Advanced Foundation Engineering
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Lecture – 70
Foundations on Difficult Soils - II

So, last class I have discussed about the foundation on collapsible soil. So, today I will discuss the foundation on another type of difficult soil. So, that is the expansive soil.

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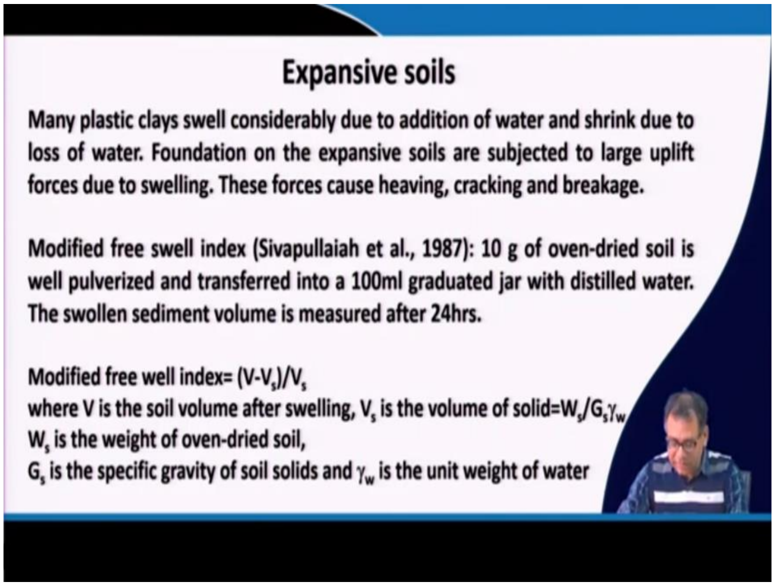

Expansive soils

Many plastic clays swell considerably due to addition of water and shrink due to loss of water. Foundation on the expansive soils are subjected to large uplift forces due to swelling. These forces cause heaving, cracking and breakage.

Modified free swell index (Sivapullaiah et al., 1987): 10 g of oven-dried soil is well pulverized and transferred into a 100ml graduated jar with distilled water. The swollen sediment volume is measured after 24hrs.

Modified free well index= $(V-V_s)/V_s$
where V is the soil volume after swelling, V_s is the volume of solid=$W_s/G_s\gamma_w$
W_s is the weight of oven-dried soil,
G_s is the specific gravity of soil solids and γ_w is the unit weight of water

So, now that many plastic clayey soils swell considerably due to addition of water and shrink due to loss of water. So, foundation on this expansive type of soil is subjected to large uplift due to the swelling. So, swelling in soil provides a large uplift into the soil, these forces cause heaving, cracking and breakage. So, we have to design our foundation suitably to tackle this type of soil. Now, how we can understand that whether soil is expansive soil and what is the degree of expansion.

So, there are a number of methods and a number of criteria are there. So, I am giving one of them. So, that is the modified free well index. So, here the 10 gm of oven-dried soil is taken and it is transferred to 100 mm graduated jar with distilled water and swollen sediment volume is measured after 24 hours. So, that sediment due to the swelling of the soil so, that sediment is measured after 24 hours.

Then the modified free swell index is calculated by using this equation where V is the soil volume after swelling and V_s is the volume of solid and that is weight of solid that means the oven dried soil divided by G_s where G_s is the specific gravity of soil solids and γ_w is unit weight of water.

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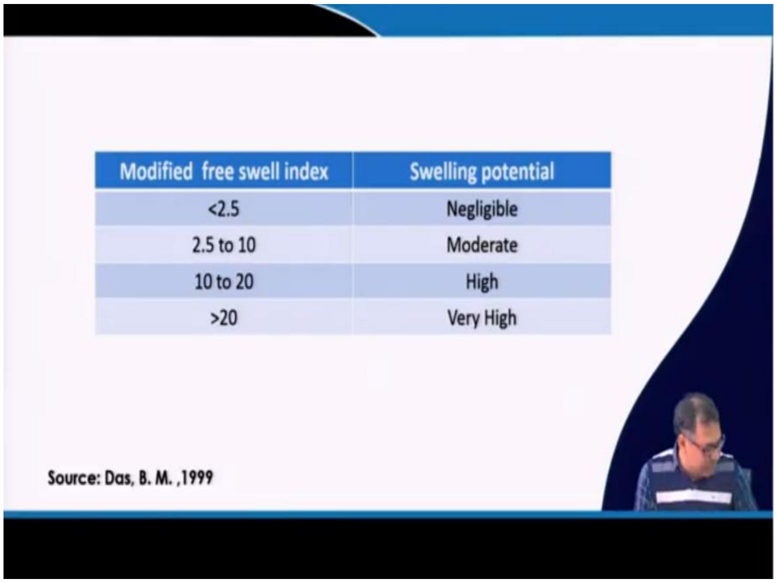

Modified free swell index	Swelling potential
<2.5	Negligible
2.5 to 10	Moderate
10 to 20	High
>20	Very High

Source: Das, B. M. ,1999

Now, if this modified free soil index value is less than 2.5 then the swelling potential is negligible, if it is 2.5 to 10 then it is moderate, if it is 10 to 20 then it is high, if it is greater than 20 then it is very high. So, based on that we can understand or we can determine the swelling potential of the soil.

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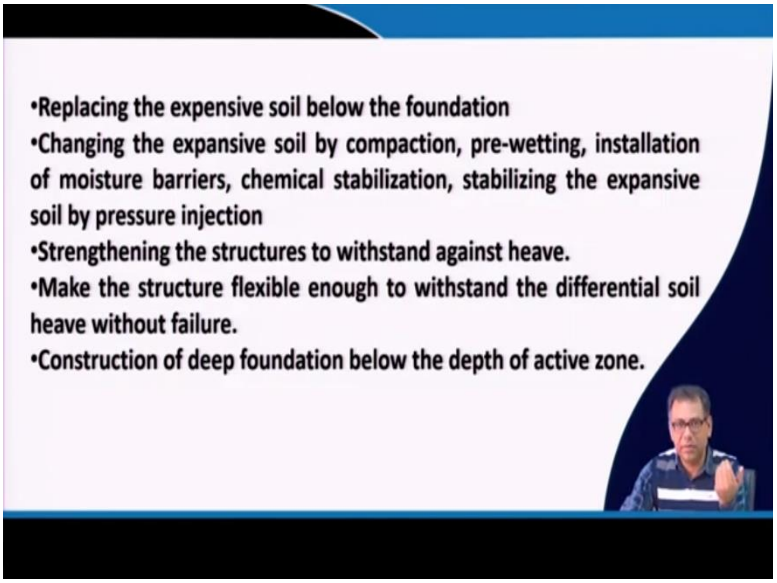

- Replacing the expensive soil below the foundation
- Changing the expansive soil by compaction, pre-wetting, installation of moisture barriers, chemical stabilization, stabilizing the expansive soil by pressure injection
- Strengthening the structures to withstand against heave.
- Make the structure flexible enough to withstand the differential soil heave without failure.
- Construction of deep foundation below the depth of active zone.

Now, once the soil is the swelling type of soil, then all expansive soil can be replaced below the foundation thus changing the expansive soil. So, we can provide the compaction, pre-wetting, installation of moisture barrier, chemical stabilization, stabilizing the expansive soil by pressure injection, strengthening the structure to withstand against the heave because as I mentioned because of this uplift force there will be the heave.

So, you have to strengthen the structure. So, that this structure can withstand this heave also, the structure is made flexible enough to withstand a differential soil heave without failure and construction of deep foundation below this depth of active zone is recommended again that as I mentioned in case of collapsible soil also, we can provide the deep foundation and we can provide foundation below this active zone. So, we can provide foundation such as pile.

So, I will discuss that two types of foundation that can be provided. So, for this swelling or the expansive type of soil, so, that means here the soil will expand due to the swelling. So, there will be an uplift force and then at the same time there will be a downward force also. So, we have to provide such type of foundation that it can sustain or it can withstand again the uplift as well as the compressive load.

So, that means it has sufficient amount of compressive load carrying capacity as well as the pullout capacity. So, I will discuss two types of such foundation. Those are suitable those are generally used for the expansive soil.

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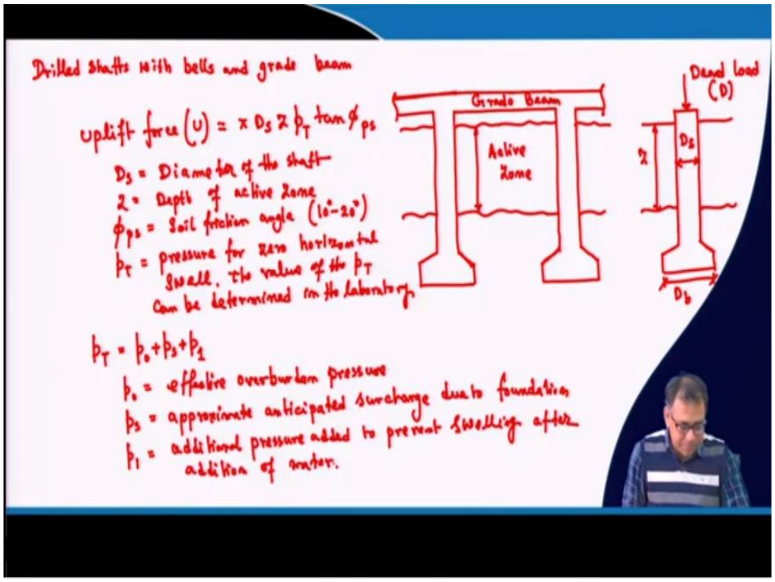

Drilled shafts with bells and grade beam

uplift force $(U) = \pi D_s Z p_T \tan\phi_{ps}$

D_s = Diameter of the shaft

Z = Depth of active zone

ϕ_{ps} = Soil friction angle (10°-20°)

p_T = pressure for zero horizontal swell. the value of the p_T can be determined in the laboratory.

$p_T = p_0 + p_s + p_1$

p_0 = effective overburden pressure

p_s = approximate anticipated surcharge due to foundation

p_1 = additional pressure added to prevent swelling after addition of water.

So, one is the drilled shaft with bells and grade beam what is that? So, suppose if this is your active zone. So, let us start that. So, we are providing the shaft with enlarged base. So, and then another one with enlarged base and then these shafts are connected with beams, so, this is the beam and this is the active zone means here the soil is expansive soil. Now, how I will calculate or I will check whether this type of foundation is suitable or not.

So, to do that, so suppose this is my active zone and here we are taking one particular one single shaft. Then this is the dead load D and the thickness of the active zone is Z and D_s is the diameter of the shaft and D_b is the base diameter so, now the uplift force that will be subjected due to swelling is $\pi D_s \times Z p_T \tan\phi_{ps}$. So, Z is the thickness of this active zone, D_s is the diameter of the shaft and what is p_T? What is ϕ_{ps}?

So, I am writing that the D_s is the diameter of the shaft, then Z is the depth of active zone, ϕ_{ps} is the soil friction angle which is generally taken us 10° to 20°. And p_T is the pressure for zero horizontal swell. So, the value of the p_T can be determined in the laboratory, how this p_T is determined? So, first step is that we take the soil sample in a consolidation ring and then we have to apply p_0 and p_s, now let me write what is actually $p_T = p_0 + p_s + p_1$. So, now what is p 0? p_0 is the effective overburden pressure then p_s is the approximate anticipated surcharge due to the foundation.

So, first we have to apply the p_0 which is equal to effective overburden pressure of that site and then we have to add additional amount of stress which is coming due to the foundation and then p_1 is the additional pressure added to prevent swelling after addition of water, so, what does it mean? So, this p_T is the amount of pressure that is applied to prevent the swelling. So, suppose if I apply the stress because of when water is added.

So, this soil starts swelling. So, now if I apply stress so, we can prevent that swelling. So, that stress is p_T, so, $p_T = p_0 + p_s + p_1$. So, that means, first it is placed in an oedometer reading and then the p_0 is applied which is the effective overburden pressure then the p_s is applied which is the anticipated surcharge due to the foundation then the water is added into the soil.

So, that mean now under this stress is not enough. So, under this stress also this soil will start swelling so, and that condition so, gradually a load a stress is applied up to p_1 such that there will be 0 amount of swell. So, to achieve that 0 amount of swell total stress is equal to p_T which is summation of p_s, p_0 and the additional stress p_1. So, these we can determine in the laboratory this p_T value.

Then sometimes if this laboratory value is not available, then it is recommended that you can use $p_T \tan \phi_{ps}$ this time equal to c_u but I would say that you do the test and get this p_T value in the laboratory and then you use this p_T value here.

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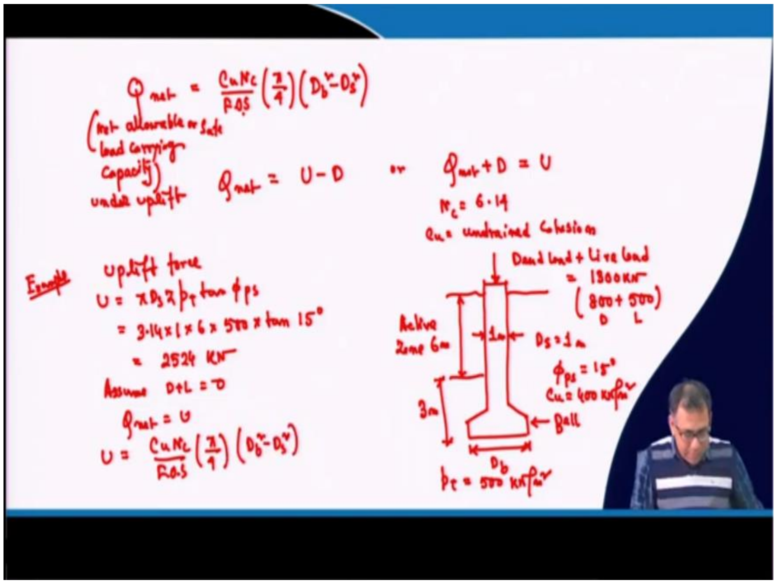

$Q_{net} = \frac{C_u N_c}{F.O.S}\left(\frac{\pi}{4}\right)\left(D_b^2 - D_s^2\right)$

(net allowable or safe load carrying capacity) under uplift

$Q_{net} = U - D$ or $Q_{net} + D = U$

$N_c = 6.14$

C_u = undrained cohesion

Example

uplift force

$U = \pi D_s z p_r \tan\phi_{ps}$

$= 3.14 \times 1 \times 6 \times 500 \times \tan 15°$

$= 2524$ kN

Assume $D + L = 0$

$Q_{net} = U$

$U = \frac{C_u N_c}{F.O.S}\left(\frac{\pi}{4}\right)\left(D_b^2 - D_s^2\right)$

So, next one is that Q_{net}. So, what is Q_{net}? Ultimate load carrying capacity of the shaft because here we have applied the drilled shaft where we are given the extended base width so, that is base. So, this extended base width will help that when there will be an uplift then this extended base will give us the resistance during the uplift this extended base this side one, two sides of the shaft.

But when there will be a compressive load then also this extended base will give the resistance. So, that is the advantage of providing this extended base. So, this will help for uplift as well as under compressive load. So, now we can say that that Q_{net}, net ultimate load carrying capacity so that will be $\frac{c_u N_c}{\text{factor of safety}}\left(\frac{\pi}{4}\right)\left(D_b^2 - D_s^2\right)$.

So, area of this shaft portion we are not taking we are taking the extended base portion because it is under uplift. So, this is the net ultimate load carrying capacity. So, this is under uplift and this is the factor of safety. So, finally, that Q_{net} should be equal to the uplift minus dead load because uplift force that this is allowable or safe. This is allowable or I can say or safe load carrying capacity under uplift because a factor of safety is applied.

So, $Q_{\text{net}} = U - D$ or I should write that the Q_{net} that we are getting + dead load that should be equal to the uplift for that pile is subjected because these two forces are acting in a downward direction only here it is acting in upward direction which is U and this is the D and here it is Q_{net}.

So, $Q_{\text{net}} + D$ should be equal to uplift, this uplift is due to the swelling. So, here $N_c = 6.14$ and then c_u is the undrained cohesion.

So, now, I will show you one example problem, in a shaft so, dead load + live load is equal to 1300 kN that means dead load is 800 kN, live load is 500 kN this is dead load, this is live load and the active zone is 6 m, diameter of the shaft is 1 m. So, that mean D_s is 1 m. Now, what would be the D_b that we have to find, so, this is the bell. Now the depth of the shaft below that active zone is 3 m.

So, and then other parameters are given, p_T is given which is measured in laboratory is 500 kN/m^2, ϕ_{ps} is 10° to 20°. So, we have taken average value of 15° and undrained cohesion is 100 kN/m^2. So, these values are given. So, the uplift force $U = \pi D_s Z p_T \tan\phi_{ps}$. So, this is 3.14, D_s is 1, Z is 6, $p_T = 500 \times \tan 15°$. So, this is 2524 kN.

Now, assuming we are not taking the dead load and live load effect, so, we are taking this is 0. So, if this is 0 dead load is 0 that means, the Q_{net} will be equal to uplift. So, uplift will be equal to Q_{net} that is $\frac{c_u N_c}{\text{factor of safety}}\left(\frac{\pi}{4}\right)(D_b^2 - D_s^2)$.

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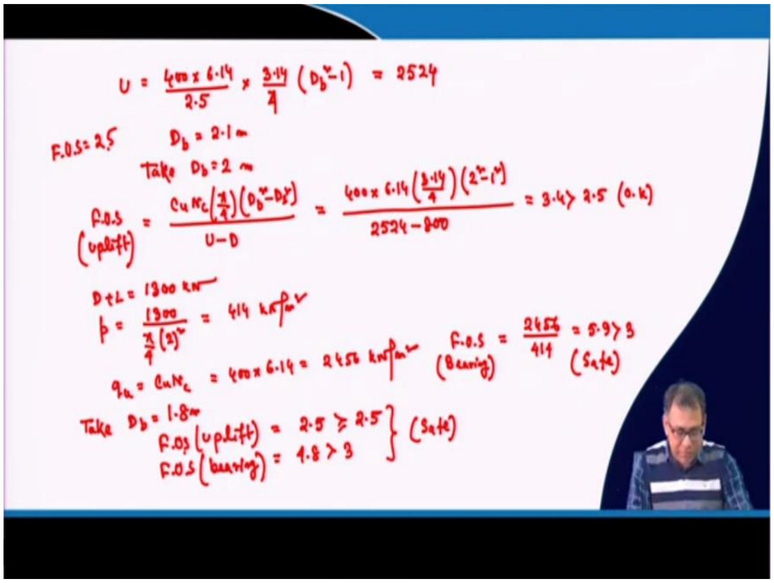

$U = \frac{400 \times 6.14}{2.5} \times \frac{3.14}{4}(D_b^2 - 1) = 2524$

F.O.S = 2.5 $\quad D_b = 2.1$ m

Take $D_b = 2$ m

$\underset{(\text{uplift})}{\text{F.O.S}} = \frac{c_u N_c \left(\frac{\pi}{4}\right)(D_b^2 - D_s^2)}{U - D} = \frac{400 \times 6.14 \left(\frac{3.14}{4}\right)(2^2 - 1^2)}{2524 - 800} = 3.4 > 2.5$ (O.K)

$D + L = 1300$ kN

$p = \frac{1300}{\frac{\pi}{4}(2)^2} = 414$ kN/m^2

$q_u = c_u N_c = 400 \times 6.14 = 2456$ kN/m^2 $\quad \underset{(\text{Bearing})}{\text{F.O.S}} = \frac{2456}{414} = 5.9 > 3$ (Safe)

Take $D_b = 1.8$ m

$\left.\begin{array}{l} \text{F.O.S (uplift)} = 2.5 \geq 2.5 \\ \text{F.O.S (bearing)} = 4.8 > 3 \end{array}\right\}$ (Safe)

So, c_u is 400, N_c is 6.14, factor of safety say we are taking here 2.5, and this $\frac{\pi}{4}$ is $\frac{3.14}{4}$3.14 and then we do not know the value of D_b^2 because the value of D_b is unknown, so, $D_b^2 - 1$. So, now, this will be equal to U this is equal to 2524. So, if I solve these then I will get the $D_b = 2.1$ m. So, for this trial take our D_b value is 2 m for first case.

Now, we have to calculate the factor of safety considering dead load also because actually equation is $Q_{\text{net}} = U - D$, but we have neglected D for this particular case. So, we are now calculating the factor of safety for uplift. So, that is $\frac{c_u N_c \left(\frac{\pi}{4}\right)\left(D_b^2 - D_s^2\right)}{Q_n}$, so if it factor of safety means $\frac{c_u N_c \left(\frac{\pi}{4}\right)\left(D_b^2 - D_s^2\right)}{U - D}$.

So, this is $\frac{400 \times 6.14 \times \left(\frac{\pi}{4}\right)\left(2^2 - 1^2\right)}{2524 - 800}$ because live load is not considering right now, because live load may not be always present in its maximum value. So, this is equal to 3.4 which is greater than 2.5, so safe. But now, as I mentioned we have to check it for both uplift as well as the compressive load. So, this is this uplift we have checked now we have to calculate the factor of safety for compressive load also.

So, now we know that $D + L$ is 1300 kN. So, the stress which is acting is 1300 kN divided by $\frac{\pi}{4} \times 2^2$. So, this is 414 kN/m^2. Now ultimate bearing capacity, q_u will be $c_u N_c$ for that particular soil. So, now we are calculating this stress or the load carrying capacity under compressive loads total D_b you have to consider and we are not considering the frictional resistance we are taking only the base resistance.

So, base resistance in uplift will be only the enlarged portion will not consider the shaft region, but for the compressive load you will consider total diameter of the base. So, and that equation is $c_u N_c$, so, c_u is 400, N_c is 6.14. So, this is 2456 kN/m^2. So, what is the factor of safety? So, the factor of safety under bearing or compressive load is equal to $\frac{2456}{414}$, 414 in this case which is acting and 2456 is the load carrying capacity or stress carrying capacity.

So, this is 5.9 which is greater than 3, safe. What you can say under uplift also it is 3.4 and it is 5.9 so, slightly higher values so, we can further reduce the D_b value. So, how we can take the D_b value now, if we take in second trial that $D_b = 1.8$ m. So, factor of safety under uplift the same way we can calculate will be equal to 2.5 which is greater than or equal to 2.5. So, it is acceptable and a factor of safety under bearing will be equal to 4.8 which is also greater than 3. So, both are safe.

So, we can provide a width of the shaft base width of the bell is 1.8 m. So, and remember that we have not considered the frictional resistance because most of the zone is the active zone and that active zone is given only the uplift.

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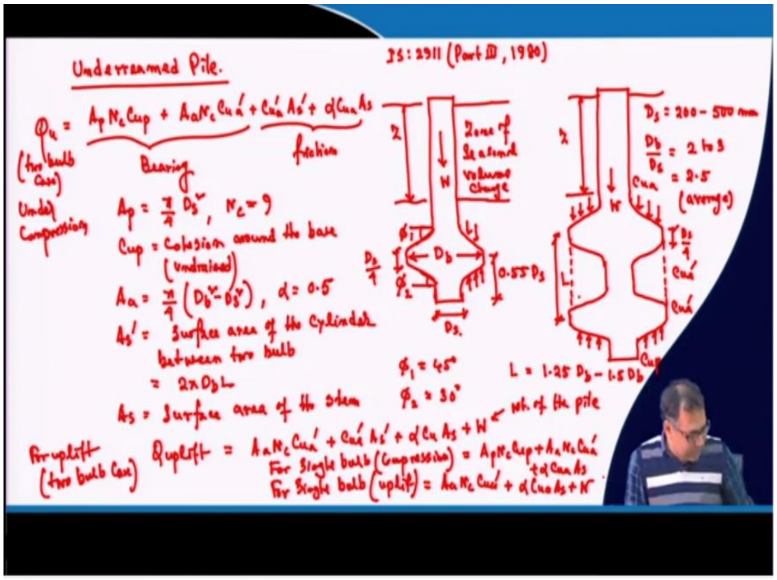

Underreamed Pile.

IS: 2911 (Part III, 1980)

$Q_u = \underbrace{A_p N_c C_{up} + A_a N_c C_{ua}'}_{\text{Bearing}} + \underbrace{C_{ua}' A_s' + \alpha C_{ua} A_s}_{\text{friction}}$

(two bulb case)
Under compression

$A_p = \frac{\pi}{4} D_s^2$, $N_c = 9$

C_{up} = Cohesion around the base (undrained)

$A_a = \frac{\pi}{4}(D_b^2 - D_s^2)$, $\alpha = 0.5$

A_s' = Surface area of the cylinder between two bulb $= 2\pi D_s L$

A_s = Surface area of the stem

$\phi_1 = 45°$

$\phi_2 = 30°$

$L = 1.25 D_s - 1.5 D_b$

For uplift (two bulb case) $Q_{uplift} = A_a N_c C_{ua}' + C_{ua}' A_s' + \alpha C_{ua} A_s + W$ ← wt. of the pile

For single bulb (compression) $= A_p N_c C_{up} + A_a N_c C_{ua}' + \alpha C_{ua} A_s$

For single bulb (uplift) $= A_a N_c C_{ua}' + \alpha C_{ua} A_s + W$

$D_s = 200 - 500$ mm

$\frac{D_b}{D_s} = 2$ to 3

$= 2.5$ (average)

So, next type of foundation that we are considering the under-reamed pile which is very famous in India. So, in this under-reamed pile, there is a bulb. So, which is similar to the drilled shaft that I have discussed with the enlarged base here also this bulb will act as the enlarged base and will give you the resistance against the uplift as well as the bearing.

So, this is the diameter of the shaft D_s and this is the diameter of the bulb and this is the active zone which is Z and where weight of the shaft is also the weight of the pile. So, this is zone of seasonal volume change because it will swell as well as shrink. So, now these are the different values I am giving so first this bulb center, the lower bulb center should be $0.55D_s$, so this one is $\frac{D_s}{4}$.

Now and this angle is ϕ_1 and this angle is ϕ_2. Now, generally this ϕ_1 is close to 45° and ϕ_2 is close to 30° this figure may not be in proper scale, but you should know that so, these are the recommendations as per IS:2911 part 3, 1980. Now, there can be multi bulb but two bulb case also. So, this is one bulb and this is the other bulb. So, this distance between two bulbs is L. So, again this Z is the thickness of the zone of seasonal variation and here I will explain why these are dotted lines.

Now, here D_s is generally recommended or the range of D_s is 200 mm to 500 mm, and $\frac{D_b}{D_s}$ is 2 to 3 or this is equal to 2.5 which is the average value. This means the bulb diameter is around 2.5 times the shaft diameter. Now, this L is roughly $1.25D_b$ to $1.5D_b$ and again this value is $\frac{D_s}{4}$.

Now, the uplift capacity of the two-bulb case will be $A_P N_c c_{up} + A_a N_c c_{ua'} + c_{ua'} A_{s'} + \alpha c_{ua} A_s$. what is this time let me explain. So, these two terms are giving the bearing, and these two terms are giving the friction, because here the friction is also considered. Now, this is not for the uplift this is actually under compression. Now here $A_P = \frac{\pi}{4} D_s^2$, $N_c = 9$, c_{up} is the cohesion or undrained cohesion around the base.

A_a is $\frac{\pi}{4} \times (D_b^2 - D_s^2)$, α is taken as adhesion factor which is 0.5 and $A_{s'}$ is the surface area of the cylinder between two bulbs that is equal to $2\pi D_b L$ and A_s is equal to surface area of the stem. So, first part is $A_P N_c c_{up}$. So, that means this small portion I am talking about the two-bulb case, so, this small portion will give us a tip resistance.

So, that small portion tip resistance is $A_P N_c c_{up}$. So, c_{up} is undrained cohesion at this portion A_P is the area which is $\frac{\pi D_s^2}{4}$ and N_c is 9. Then the next portion is this outer portion this bulb will also give you the resistance this is under compression and this will give under tension. So, this will give under tension for multiple bulbs. So, that means it will give the tension resistance here.

Single bulb which will give here and it will give under compression. So, that means here under compression this will give you the tip resistance the bulb portion. So, that is the second part where

A_a is the area beyond that shaft portion of that bulb is considered and here N_c is again 9 and this is the cohesion at that region. So, that means in this region this is the cohesion c_{up} here the cohesion is $c_{ua'}$.

Now, the next portion is the friction. So, where this friction is getting suppose we have a bulb when there is an uplift or compression in the soil within these two bulbs, they will form a cylindrical shape of the soil and they will either deform or it will go in the upward direction. So, there will be friction between soil cylinder and outside soil. So, here along this dotted line friction will develop.

So, that friction will get there this periphery is πD_b and the length is L and then the cohesion at that point and add this friction between soil and soil. So, α value will be 1, so, that is why α is taken as 1 and then above the second bulb. So, there will be the friction between the shaft and the soil and A_s is the surface area of the stem. So, this is the stem and the cohesion at that point and the α which is taken 0.5. So, this is two-bulb under compression case.

Now, I will just show you another three cases then I will finish this class and then that means for uplift for two-bulb case. So, this is uplift, this is compression. So, during uplift there will not be tip resistance for the shaft. But there will be tip resistance from this bulb portion. So that is the advantage of providing the enlarged base. So that means for uplift the equation will be $A_a N_c c_{ua'}$ and first term will not be there.

Other 3 terms will be there $+c_{ua'} A_{s'} + \alpha c_{ua} A_s$ this is for uplift of two-bulb case. That means stem frictional resistance will be there, the cylinder will be again there, but only the direction of the friction will change soil cylinder, but only this portion resistance will not come into picture. Then one more case now for single bulb under compression. So, single bulb under compression.

So, this frictional part will not be there, this frictional part for the cylinder will not be there, but for the shaft will be there because in this zone there will be friction, this zone will be fictional in the sand, but the cylinder will not take place in case of single bulb. So, the equation will be $A_P N_c c_{up} + A_a N_c c_{ua'} + \alpha c_{ua} A_s$. So, only the third term will not be there.

First term will be the tip resistance due to the shaft portion then there will be tip resistance due to the enlarged base portion then the friction resistance for this stem will be there. Now, the last case that for single bulb under uplifts so, under uplift $+W$ will also be there, because W is also acting in their downward direction which is the weight of the pile.

So, for uplift, single bulb, third term will not be there and the first term will not be there also only there will be second term and the third term. So, this will be $A_a N_c c_{ua'} + \alpha c_{ua} A_s + W$. So, these are the four cases for single bulb and the two-bulb cases are discussed under uplift as well as compressive load. So, remember that here we have to check both the condition under uplift as well as the compressive and providing the enlarged base is the advantage.

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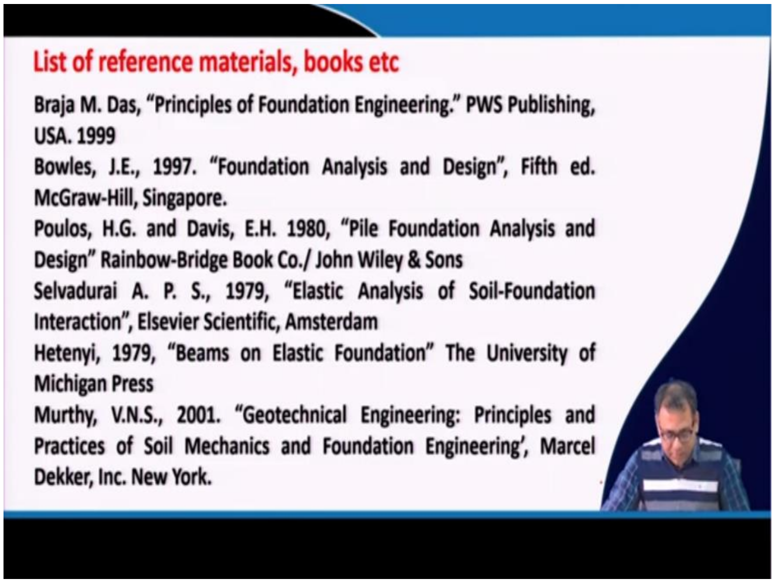

List of reference materials, books etc

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Poulos, H.G. and Davis, E.H. 1980, "Pile Foundation Analysis and Design" Rainbow-Bridge Book Co./ John Wiley & Sons

Selvadurai A. P. S., 1979, "Elastic Analysis of Soil-Foundation Interaction", Elsevier Scientific, Amsterdam

Hetenyi, 1979, "Beams on Elastic Foundation" The University of Michigan Press

Murthy, V.N.S., 2001. "Geotechnical Engineering: Principles and Practices of Soil Mechanics and Foundation Engineering', Marcel Dekker, Inc. New York.

So, now, I have finished the total course and these are the list of books for the reference. So, these books are used to prepare my notes and I have given their names inside the lectures also where I have used their material and these are the name of the books 'Principles of Foundation Engineering' by B M. Das, 'Foundation Analysis and Design' by Bowles, then 'Pile Foundation Analysis and Design' by Poulos and Davis.

Then 'Elastic Analysis of Soil-Foundation Interaction' by Selvadurai then 'Beams on Elastic Foundation' by Hetenyi, then 'Geotechnical Engineering: Principles and Practices of Soil Mechanics and Foundation Engineering' by V.N.S Murthy.

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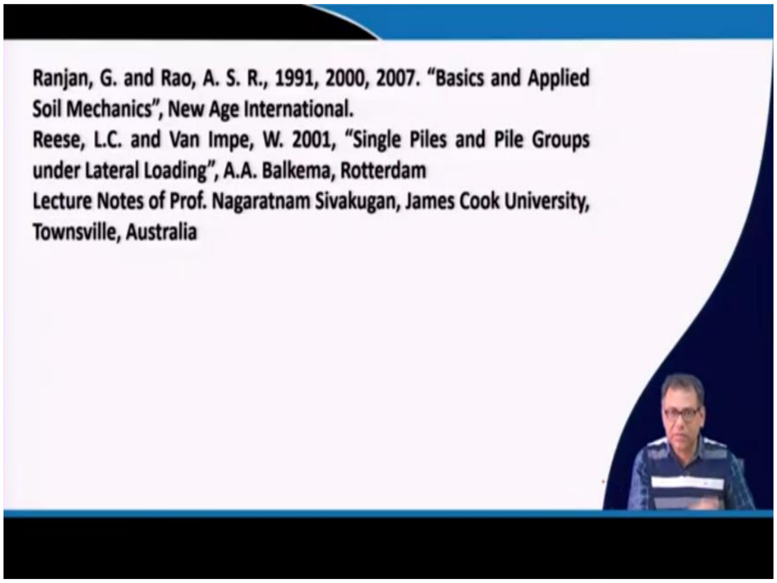

Ranjan, G. and Rao, A. S. R., 1991, 2000, 2007. "Basics and Applied Soil Mechanics", New Age International.
Reese, L.C. and Van Impe, W. 2001, "Single Piles and Pile Groups under Lateral Loading", A.A. Balkema, Rotterdam
Lecture Notes of Prof. Nagaratnam Sivakugan, James Cook University, Townsville, Australia

Then 'Basics and Applied Soil Mechanics' by Ranjan and Rao, then 'Single Pile and Pile Groups under Lateral Loading' by Reese and Van Impe, and lecture notes of Professor Sivakugan, James Cook University of Townsville Australia. So, these are the references and few references I have used inside the text inside my lectures for those detailed reference you will get from these books or these references so you can get these things. So that is it. So that is the end of this course. And I wish you best of luck.