Soil Structure Interaction
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Lecture-66
Soil Structure Interaction for Pile Foundation (Contd.)

In this class I will show how to determine the settlement of a pile group subjected to lateral load. In the last class, the settlement of a single pile was determined because it should be known to determine the settlement of a pile group. The calculations done so far are shown in the below slide.

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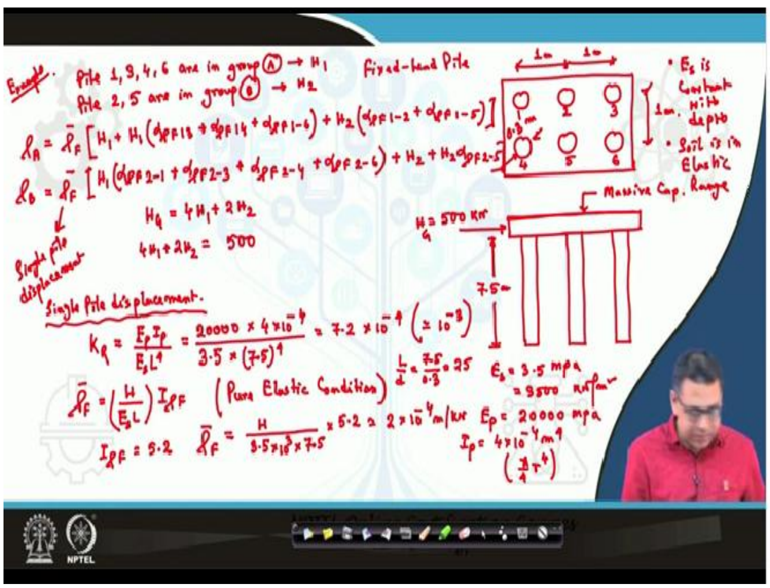

The single pile settlement under unit load was calculated to be 2×10^{-4} m/kN. The next step after this is to calculate the interaction factors between different combination of piles.

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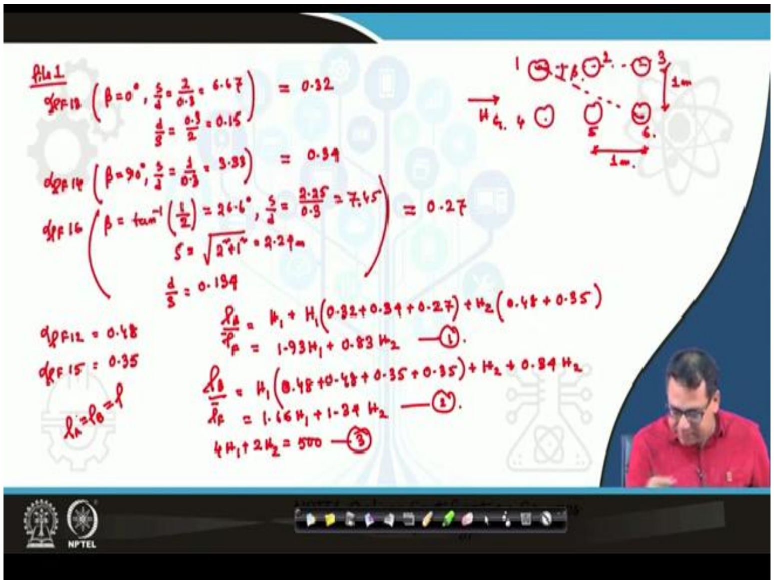

The pile arrangement is drawn again in the above slide with the numbering. The spacing between the piles in horizontal direction (load direction) and vertical direction is 1 m. First of all let us calculate the interaction factor between the piles 1 & 3. For these two piles (1 & 3), the spacing is 2 m (1 m + 1 m) as there is a pile in between them and the centre to centre spacing of the piles is 1 m in this group. The line joining the centers of both piles is a horizontal line or is parallel to the load direction and hence the β value will be 0^o. The S/d ratio will be:

$$\frac{S}{d} = \frac{2}{0.3} = 6.67$$

As the S/d ratio is greater than 5, it cannot be used and the d/S ratio should be considered to determine the interaction factor value from the charts:

$$\Rightarrow \frac{d}{S} = \frac{0.3}{2} = 0.15$$

So, for a d/S ratio of 0.15, k_R value of 7.2×10^{-4}, L/d ratio of 25 and β value of 0^o, the interaction factor between the 1 & 3 piles ($\alpha_{\rho F13}$) will be 0.32 from the chart.(will be shown again below the chart)

Similarly, the interaction factor between 1 & 4 piles can be calculated. For this case, the β value will be 90^o as the line joining the centers of these two piles is in the vertical direction. As they are adjacent, the spacing in this case is 1 m. So, the S/d ratio is 3.33 (1/0.3).

So, for a d/S ratio of 3.33, k_R value of 7.2 × 10^{-4}, L/d ratio of 25 and β value of 90^o, the interaction factor between the 1 & 4 piles ($\alpha_{\rho F14}$) will be 0.34 from the chart. (will be shown again below the chart)

Now the interaction factor between piles 1 & 4 should be calculated. Here, the line joining the centers of the piles is like a hypotenuse of a right angled triangle with sides 2 m (in the horizontal direction) and 1 m (in the vertical direction). So, the length of this hypotenuse will be the spacing between these two piles. So, the spacing between 1 & 6 piles is:

$$S_{(14)} = \sqrt{1^2 + 2^2} = 2.23$$

So, the S/d ratio will be: $\frac{S}{d} = \frac{2.23}{0.3} = 7.45$

As S/d ratio is more than 5, use the d/S ratio: $\Rightarrow \frac{d}{S} = \frac{0.3}{2.23} = 0.134$

Now, as of the β value, it is already mentioned that the line joining the centers of the piles 1 & 4 is a hypotenuse of a right angle. So, the angle this line makes with the horizontal line or the loading direction will be:

$$\beta = \tan^{-1}\left(\frac{1}{2}\right) = 26.6^o$$

So, for a d/S ratio of 0.134, k_R value of 7.2 × 10^{-4}, L/d ratio of 25 and β value of 26.6^o, the interaction factor between the 1 & 6 piles ($\alpha_{\rho F16}$) will be 0.27 from the chart. (will be shown again below the chart)

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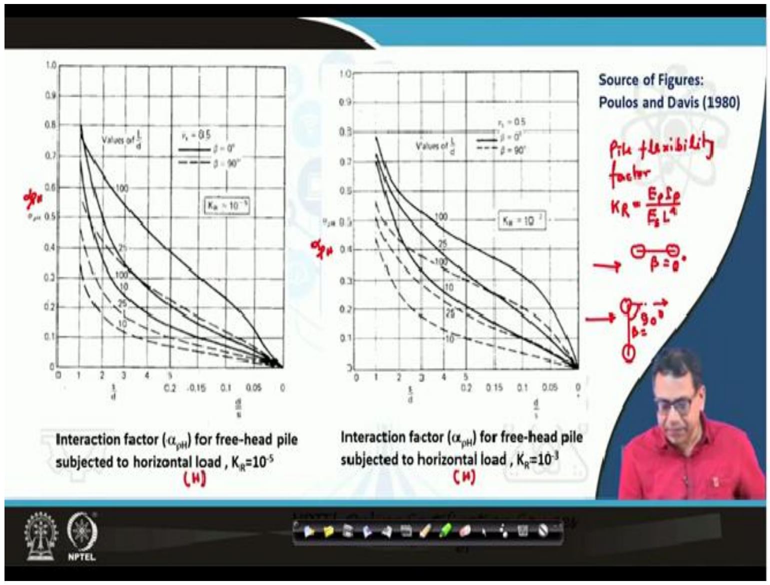

The above are the charts for settlement interaction factor under H but for free-headed pile. But, here the condition is fixed-head.

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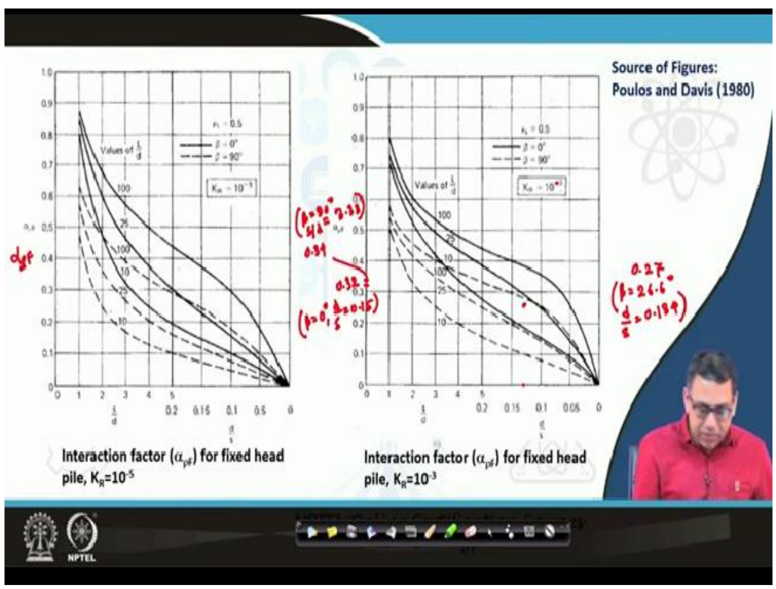

The above are the charts for $\alpha_{\rho F}$ under different K_R values. The right side chart is for a K_R value of 10^{-3} which should be used now as the K_R value for this problem is close to it (7.2×10^{-4}). If the K_R value is not near to the values for which the charts are developed, the α value should be read from both the charts and the actual factor can be calculated by interpolation.

So, for a d/S ratio of 0.15, k_R value of 7.2×10^{-4}, L/d ratio of 25 and β value of 0^o, the interaction factor between the 1 & 3 piles ($\alpha_{\rho F13}$) will be 0.32 from the above chart.

For a d/S ratio of 0.134, k_R value of 7.2×10^{-4}, L/d ratio of 25 and β value of 26.6°, the interaction factor between the 1 & 6 piles ($\alpha_{\rho F16}$) will be 0.27 from the above chart.

For a d/S ratio of 3.33, k_R value of 7.2×10^{-4}, L/d ratio of 25 and β value of 90°, the interaction factor between the 1 & 4 piles ($\alpha_{\rho F14}$) will be 0.34 from the above chart.

Similarly, the interaction factors between piles 1 & 2 and piles 1 & 5 will be: $\alpha_{\rho F12}$ = 0.48 and $\alpha_{\rho F15}$ = 0.35. The below is the equation developed already for the group A settlement:

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

Substituting the interaction factor values in the above equation:

$$\frac{\rho_A}{\bar{\rho}_F} = \left[H_1 + H_1 \left(\underbrace{0.32}_{1-3} + \underbrace{0.34}_{1-4} + \underbrace{0.27}_{1-6} \right) + H_2 \left(\underbrace{0.48}_{1-2} + \underbrace{0.35}_{1-5} \right) \right]$$

$$\Rightarrow \frac{\rho_A}{\bar{\rho}_F} = 1.93 H_1 + 0.83 H_2 \rightarrow (1)$$

Similarly the factors can also be determined for the group B. The equation for the group B settlement already developed is:

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

The procedure will be same and hence the equation will be written directly:

$$\frac{\rho_B}{\bar{\rho}_F} = \left[H_1 \left(\underbrace{0.48}_{2-1} + \underbrace{0.48}_{2-3} + \underbrace{0.35}_{2-4} + \underbrace{0.35}_{2-6} \right) + H_2 + H_2 \left(\underbrace{0.34}_{2-5} \right) \right]$$

$$\Rightarrow \frac{\rho_B}{\bar{\rho}_F} = 1.66 H_1 + 1.34 H_2 \rightarrow (2)$$

The equation of the distribution of the group load, H_G is:

$$4H_1 + 2H_2 = 500 \rightarrow (3)$$

As the piles are in fixed-head condition (rigid cap), the settlement of all the piles will be the same and hence: $\rho_A = \rho_B = \rho$. The $\bar{\rho}_F$ value is known as it is calculated in the previous class. So, there are three equations and three unknowns and can be solved.

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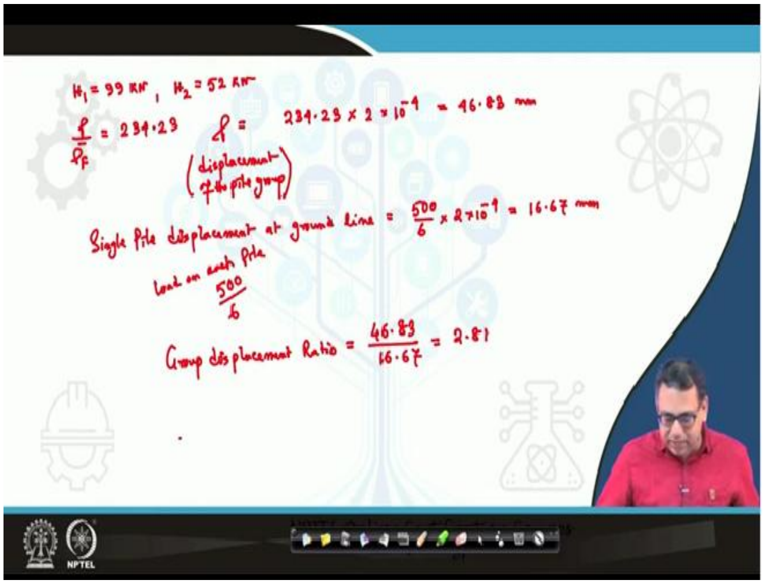

By solving the three equations, we get:

$$H_1 = 99 \text{ kN}, H_2 = 51 \text{ kN and } \frac{\rho}{\bar{\rho}_F} = 234.23$$

$$\Rightarrow \rho = 234.23 \times 2 \times 10^{-4} = 46.83\,mm$$

In the above calculation, observe that the units of $\rho / \bar{\rho}_F$ is in terms of load only. As $\rho / \bar{\rho}_F$ equals the sum of forces (H_1 & H_2) and so its units are in kN and the $\bar{\rho}_F$ units are in m/kN. So, by multiplying the value 234.23 with $\bar{\rho}_F$, we get displacement in terms of length units alone. So, the displacement of the pile group, ρ is 46.83 mm. The displacement of single pile was determined, but under unit load. So, the actual single pile displacement will be:

$$\text{Single pile displacement at ground line} = \frac{500}{6} \times 2 \times 10^{-4} = 16.67\,mm$$

Since there are 6 piles in the group and the total group load is 500 kN, the load on each pile was considered.

The single pile settlement is 16.67 mm and the group pile settlement is 46.83 mm. So, the group displacement ratio will be:

$$\text{Group displacement ratio} = \frac{46.83}{16.67} = 2.81$$

This is the calculation of a group pile settlement under lateral load. Here, only a horizontal point load was considered because this is a fixed-head pile group and hence no moment can act on it. The settlement calculation was focused upon, but the determination of H_u for granular soil was also discussed. The procedure to determine H_u for cohesive soil was also explained.

The 3 types of loading that can act on a pile are the compressive load, lateral loaded and uplift load. The uplift capacity of piles completes the discussion about piles and hence the next topic is about uplift capacity of the piles. The calculation pf the uplift capacity of a pile will be explained.

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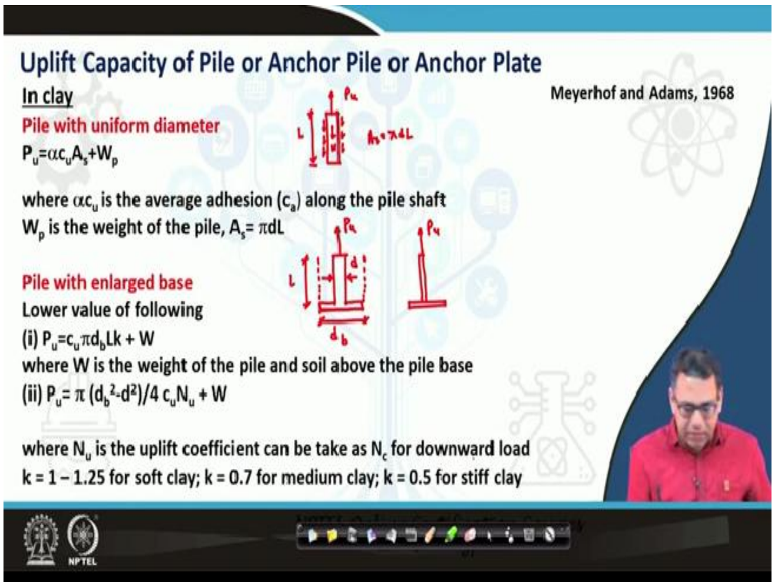

The above shown are the cases in which the uplift capacity of a pile or pile anchor or anchor plate may have to be calculated; proposed by Meyerhof and Adams in 1968. The first case is when a pile with uniform diameter is subjected to uplift load. If a pile is subjected to uplift load, the tip resistance will not act and only the friction resistance along the pile and the weight of the pile will come into picture. So, the frictional resistance can be given by:

$$P_u = \alpha c_u A_s + W_p$$

where, αc_u is the average adhesion (c_a) along the pile shaft (*α value can be taken the same as that in case of compressive load*), A_s is the area of pile along which the skin friction acts to resist the uplift (=πdL), W_p is the weight of the pile. So, if a pile resting in soil is subjected to uplift, the frictional resistance offered due to the surrounding soil will oppose the uplift and also, as the pile has to be lifted, its weight should also be overcome. This is the reason the pile weight is also considered in the uplift capacity expression.

If the pile has an enlarged base (pile anchor or anchor plate), the uplift capacity will be the least of the following:

$$(1)\ P_u = c_u \pi d_b L k + W \ \text{ OR}$$

$$(2)\ P_u = \left(\pi \left[d^2{}_b - d^2 \right] \big/ 4 \right) c_u N_u + W$$

where, W is the weight of the pile and the soil above the pile base, N_u is the same as N_c (= 9) for piles under compressive load, d is the diameter of the pile shaft, d_b is the diameter of the enlarged base and k values is: 1 – 1.25 for soft clay; 0.7 for medium clay; 0.5 for stiff clay.

If the pile has an enlarged base, the resistance acts as per the base diameter as it is the base that has to overcome the frictional resistance of soil along the pile length and hence the term $\pi d_b L$ in the first expression. Just like the coefficient, α in the previous case, a coefficient, k is proposed by Meyerhof and Adams here for which the values are given above. In the second expression, the term $\pi/4 \left[d^2{}_b - d^2 \right]$ represents the tip resistance. If a pile with enlarged base has to be uplifted, the soil above the base that surrounds the rest of the shaft should also be lifted. So, this term caters to that soil which is present within d_b and d.

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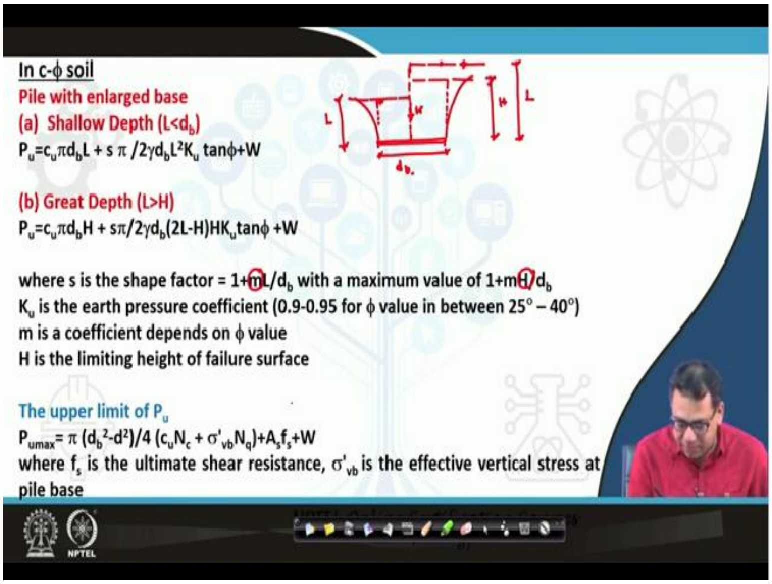


The next one is about the piles with enlarged base resting in c-φ soil. Two cases are considered in this concept, where the pile base is at a shallow depth and the other case is the pile base at a great depth. If the pile base is at a shallow depth, the failure surface will extend till the ground surface but it is not the case when the base is at a greater depth. If the height to which the failure extends is considered as H, the pile base will be considered to be at a great depth when L > H.

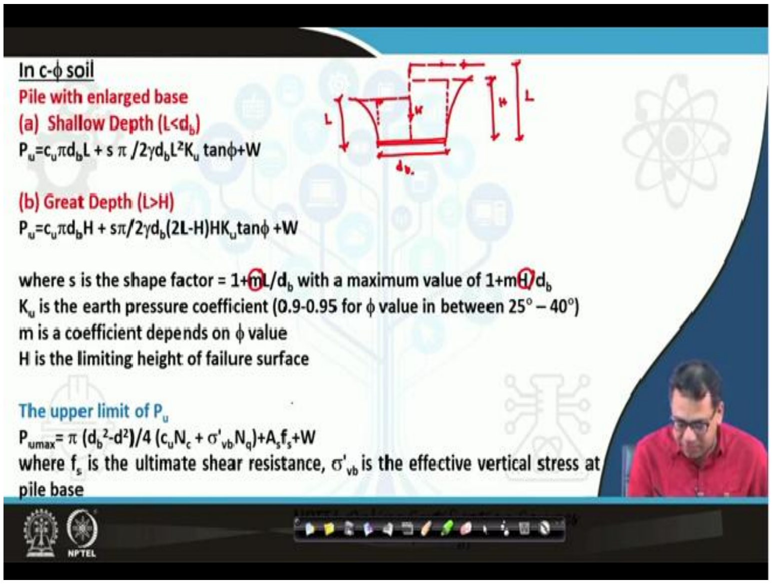
The pile base will be considered to be at shallow depth if $L < d_b$. The expression for uplift capacity in this case will be:

$$P_u = c_u \pi d_b L + s\left(\pi/2\right)\gamma d_b L^2 K_u \tan\phi + W$$

If the pile base is at great depth, (L > H)

$$P_u = c_u \pi d_b H + s\left(\pi/2\right)\gamma d_b (2L - H) H K_u \tan\phi + W$$

where, s is the shape factor = $1+mL/d_b$ with a maximum value of $1+mH/d_b$, m is a coefficient dependent on φ value, Ku is the earth pressure coefficient (0.9-0.95 for φ value in between 25^o-40^o), H is the limiting height of failure surface.



The P_u value should not exceed:

$$P_{u-\max} = \pi\left[d^2{}_b - d^2\right]/4\left(c_u N_c + \sigma'_{vb} N_q\right) + A_s f_s + W$$

A_s is the area of the shaft for skin resistance and f_s is the frictional resistance of the pile shaft. Now, the question is how to get the m value and H value.

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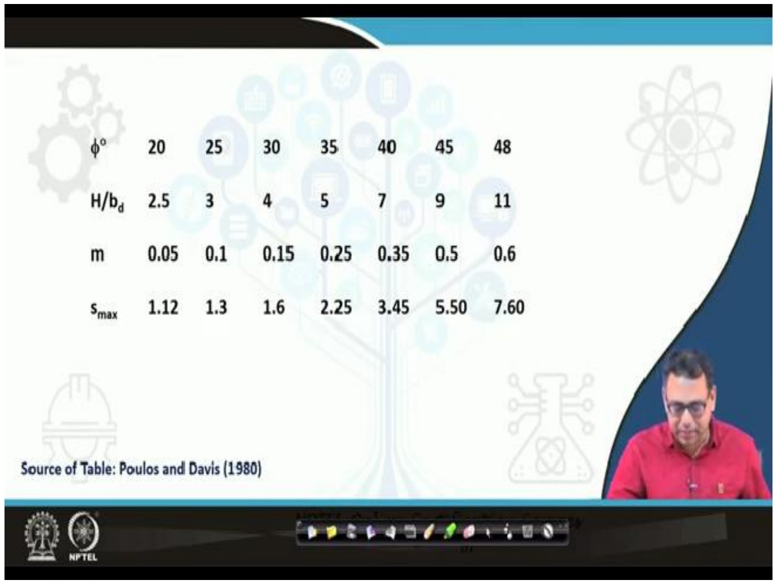

The above table shows the values of m and H for different values of φ if the d_b value is known. So, for a particular φ value, the H/d_b value can be obtained from the table and the H value can be calculated. These are the expressions and various factors involved in the case of piles resting in c-φ soil.

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These are the books from which I have taken most of the material. The first 3 books: Selvadurai, Hetenyi and Poulos & Davis books are the major source of this course. I have taken the help of other books like Bowles- foundation analysis and design.

Then the books by V.N.S Murthy, Ranjan & Rao and Reese & Van Impe are referred to, for lateral loaded pile. In addition to these, I have used several references during the whole course which are available in these books.

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In addition, the above references: Shukla & Chandra, Ghosh & Madhav, Kodner and lecture note of Professor Sivakugan (from James Cook University) are also used. These are the references and this is the end of this course.

Though many charts and tables are used during this course, they will not be allowed in the exam. But if any coefficient or any values are required from those charts and tables, those will be provided in the question paper. It is not required to remember those table values or chart values.

Most of the things covered in this course are pretty simple, but very effective and those solutions of models will give effective solutions to number of problems already discussed. I have shown you some real applications also, and there are several other applications. So, people have worked on this area and still working on this area. It is a very interesting area which you can work upon. Thank you for very much for watching these lectures. I wish best of luck to you for the exam. Thank you.