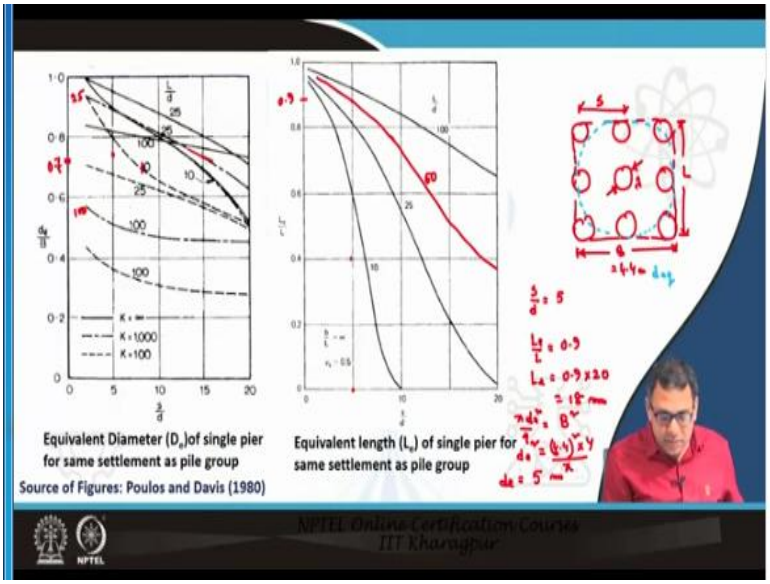

To implement the equivalent length concept, the equivalent length ratio should be read from the chart above (to the right). For an s/d ratio of 5 and L/d ratio 50, the L_e/L value from the chart will be 0.9.

$$\frac{L_e}{L} = 0.9$$

$$\Rightarrow L_e = 0.9 \times 20 = 18\,\text{m}$$

Now, the equivalent diameter should be calculated for the 18 m long equivalent pile:

$$\frac{\pi \times (d_e)^2}{4} = B^2$$

$$\Rightarrow \frac{\pi \times (d_e)^2}{4} = 4.4^2$$

$$\Rightarrow (d_e)^2 = 4.4^2 \times \frac{4}{\pi}$$

$$\therefore d_e = 5\,\text{m}$$

Now the total pile group is converted to a pier, whose diameter is 18 m and length is 5 m. The expression to calculate the settlement of all the layers is:

$$\rho = \rho_{\circ} + \frac{P}{L}\left[\frac{I_m}{E_{sm}} + \sum_{j=2}^{m-1} \frac{I_j - I_{j-1}}{E_{sj}}\right]$$

In the above expression, the term ρ_o (= 9.7 mm) was already determined which is nothing but the settlement of pile group in the first layer. The remaining terms of the equation will be calculated and it will be clear if the values are tabulated.

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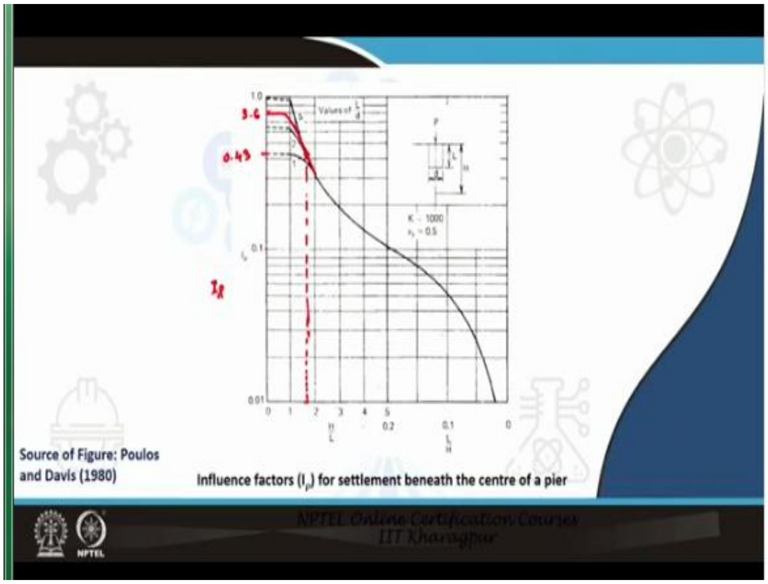

This is the curve to determine the influence factor for settlement, I_j and I_{j+1}. For the first layer here, or the layer-2, I_j will be the top of the layer and I_{j+1} will be the bottom of the layer. As the layer thickness is 30 m and pile length is 18 meter, H_j/L = 1.67. The L_e/d_e or L/d ratio will be 18/5 = 3.6. So for these values, the I_ρ value is 0.43 from the chart. The H_{j+1} value will be 40 (30+10) as it refers to the bottom of layer-2. So, H_{j+1}/L will be 2.22 and for that value, I_ρ will be 0.28. The elastic modulus of the soil in this layer (layer-2) was given as 9000 kN/m^2. Using all these values, the term $\left(I_j - I_{j+1}\right)/E_{sj}$ can be calculated as shown in the table below. The similar procedure should be adopted for the next layer also. The values of layer-3 are also tabulated below.

Layer	H_j/L_e	$\frac{L}{d}$ or $\frac{L_e}{d_e}$	I_j	H_{j+1}/L_e	I_{j+1}	E_{sj} (kN/m^2)	$\left(I_j - I_{j+1}\right)/E_{sj}$ $\frac{m^2}{mm}$
2	1.67	$\frac{18}{5}=3.6$	0.43	$40/18 = 2.22$	0.28	9000	$\left(0.43-0.28\right)/9 = 0.0167$
3	2.22	$\frac{18}{5}=3.6$	0.28	$45/18 = 2.5$	0.23	15000	$\left(0.28-0.23\right)/15 = 0.0033$

$$\text{So, } \sum_{j=2}^{m-1} \frac{I_j - I_{j-1}}{E_{sj}} = 0.0167 + 0.0033 = 0.02$$

$$\rho = \rho_\circ + \frac{P}{L}\left[\frac{I_m}{E_{sm}} + \sum_{j=2}^{m-1} \frac{I_j - I_{j-1}}{E_{sj}}\right]$$

The term I_m/E_{sm} will be zero because m^{th} layer refers to the last or the bottom most layer in the soil profile which, in this case is a rigid layer. For a rigid layer, the elastic modulus will be infinity $(E_m = \infty)$ making the I_m/E_{sm} term 0. Substituting all the determined values in the above expression, we get:

$$\rho = 9.7 + \frac{5}{18} \times 0.02 \times 1000 = 9.7 + 5.56 = 15.26 \approx 15.3\,\text{mm}$$

This is the total settlement of the pile group in the given layered soil, considering the settlement of all the layers.

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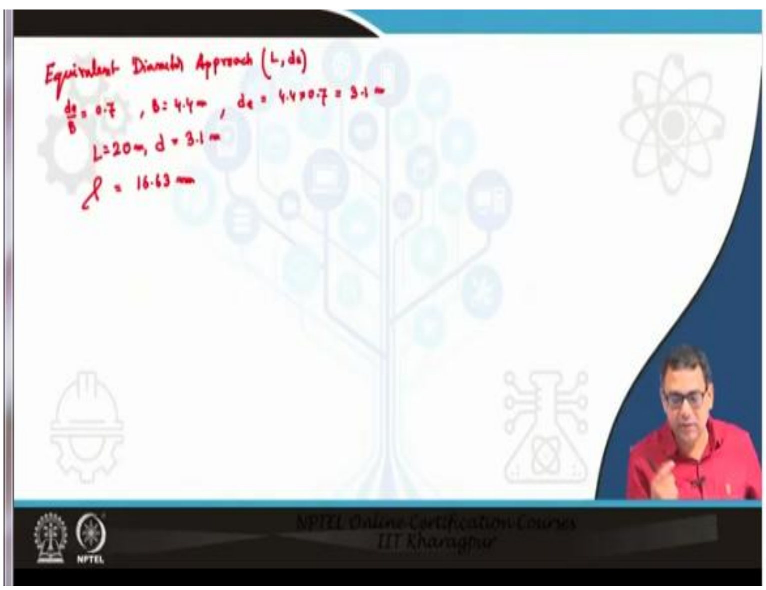

Now let us see the equivalent diameter concept. In previous case, the equivalent length was found out from the chart available and the equivalent diameter was calculated. The chart for to determine the equivalent diameter ratio depend upon the s/d ratio (= 5). L/d ratio (= 50) and the k value (= 1000). For these values, the equivalent diameter ratio (d_e/B) from the chart will be 0.7.

$$\therefore \frac{d_e}{B} = 0.7 \quad \Rightarrow d_e = 0.7 \times 4.4 = 3.08 \approx 3.1\,\text{m}$$

Now the settlement calculation should be done in the same way followed for the equivalent length approach. The only difference in both the cases will be that here L_e will be 20 m and d_e will be 3.1 m. The rest of the calculations and procedure will be completely similar. By solving this in the similar way, the group settlement obtained will be equal to 16.63 mm. So the settlement calculated through the equivalent diameter approach will be slightly higher than that of the equivalent length approach (15.3 mm).

This way the settlement of the pile group in a layered soil can be determined. Remember one thing that here the pile is completely in a single layer. But if the pile is in different layers, then it is suggested to take the weighted average of the E values.

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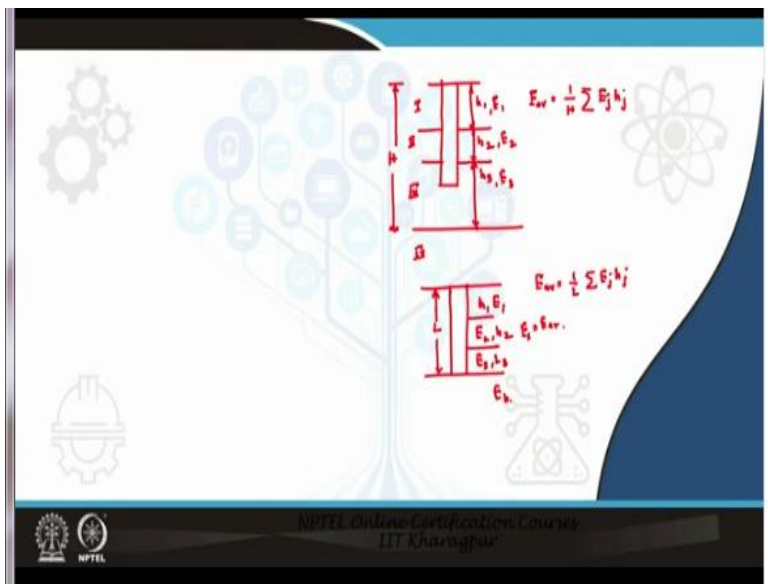

So, if the pile passes through different layers throughout its length as shown in the first figure above, the weighted average of E should be calculated by:

$$E_{av} = \frac{1}{H} \sum E_j h_j$$

where, H is the total height of all the layers, E_1, E_2, E_3, ….. and h_1, h_2, h_3, ….. are the elastic modulus values and heights of the layers 1, 2, 3,….. respectively.

There can be another case where pile rests in more than one layer as shown in the second figure above i.e., the pile may rest on a layer. That means it is an end bearing pile, but passes through number of layers. In this case, the average value of elastic modulus will be:

$$E_{av} = \frac{1}{L}\sum E_j h_j$$

where, L is the length of the pile and the remaining terms, as described before.

So if a pile rests in multiple layers within its length, the first step is this and then the settlement can be calculated using the same procedure solved in the example before.

Till now I have discussed the determination of the settlement of pile group based on the consolidation theory, and based on the elastic approach. I have discussed how 2 different procedures by which the settlement of the pile group can be determined in both single layer and multiple layered soil. There is still one method to be discussed which is based on the empirical formulae. I will discuss that in the next class and then I will go to the next topic, laterally loaded piles. Thank you.