Soil Structure Interaction
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Lecture-65
Soil Structure Interaction for Pile Foundation (Contd.)

In this class I will show how to determine the settlement of a single pile and the pile group based on the elastic analysis.

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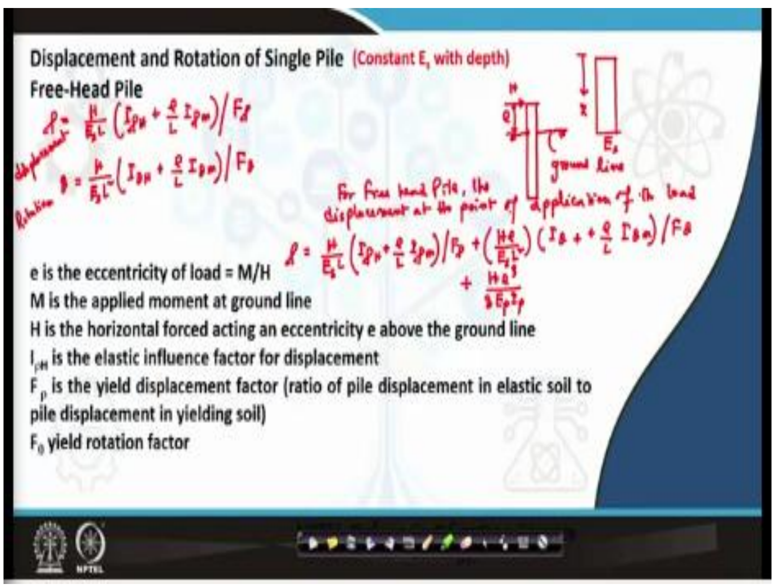

These are the expressions for single pile for a free-head condition.

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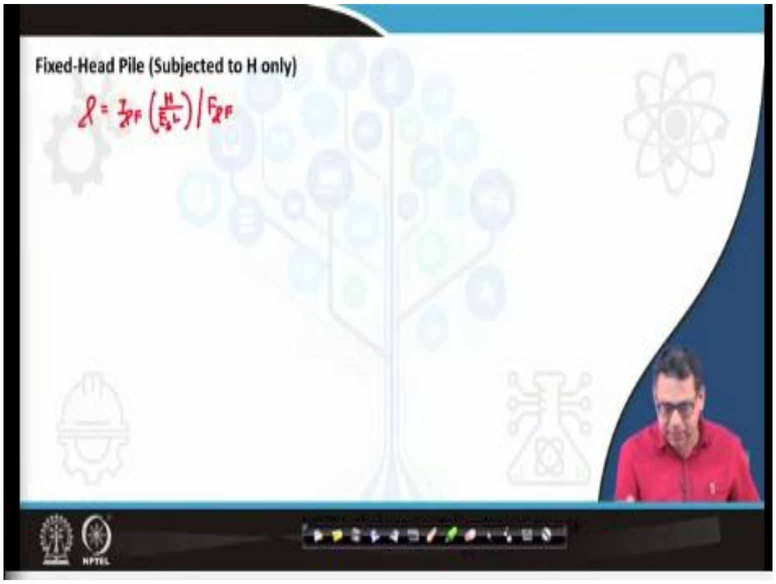

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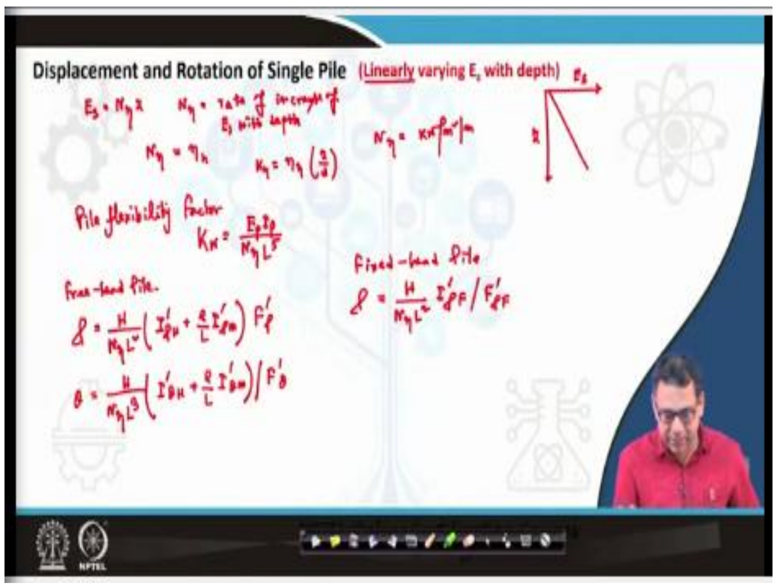

The expressions for displacement and rotation for a single pile under free head condition and for displacement under fixed head condition when E varies linearly with depth are given above.

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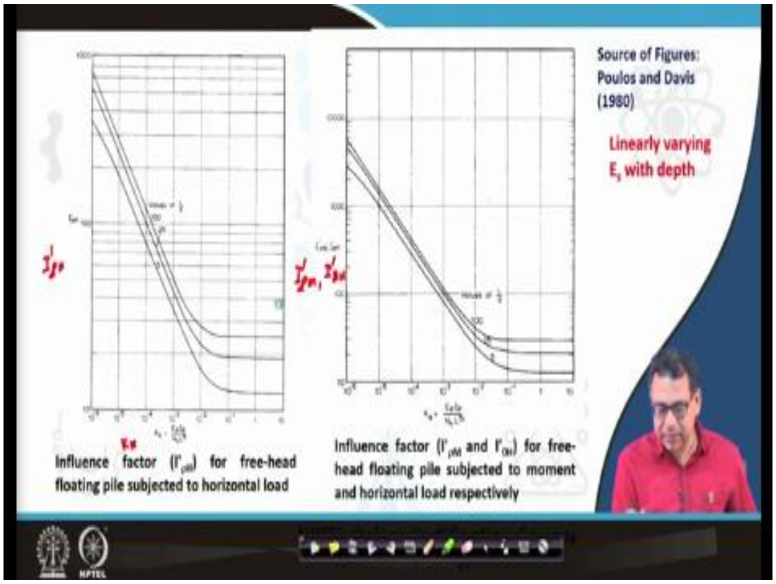

These are the charts for interaction factors for free-head piles.

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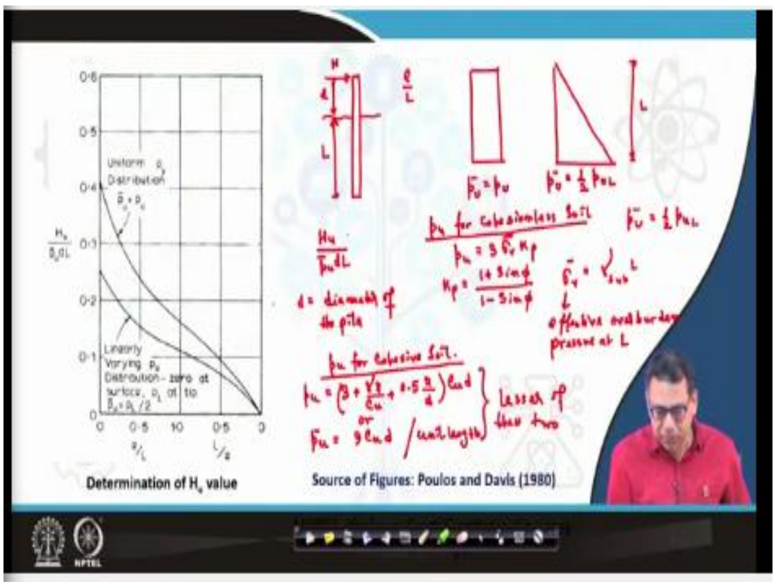

This is the chart and slide showing procedure to calculate the H_u value.

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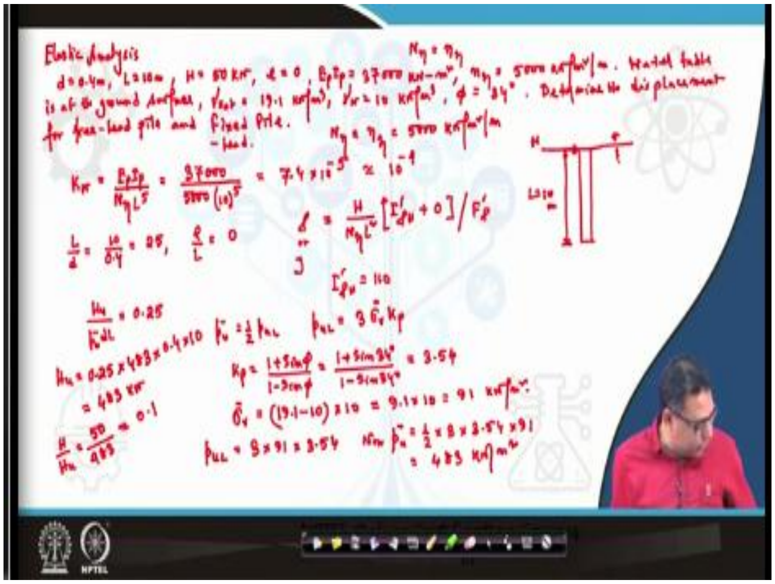

Now let us see an example problem to determine the settlement of a single pile in soil with linearly varying E_s similar to the one solved for the varying k_h case. The diameter of the pile, d = 0.4 m, the length of the pile, L = 10 m and H = 50 kN which is applied at the ground surface. The e value is 0 as it is applied at the ground surface and E_pI_p = 37000 kN/m^2. The η_h value is 5000 kN/m^2/m, water table is at the ground surface and the saturated unit weight is 19.1 kN/m^3 and unit weight of water is 10 kN/m^3. The displacement of the pile under free-head and fixed- head conditions should be determined if $\varphi = 34^o$.

This problem is the same as that of the varying k_h which was solved by the Reese and Matlock approach. So first, the K_N value should be calculated:

$$K_N = \frac{E_pI_p}{N_\eta L^5} = \frac{37000}{5000\times10^5} = 7.4\times10^{-5} \approx 10^{-4}$$

$$L/d = 10/0.4 = 25;$$

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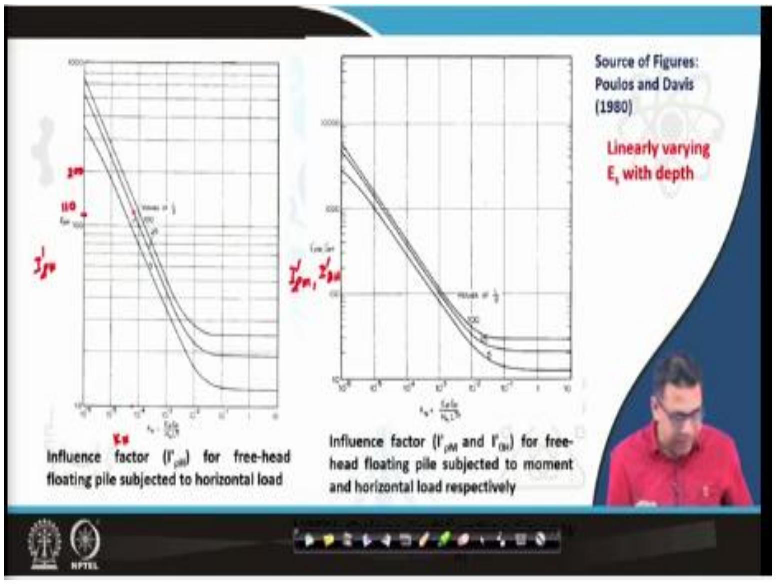

For a K_N value of 7.5×10^{-4} and L/d ratio of 25, the chart (left side in the above slide) of $I'_{\rho H}$ reads a value of 110 approximately.

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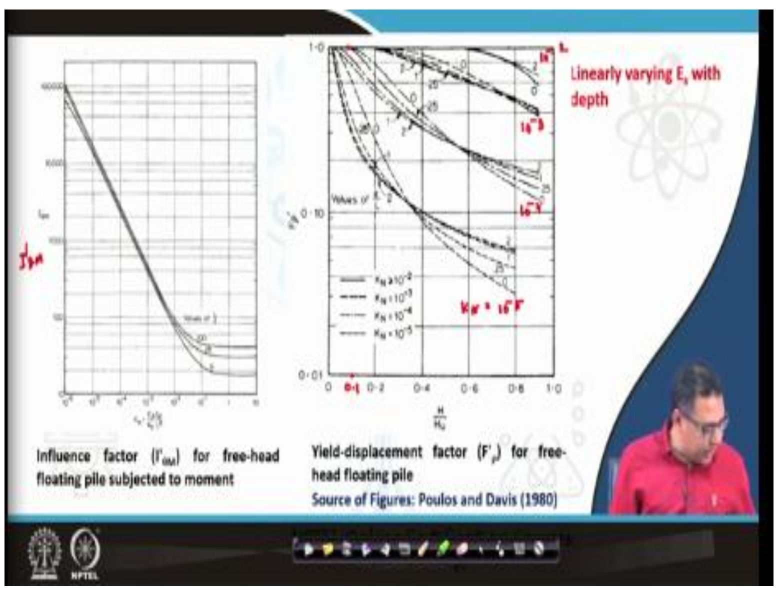

The F'_ρ value should yet be determined (from the above chart to the right) for which the H/H_u ratio is required. The H value is already known, but the H_u value should be determined from another chart which is shown below.

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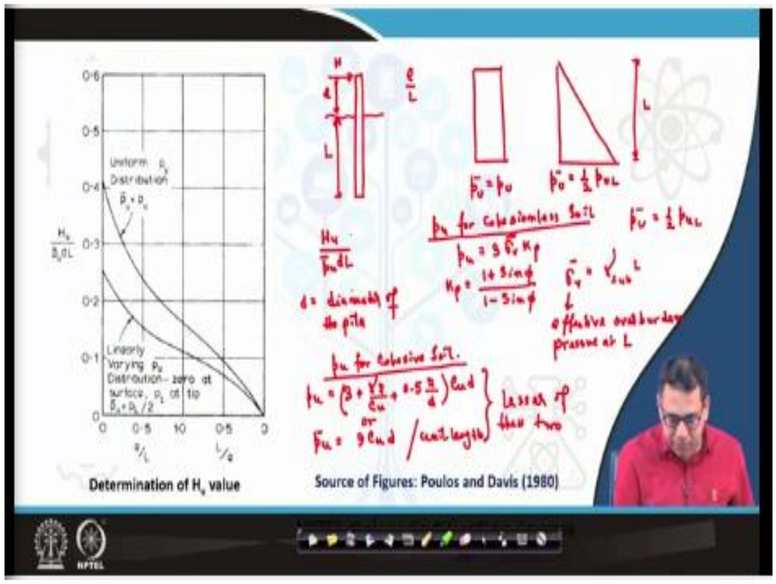

From the data given in the problem, it is evident that e/L = 0 and p_u is linearly varying that too forming a triangular distribution (0 at the top). So in the above chart, the curve which is below the curve for constant p_u should be used to determine H_u. From that curve, the value of $\frac{H_u}{\bar{p}_u dL}$ will approximately be 0.25. In the problem the φ value was alone given indicating that it is a cohesionless soil (sandy soil). So, the $\bar{p}_u$ can be found out using the expression:

$$p_u = 3\bar{\sigma}_v k_p\,; \quad \text{where, } k_p = \frac{1+\sin\varphi}{1-\sin\varphi}$$

$$\Rightarrow k_p = \frac{1+\sin(34)}{1-\sin(34)} = 3.54$$

The overburden pressure of $\bar{\sigma}_v$ can be calculated as:

$$\bar{\sigma}_v = \gamma_{sub} \times L = (19.1-10)\times 10 = 91 kN/m^2$$

As length of the pile, L = 10 m and because water table is at ground level, the overburden pressure of the entire soil will be due to the submerged unit weight only. Substituting the values of kp and $\bar{\sigma}_v$ in the expression for p_u, we get:

$$p_{uL} = 3\times 91\times 3.54$$

$$\Rightarrow \bar{p}_u = \frac{1}{2}\times 3\times 91\times 3.54 = 483 kN/m^2$$

Now substitute the value of $\bar{p}_u$ in the expression $\frac{H_u}{\bar{p}_u dL}$:

$$\frac{H_u}{\bar{p}_u dL} = 0.25$$

$$\Rightarrow \frac{H_u}{483 \times 0.4 \times 10} = 0.25$$

$$\Rightarrow H_u = 0.25 \times 483 \times 0.4 \times 10 = 483 kN$$

As the horizontal load acting on the pile, H = 50 kN, the H/H_u ratio will be:

$$\frac{H}{H_u} = \frac{50}{483} \approx 0.1$$

This is the procedure to determine the ultimate load carrying capacity of laterally loaded pile, H_u.

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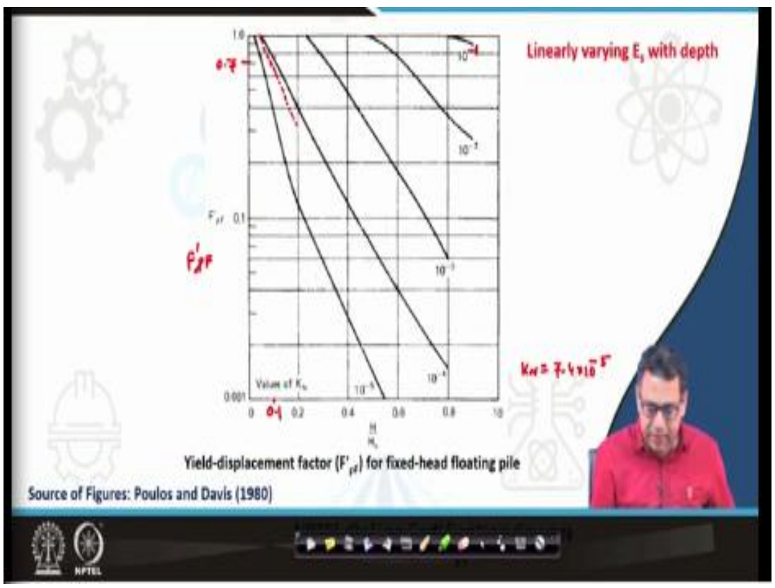

Now, as the H/H_u ratio was determined, the factor $F'_{\rho F}$ can be read from the above chart. The $F'_{\rho F}$ value for an e/L ratio of 0, K_N value of 10^{-4} and H/H_u ratio of 0.1, will be equal to 1.

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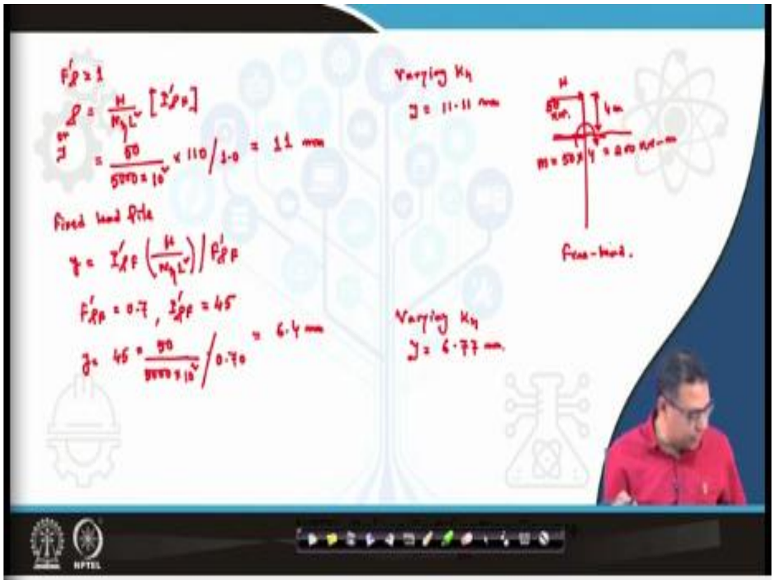

Now, the settlement expression for a free-headed pile for this case (linearly varying E_s) will be:

$$\rho = \frac{H}{N_\eta L}\frac{\left(I'_{\rho H} + \frac{e}{L}I'_{\rho M}\right)}{F'_\rho}$$

As the eccentricity is 0, the e value or e/L ratio will be 0. So, there is no need to determine the influence factor, $I'_{\rho M}$. (*Also, as there is no moment acting on the pile, this interaction factor itself will be 0*) So, the above expression reduces to:

$$\rho = \frac{H}{N_\eta L}\frac{\left(I'_{\rho H}\right)}{F'_\rho}$$

$$\rho = \frac{50}{5000 \times 10} \times \frac{110}{1} = 11\,mm$$

In the previous case, when this problem was solved using the subgrade modulus approach considering a linearly varying k_h, the settlement value was 11.11 mm. So, the settlement value determined from both the approaches is almost the same.

Now, consider the fixed head pile case in the problem. The expression in case of a fixed-head pile is:

$$y\left(or\right)\rho = I'_{\rho F}\left(\frac{H}{N_\eta L^2}\right)\Big/ F'_{\rho F}$$

From the charts: $F'_{\rho F} = 0.7$; $I'_{\rho F} = 45$

$$\Rightarrow y = 45 \times \frac{\dfrac{50}{5000 \times 10^{2}}}{0.7} = 6.4mm$$

In the varying K_h case, the y value was 6.77 mm. So both the subgrade modulus approach and elastic theory approach gives similar values for both free-headed and fixed-head conditions.

In this problem, the H is applied at the ground level. But, if H is applied at a height of 4 m from the ground line, there will be a few changes. As the eccentricity value will be non-zero, the term, $\frac{e}{L} I'_{\rho M}$ in the below expression will also not be zero. Also, because of the eccentricity a moment develops in the pile which indicates that the interaction factor also will have certain value.

$$\rho = \frac{H}{N_{\eta} L} \frac{\left(I'_{\rho H} + \frac{e}{L} I'_{\rho M} \right)}{F'_{\rho}}$$

In such a case, the moment and H should be considered. Note that this is valid only in case of a free-headed pile but not for fixed head pile. There is no chance for a fixed head pile to develop moment in it.

Now let us look into the group pile settlement calculation which is the ultimate objective.

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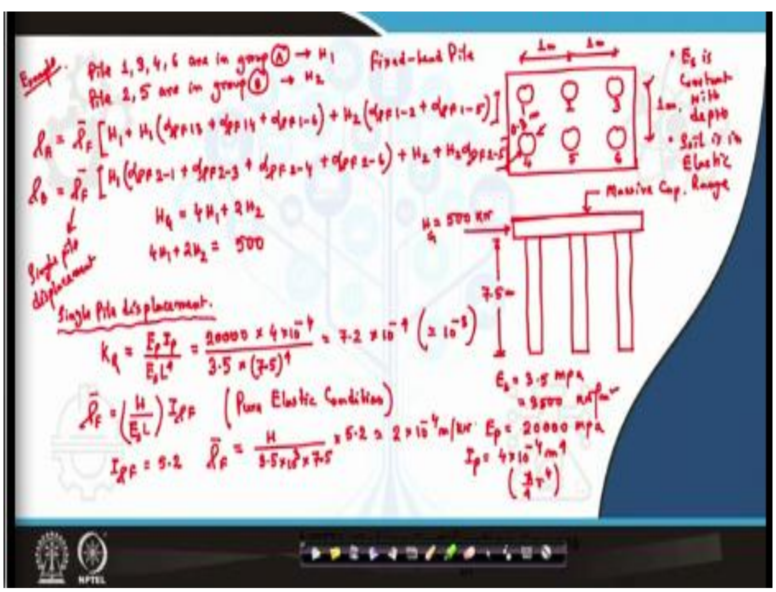

The next example is for a pile group of 6 piles, which are numbered 1, 2, 3, 4, 5 and 6 as shown in the figure above. The centre to centre spacing between the piles is 1 m, the diameter of the piles is 0.3 m and length is 7.5 m. The pile cap on this group is a very massive cap which means that it is a rigid cap referring to fixed head piles. The pile group is subjected to a lateral load of H = 500 kN which can be denoted by H_G meaning that it is the load on the entire pile group. The piles are floating piles and the E_s value is given to be 3.5MPa or 3500 kN/m^2. The elastic modulus of the pile material, E_p is given as 2×10^4 MPa and the moment of inertia of the pile, $I_p = 4 \times 10^{-4}$ m^4. The E_s value is constant or uniform throughout the depth and the soil is in elastic range.

Similar to the case of piles under compressive load, the piles 1, 3, 4 and 6 can be considered to be under one group and name this as group A. The piles 2 and 5 belong to the same group which can be called as group B. To start with the calculation of settlement of any pile, pick any group and calculate settlement for one pile in the group. So, if group A is selected first, the settlement should be calculated for any one of the piles 1, 3, 4 or 6.

As this is a fixed head pile group, the settlement will be same for all the piles and hence the load onto a pile in group A may be considered as H_1 and the load onto a pile in group B may be considered as H_2. It means that each pile in group A carries H_1 load and each pile in group B carries a load of H_2. So, the total load on the group, H_G will be equal to:

$$H_G = 4H_1 + 2H_2$$

$$\Rightarrow 4H_1 + 2H_2 = 500$$

Consider the pile 1 of group A and evaluate the interaction factors between pile 1 and all the piles in the group. To calculate this, the interaction factors between the pile 1 and all group A piles should be multiplied by the load acting on each of them. So, the interaction factor between pile 1 and itself will be 1 and so in the below expression, the interaction factors between pile 1 and piles 3, 4, 6 are considered. Similar formulation applies to the group B also. The settlement of a pile in group A can be given by:

$$\rho_A = \bar{\rho}_F \left[H_1 + H_1\left(\alpha_{\rho F13} + \alpha_{\rho F14} + \alpha_{\rho F16}\right) + H_2\left(\alpha_{\rho F12} + \alpha_{\rho F15}\right)\right]$$

Similarly, the settlement of a pile in group B can be given by:

$$\rho_B = \bar{\rho}_F \left[H_1 \left(\alpha_{\rho F21} + \alpha_{\rho F23} + \alpha_{\rho F24} + \alpha_{\rho F26} \right) + H_2 + H_2 \left(\alpha_{\rho F25} \right) \right]$$

where, $\bar{\rho}_F$ is the single pile settlement

So, it is understood that to calculate the pile group settlement, the single pile settlement or displacement should be calculated. It was mentioned that the soil deformation is in the elastic range and hence the yielding factor will be 1. To calculate the single pile displacement we need to calculate the k_R value first:

$$k_R = \frac{E_p I_p}{E_s L^4} = \frac{20000 \times 4 \times 10^{-4}}{3.5 \times (7.5)^4} = 7.2 \times 10^{-4} \left(\approx 10^{-3} \right)$$

The settlement of a fixed head pile is:

$$\bar{\rho}_F = \left(\frac{H}{E_s L} \right) I_{\rho F}$$

(Pure elastic condition)

In the above expression, the interaction factor, $I_{\rho F}$ should be determined from the chart shown below.

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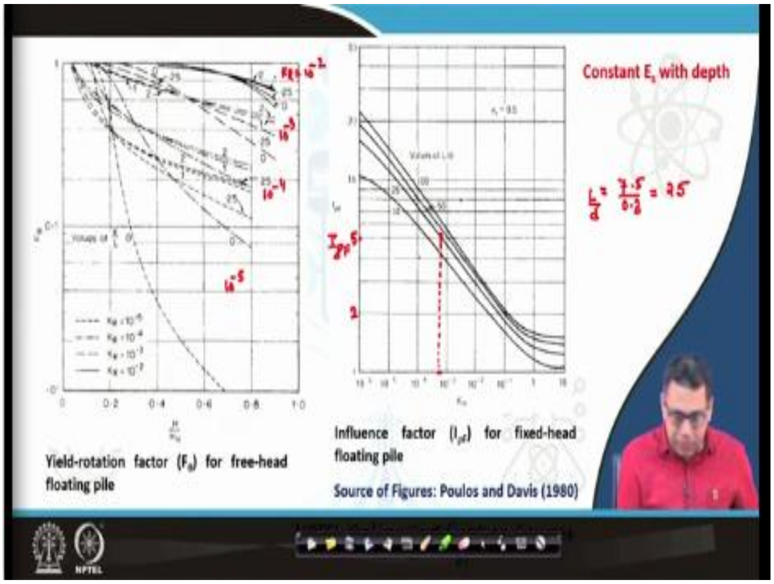

The chart to the right in the above slide should be referred to now. To determine the $I_{\rho F}$ value, L/d ratio should be known.

$$\frac{L}{d} = \frac{7.5}{0.3} = 25$$

So for a k_R value of 10^{-3} and L/d ratio of 25, the $I_{\rho F}$ value from the chart is 5.2. Substituting all the values in the expression of single pile settlement, we get:

$$\bar{\rho}_F = \left(\frac{H}{3.5 \times 10^3 \times 7.5} \right) \times 5.2 = 2 \times 10^{-4} m / kN$$

Here, the H value is not substituted and hence the settlement value is in the units of m/kN. So, this is the settlement value for a unit load of kN and should be multiplied with the load to determine the actual amount of settlement.

Till now the procedure to determine the single pile settlement is discussed. In the next class I will discuss about the procedure to calculate the group pile settlement from this single pile settlement. Thank you.