Soil Structure Interaction
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Lecture-57
Soil Structure Interaction for Pile Foundation (Contd.)

In my previous lecture I discussed the procedure to determine the settlement of pile group based on interaction factor approach. I have mentioned that there are 3 ways to determine the settlement of the pile group: based on the consolidation theory, based on the empirical equation and the third is based on the elastic analysis or based on the interaction factor approach.

I have solved one problem to show how to determine the settlement of pile group based on the consolidation theory approach. Then I have shown an example to determine the settlement of the pile group based on elastic analysis or the interaction factor approach. Today I will summarize all the methods based on the elastic analysis.

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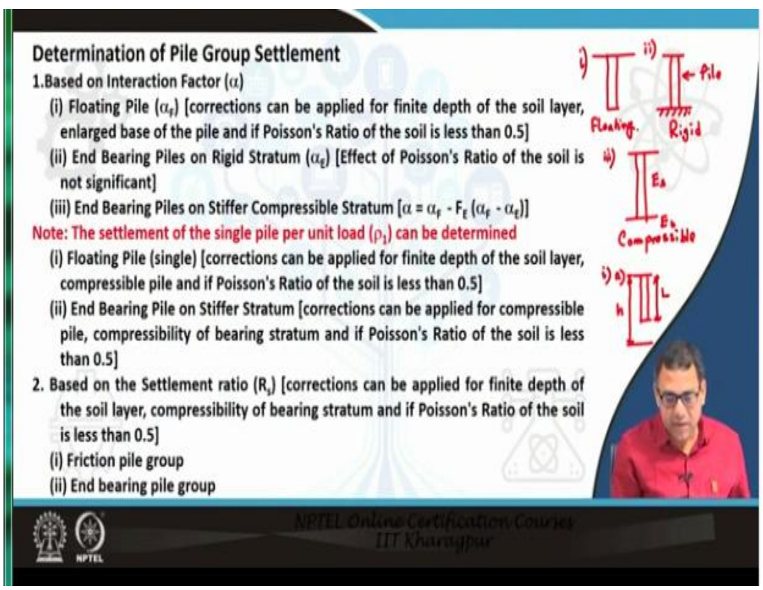

Firstly the determination of the pile group settlement based on the interaction factor approach. Basically there are 3 types of piles: floating pile, end bearing piles on rigid stratum and end bearing pile on stiffer compressible stratum. In the case 1 the floating pile resting in a layer of infinite depth was discussed. There is another sub case in floating pile where the pile rests in a layer of finite depth. The interaction factor, α_f used in the first case does not need a correction for finite layer depth whereas when the floating piles rests in a finite layer, this correction comes into picture.

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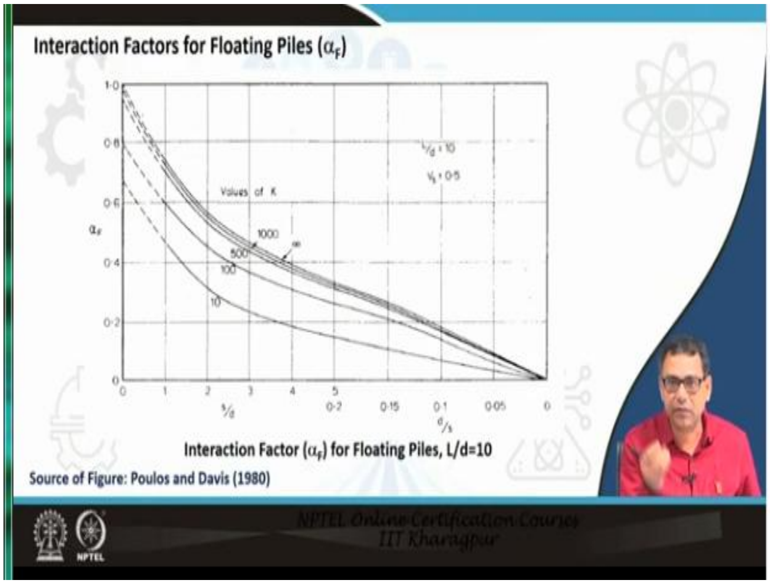

This is one of the several curves, from which the α_f value can be determined. This particular curve is for an L/d ratio of 10 and for a Poisson's ratio of 0.5. So, if the pile rests in a soil with a Poisson's ratio less than 0.5, the correction for μ should be applied. Also, if the pile has an enlarged base, the correction for that should be applied in addition. So, if a floating pile with an enlarged base rests in a soil of Poisson's ratio less than 0.5 where the layer depth is finite, three corrections should be applied to the interaction factor, α_f.

The next case discussed was about end bearing pile resting on a rigid stratum and case 3 was about end bearing pile resting on a compressible stratum. For these two cases, the interaction factor was termed as α_E (E for end bearing). The Poisson's ratio effect in these two cases was found to be not effective and so that correction need not be applied to α_E. As the pile considered here is end bearing type and it rests on a rigid stratum, the finite layer depth was also not needed here as it is obvious that the layer is finite. Finally, for the enlarged base there are no specific charts available for end bearing piles and so the charts available for the floating piles can be used here also.

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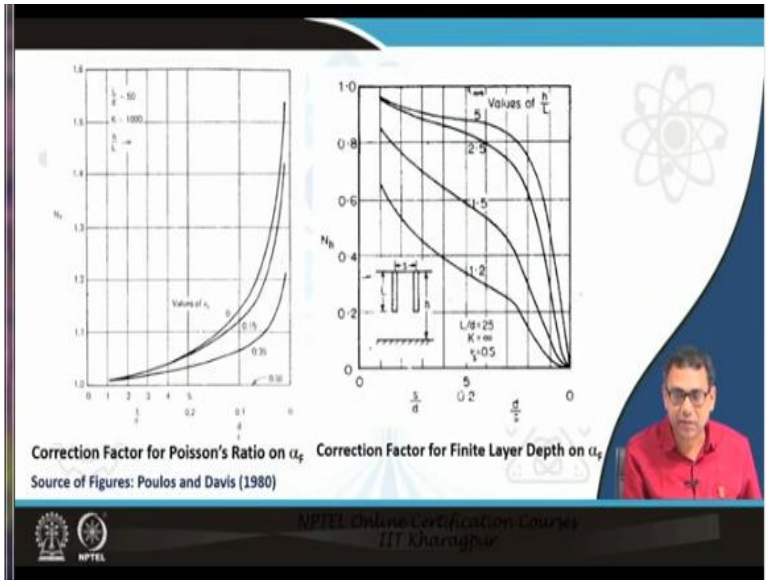

The two charts shown above are the charts to read correction factors for Poisson's ratio and finite layer depth in case of floating piles. So if in any problem, the conditions are such that these correction factors should be applied, then first the α_F value should be determined from the chart and should be multiplied with the appropriate factors.

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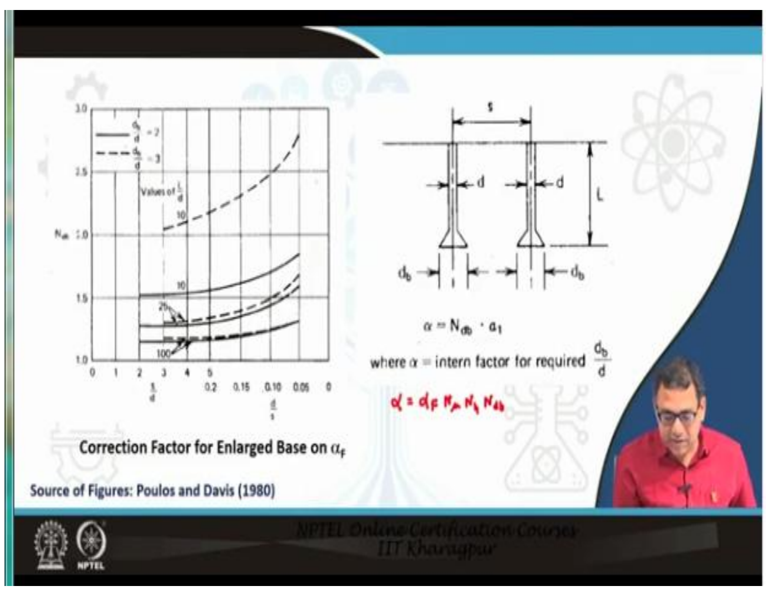

This chart helps to determine the enlarged base correction factor. The chart gives the correction factor values of $d_b/d = 2$ and 3. So finally if all the 3 corrections should be applied to the floating pile, the α_f value should be multiplied with N_μ, N_h and N_{db}.

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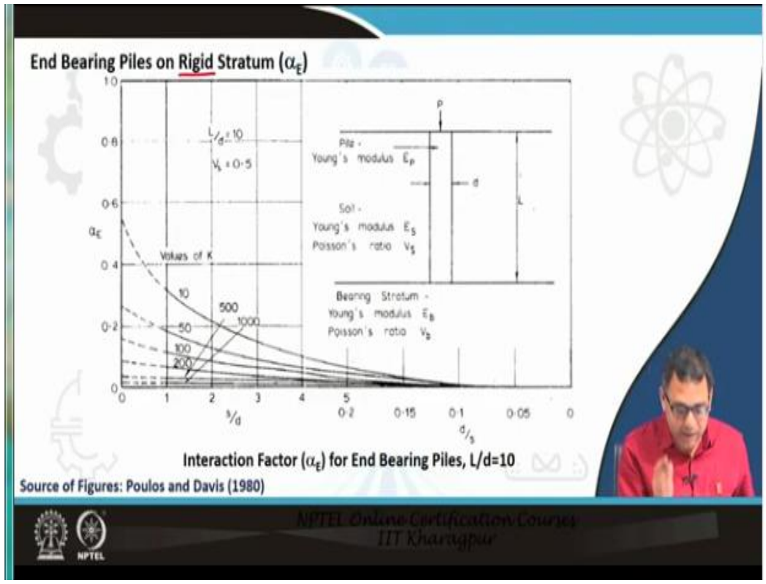

Similarly the chart for interaction factor in end bearing piles was shown above for L/d = 10.

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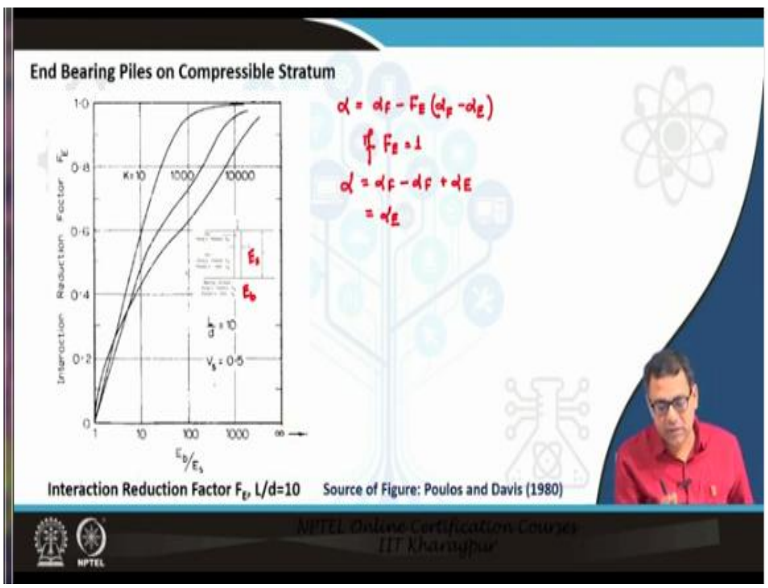

The third case in this was about piles resting on a compressible stratum the E_b and E_s values should be known. (E_b is the elastic modulus of the base stratum and E_s is the elastic modulus of the soil through which the pile is passing) The expression for α in that case was given as:

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

α_F and α_E are the interaction factors for floating pile case and end bearing case respectively after applying the applicable corrections (if any). The value of F_E will be unity if the E_b value is very high (almost infinity) and if $F_E = 1$ then α will be equal to α_E. This shows that if E_b is infinite, it means that the bearing stratum is rigid and so this case also merges into the second one where end bearing piles rest upon a rigid stratum. Remember that this F_E value also should be read from different charts each with a specific L/d value: 10, 25, 50, 100. The chart shown above is for an L/d ratio of 10.

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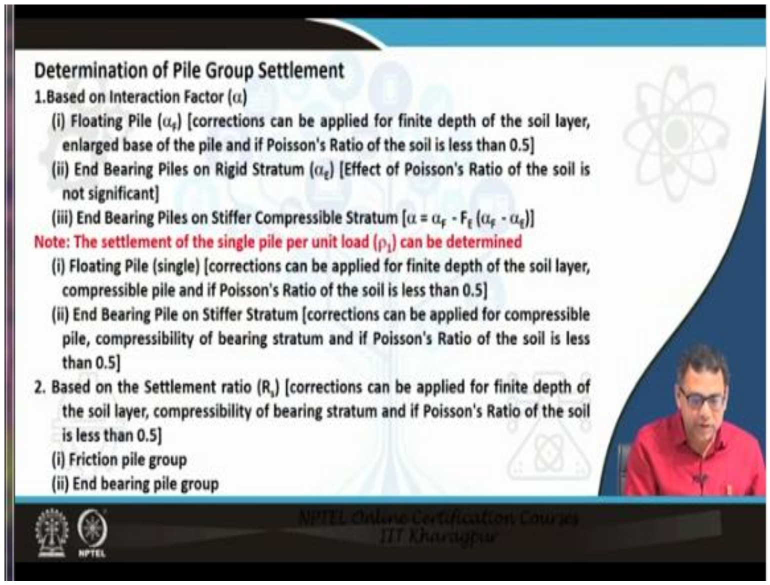

So for floating piles, 3 corrections and for the end bearing piles, 1 correction (enlarged base) may be applicable at the maximum. For the approach based on the interaction factor, the settlement of the single pile should be known to apply the method. That single pile settlement can be determined by the pile load test or also by the elastic analysis.

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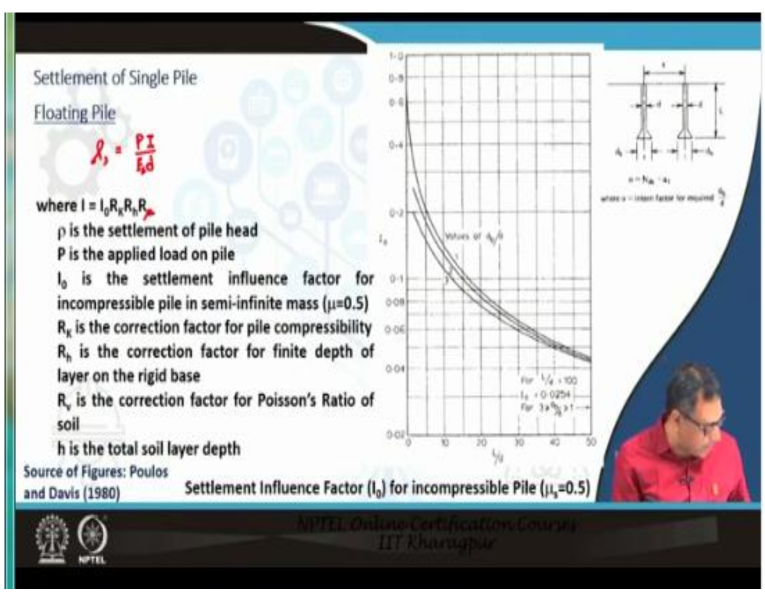

The above expression is for the floating pile single pile settlement. So I_o value can be determined from the chart in the above slide. If Poisson's ratio of the soil is 0.5, depth of the layer is infinite and pile is rigid or incompressible then $I = I_o$.

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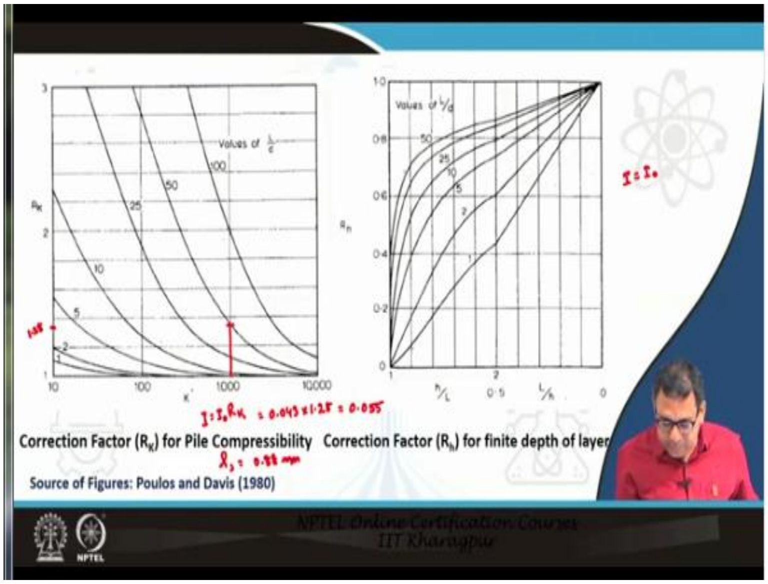

If the pile is compressible, the compressibility correction factor, R_k should be applied and if the layer in which it is resting has finite depth, the correction for finite depth, R_h should be applied.

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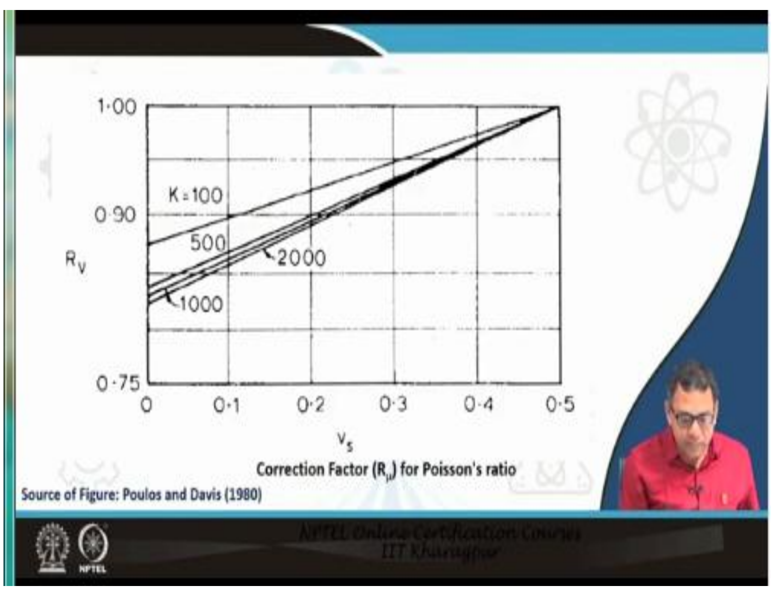

Similarly the correction for Poisson's ratio, R_μ should be applied if Poisson's ratio is not 0.5. So, the factor I_o should be calculated considering all these corrections.

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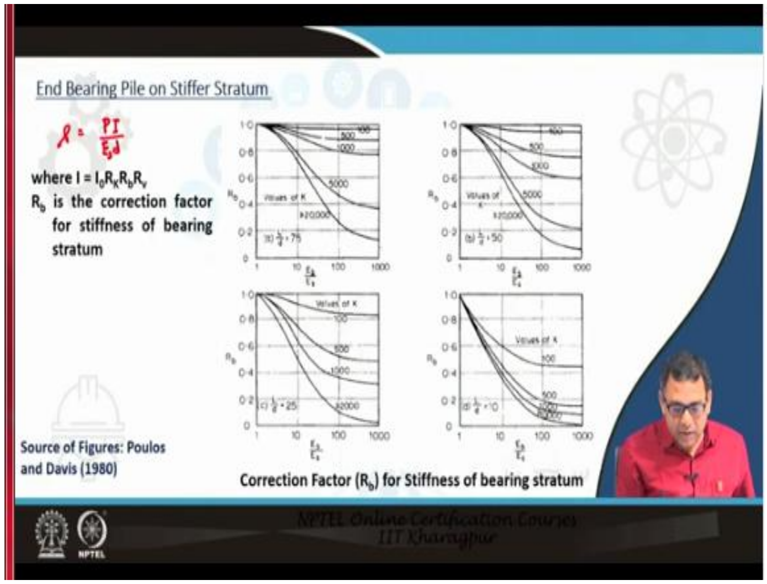

Then the settlement of single end bearing piles resting on a stiffer stratum can be calculated as shown above. The corrections applicable here are the Poisson's ratio correction R_μ, correction for pile compressibility R_k and the correction for bearing stratum stiffness, R_b. Again here, as it is an end bearing pile, the finite depth correction is not applicable.

So in case of single pile settlement, 3 correction factors at maximum are applicable for both floating pile and en bearing pile.

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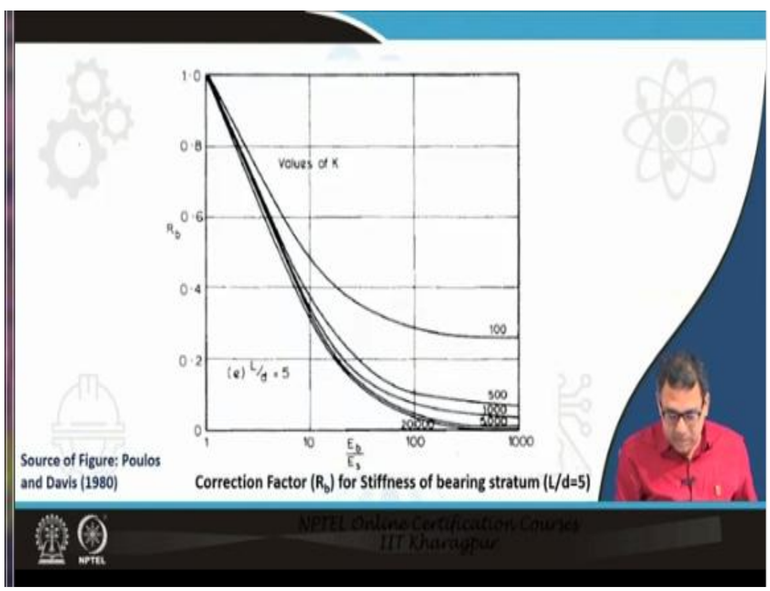

The above chart is for the R_b correction when the L/d ratio is 5.

The second approach in this regard was to determine the settlement ratio from the table directly. An example problem was solved to calculate the R_s value and then it is determined from the table to check the table. The R_s values are given separately for floating piles and the end bearing piles.

So the R_s value can directly be read from the table or calculated based on the first method. If it is read from the table, the correction factors may have to be applied to the R_s value. If the first method is followed, the corrections will be applied first and then the R_s value will be calculated.

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This is the table to determine the R_s value directly, for friction pile group. Remember that this is for the pile group with the rigid cap meaning that the settlement will be uniform.

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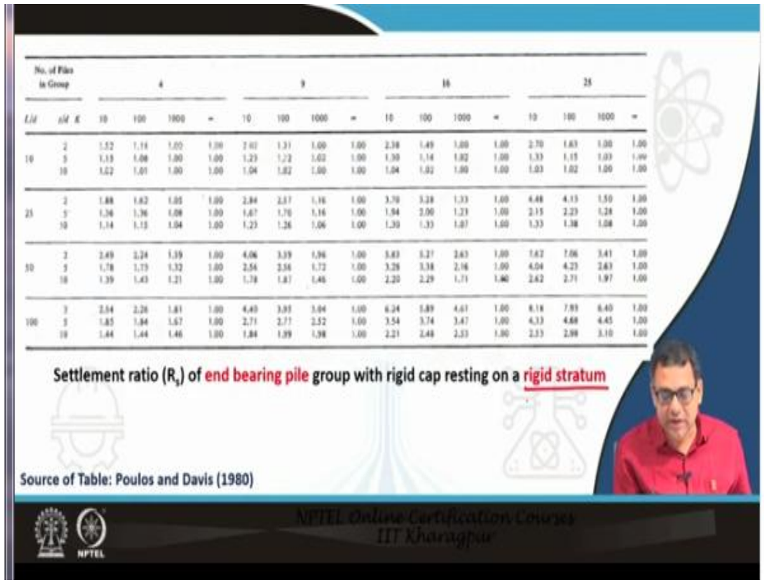

No. of Piles in Group		4				9				16				25			
L/d	s/d K	10	100	1000	∞	10	100	1000	∞	10	100	1000	∞	10	100	1000	∞
10	2	1.52	1.16	1.00	1.00	2.02	1.31	1.00	1.00	2.38	1.49	1.00	1.00	2.70	1.63	1.00	1.00
	5	1.13	1.08	1.00	1.00	1.23	1.22	1.02	1.00	1.30	1.14	1.02	1.00	1.33	1.15	1.03	1.00
	10	1.02	1.01	1.00	1.00	1.04	1.02	1.00	1.00	1.04	1.02	1.00	1.00	1.03	1.02	1.00	1.00
25	2	1.88	1.62	1.05	1.00	2.84	2.17	1.16	1.00	3.70	3.28	1.33	1.00	4.48	4.13	1.50	1.00
	5	1.36	1.36	1.08	1.00	1.67	1.70	1.16	1.00	1.94	2.00	1.23	1.00	2.15	2.23	1.28	1.00
	10	1.14	1.13	1.04	1.00	1.23	1.26	1.06	1.00	1.30	1.33	1.07	1.00	1.33	1.38	1.08	1.00
50	2	2.49	2.24	1.39	1.00	4.06	3.39	1.96	1.00	5.63	5.27	2.63	1.00	7.62	7.06	3.41	1.00
	5	1.78	1.75	1.32	1.00	2.56	2.56	1.72	1.00	3.26	3.38	2.16	1.00	4.04	4.23	2.63	1.00
	10	1.39	1.43	1.21	1.00	1.78	1.87	1.46	1.00	2.20	2.29	1.71	1.00	2.62	2.71	1.97	1.00
100	2	2.54	2.26	1.81	1.00	4.40	3.95	3.04	1.00	6.24	5.89	4.61	1.00	8.18	7.93	6.40	1.00
	5	1.85	1.84	1.67	1.00	2.71	2.77	2.52	1.00	3.54	3.74	3.47	1.00	4.33	4.68	4.45	1.00
	10	1.44	1.44	1.46	1.00	1.84	1.99	1.98	1.00	2.21	2.48	2.53	1.00	2.53	2.99	3.10	1.00

This is for rigid stratum end bearing pile on rigid strata.

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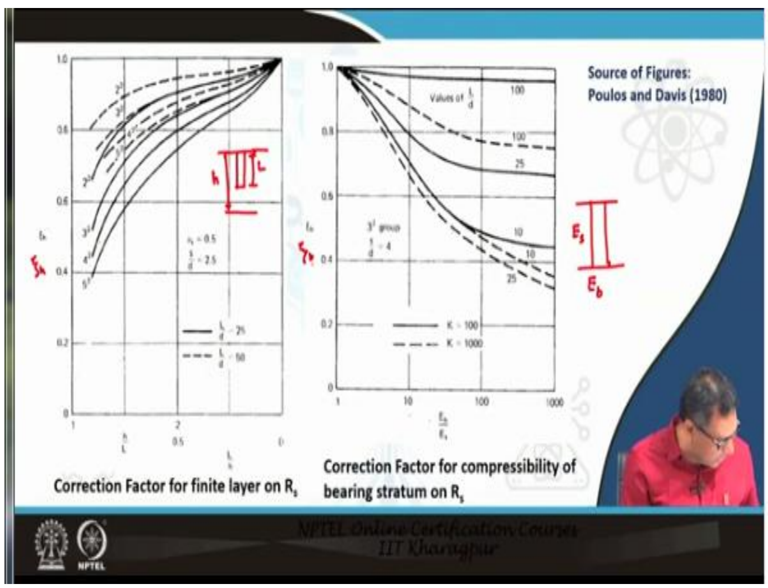

These are the charts for the correction factor on R_s. The correction factors for finite layer and compressibility of bearing stratum are shown above.

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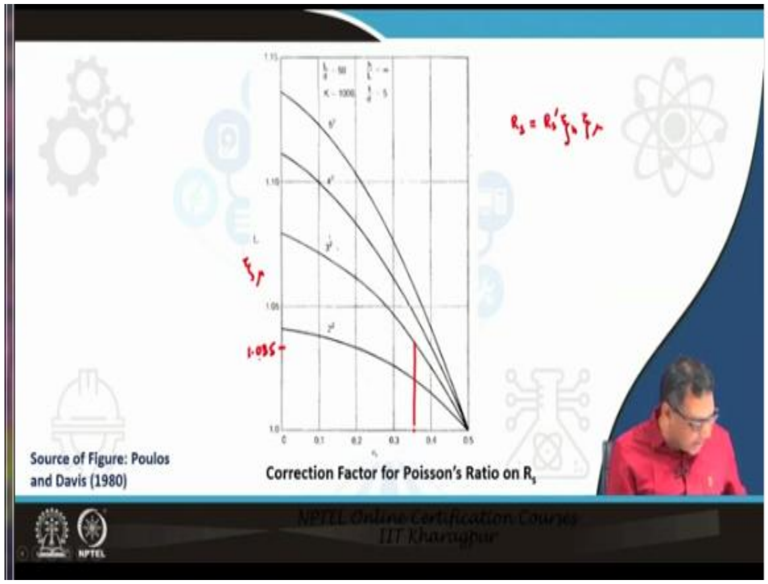

The above chart is for the Poisson's ratio correction on R_s.

After determining the R_s value from the table, the correction factors should be calculated. So the 2 possible corrections for the floating pile are the finite layer and the Poisson's ratio factors. For floating piles the base compressibility correction factor need not be applied.

And for the second case, when dealing with the end bearing piles, the compressibility of the bearing stratum will be mostly used. For the end bearing rigid pile the Poisson's ratio has the least effect.

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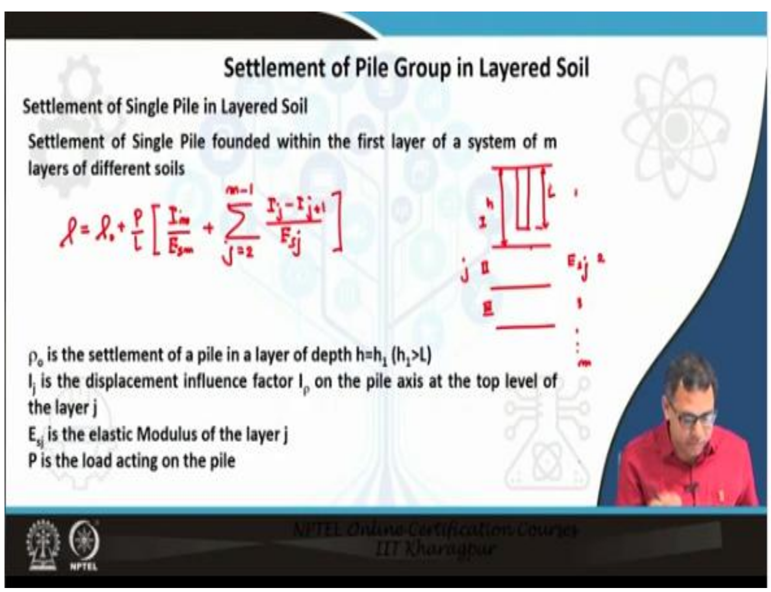

The next concept is the settlement of the pile group in layered soil which was discussed in the previous class. In the previous example problem, the settlement of the pile group based on the first approach, the interaction factor approach was calculated. Today the problem will be solved by using the second approach. That means the R_s value will be picked from the table.

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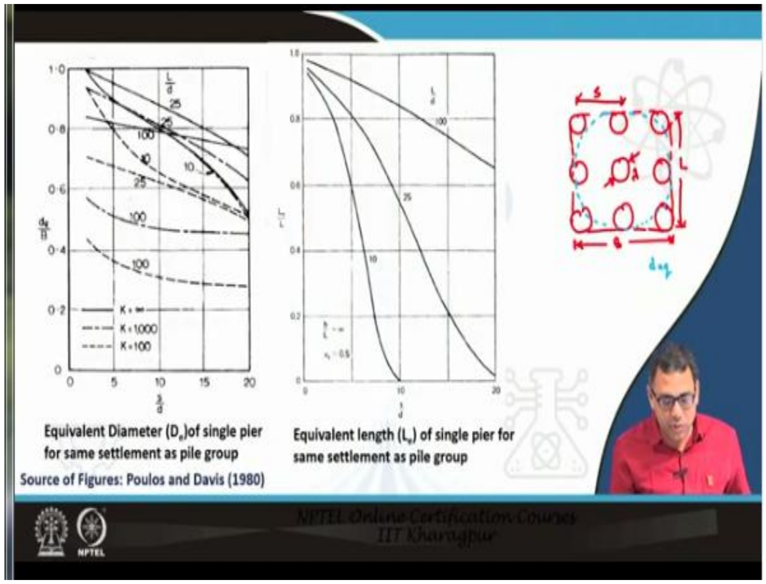

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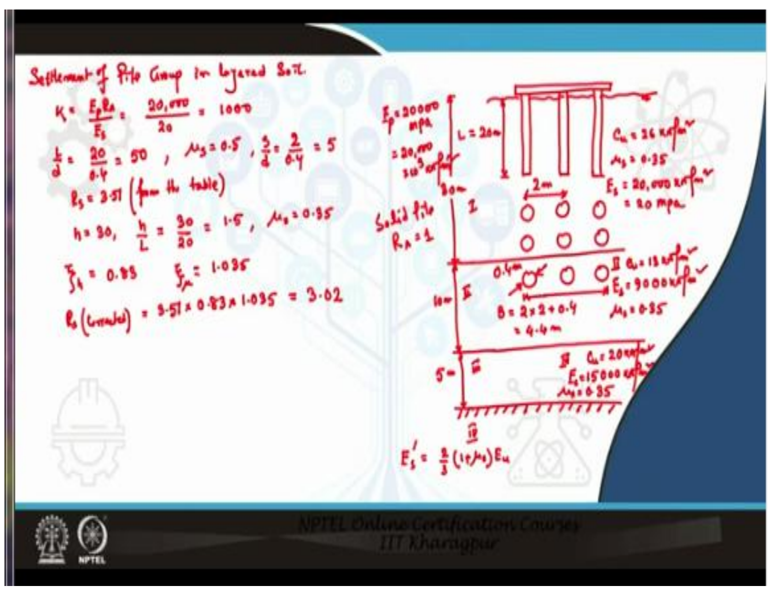

In the last example problem the single pile settlement (in layered soil) was calculated considering that the pile is very rigid. Because of that, any correction factor was not considered and $I = I_o$ was valid then. Now, if the compressibility of the pile is considered, the respective correction factor should be applied.

As k value is 1000 and L/d ratio was 50, the compressibility correction, R_k will be 1.28. So, I value will be:

$$I = I_{\circ} \times R_k = 0.043 \times 1.28 = 0.055$$

If this I value is substituted in the formula for settlement, ρ_s value will be 0.88 mm. The settlement without considering the compressibility of the pile was 0.69 mm. Now as the pile compress, the settlement also increases than the incompressible case.

Now a problem will be discussed to show the procedure to determine the settlement of a pile group in a layered soil. So the problem condition states a 3 × 3 pile group with each pile having a length of 20 m. The soil profile consists of three layers in which the top layer is of 30 m thickness. The thickness of the layer 2 is 10 meter and the thickness of layer 3 is 5 meter.

The properties of soil in the first or the top most layer are given as: c_u = 26 kN/m^2, μ_s = 0.35 and E_s = 20000 kN/m^2 (20 MPa). The properties of soil in the second layer are given as: c_u = 15 kN/m^2, μ_s = 0.35 and E_s = 9000 kN/m^2 (9 MPa). The properties of soil in the second layer are given as: c_u = 20 kN/m^2, μ_s = 0.35 and E_s = 15000 kN/m^2 (15 MPa).

The pile group consists of 9 piles arranged in a 3 × 3 pattern with center to center spacing of 2 m. The diameter of each pile is 0.4 m. So the width of this pile group block will be: (2 × 2 + 0.4 = 4.4 m). The piles are solid piles and so the R_A value will be 1.

Under these conditions the settlement of the pile group should be determined in these layers using the elastic analysis approach. In this case the elastic modulus obtained is for the undrained condition when the μ is 0.5. But the elastic modulus at any condition will be equal to:

$$E_s' = \frac{2}{3}(1 + \mu_s)E_u$$

where E_u is the elastic modulus of the soil in undrained condition. So, if the Poisson's ratio of the soil is 0.5, then E_s' will be the same as E_u. So if the E_u value is known, the elastic modulus of the soil can be calculated for any Poisson's ratio. Here, as the Poisson's ratio is 0.35, that value should be substituted in the expression if E_u was given. But here the values of elastic modulus for the different layers are given directly and hence this expression need not be used.

First let us calculate the k value:

$$k = \frac{E_p R_A}{E_s} = \frac{20000 \times 1}{20} = 1000$$

The calculations are being done considering the pile as a floating pile resting in a layer of finite depth and so the first layer elastic modulus is considered.

$$\frac{L}{d} = \frac{20}{0.4} = 50; \qquad \mu_s = 0.5; \qquad \frac{S}{d} = \frac{2}{0.4} = 5;$$

Here, if the first approach is to be followed, the R_s value should be calculated by determining the settlement of the pile group. But here, as the second approach is being followed, the R_s value will be directly determined from the table. The pile group rests in a single layer without any stiffer stratum at its base and so the floating pile chart should be referred to read the R_s value. For a 3 × 3 pile group (or 9 piles), a k value 1000, L/d of 50 and s/d ratio of 5 (2/0.4), the value of R_s from the chart will be 3.51. But, these charts are developed for a pile group resting in infinite layer and for soil with Poisson's ratio 0.5.

But here the Poisson's ratio is 0.35 and the layer is finite. So corrections should be applied for these two factors. To start with applying the corrections, the values that are to be known are:

$$h = 30\text{ m}; \qquad \frac{h}{L} = 1.5; \qquad \mu_s = 0.35$$

For floating pile group of 3 × 3 with h/L = 1.5, L/d = 50 the correction for finite layer depth on R_s is $\zeta_h = 0.83$. Similarly for a soil with $\mu = 0.35$, the correction for Poisson's ratio on R_s is $\zeta_\mu = 1.035$. So now these 2 correction factors should be applied here:

$$R_{s(corrected)} = 3.57 \times 0.83 \times 1.035 = 3.02$$

The corrected value of R_s is calculated from the table (the second approach).

In the next class, I will calculate the settlement of a single pile and multiply it with the R_s value, to get the settlement of the pile group. As this is a settlement ratio, it is not the settlement of the pile group. Thank you.