Advanced Foundation Engineering
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Lecture - 51
Pile Foundation - Under Lateral Load and Uplift - I

So, this class I am going to start a new topic that is laterally loaded pile. And in this module, I will also discuss the pile under uplift. So, first I will discuss about the laterally loaded pile then I will discuss about the uplift pile.

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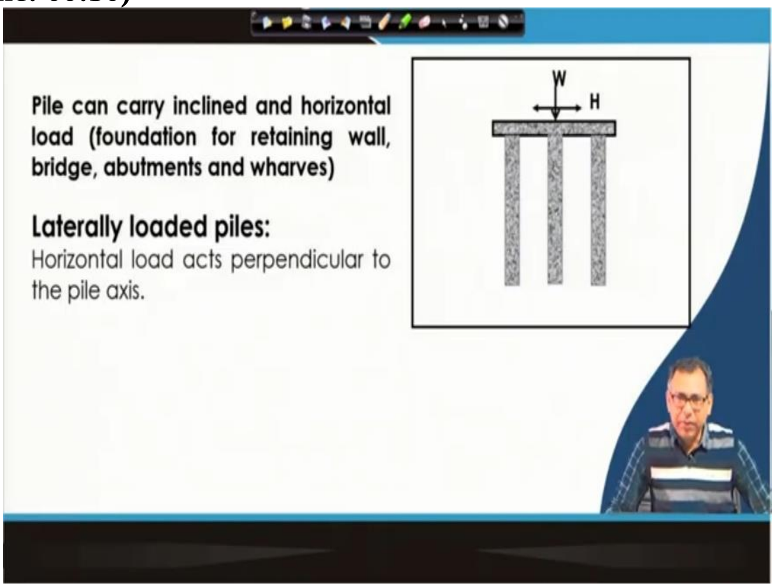

And then, as I have already discussed that pile can be subjected to compressive load, pile can be subjected to horizontal load, pile can be subjected to uplift also. So that means pile can carry the inclined load also horizontal load for example, the foundation for retaining wall where the lateral load or the horizontal load will come on the foundation. Then a bridge, abutments and if there are any wharves which is coming to the structure then those type of structure will be subjected to horizontal load.

Now, if the horizontal load acts perpendicular to the pile axis, I mean if this is the vertical pile axis and it is acting perpendicular to that pile axis then that type of load is called lateral load and that type of pile is called laterally loaded pile. So, the application area as we discussed that because the pile under compressive load which is very common. Then under lateral load retaining wall, bridges, abutment, wharves then uplift for tall structure for tower. So, where uplift load can be subjected to pile. So, first I will discuss the pile under lateral load and then first I will discuss the ultimate lateral load carrying capacity of piles.

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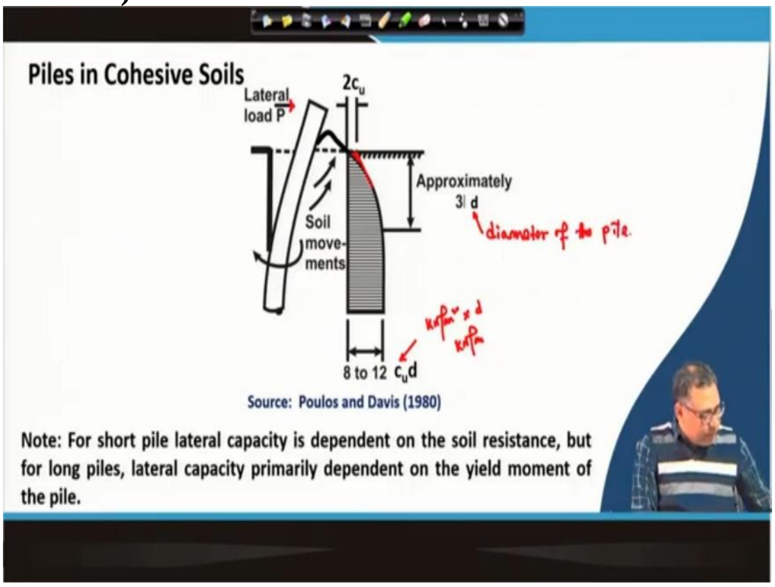

So, I will discuss the ultimate lateral load carrying capacity of piles in two types of soil first one is the cohesive soil and then the second one is for cohesionless soil. And I will also discuss the lateral load capacity of the pile for two types of piles one is the short pile, one is the long pile. So, in general that if pile is subjected to lateral load in cohesive soil then we will get this type of distribution. So, what is that distribution?

Suppose if this is the pile which is subjected to lateral load P. So, this is subjected to a lateral load P and then this pile will get resistance from the soil because it is moving in the lateral direction as the load is applied laterally. So, it will get a resistance from the soil. So that type of resistance is drawn or the pressure that pile will be subjected from the soil due to the lateral movement that is also represented here.

So, we can see that this is the pressure distribution, it starts from $2c_u$ at the top and ends at $8c_u$ to $12c_u$ at the base of the pile. So, it is $12c_u$, so $2c_u$ from the top to it will go up to $8c_u$ to $12c_u$. So, if I multiply it with the d then that will give you kN/m because actually this c_u is kN/m^2. So, now if I multiply with d then this will come in kN/m.

So, top also you can multiply it with the d. So that means actually the distribution is $2c_u$ to $8c_u$ to $12c_u$ at the base of the foundation and it is also noticed that approximately after the $3d$ from the top of the pile, the distribution is uniform. So, and it is also observed that for the short pile lateral capacity depends on the soil resistance that means the soil resistance is giving the whole lateral resistance for the laterally loaded pile.

So, lateral capacity of the pile solely depends on the soil resistance for short pile. But for the long pile lateral capacity primarily depends on the yield moment of the pile. So, based on this distribution for the lateral loaded pile in clay or cohesive soil that mean there will be uniform distribution of the stresses or the resistance, soil resistance after approximately $3d$. This is $3d$, from the top of the pile or top of the ground surface and d is the diameter of the pile. So, this d is the diameter of the pile.

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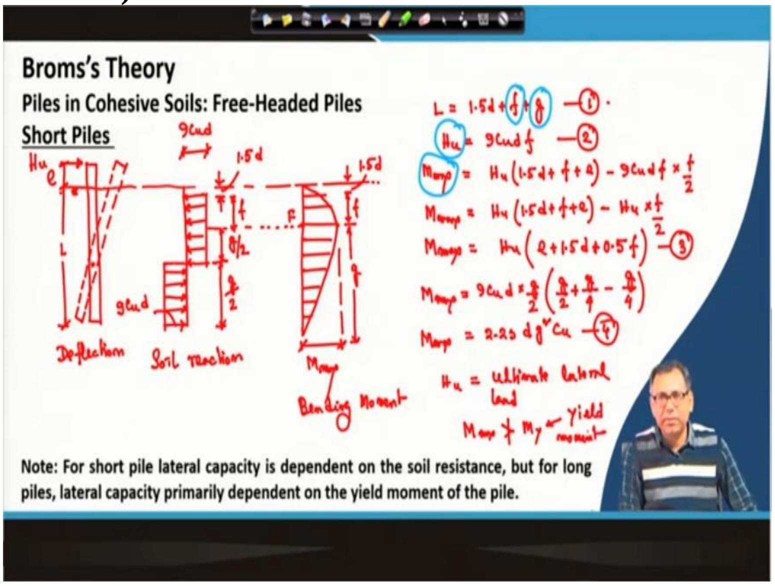

So, based on that, Broms proposed different soil pressure distributions for short piles and the long piles, pile in cohesive soil and the cohesionless soil. So, I will discuss first Broms's theory. So, Broms has suggested different pile soil pressure distribution for different types of piles that means, it can be short pile, long pile, it can be free headed, it can be fix headed. So, first I will discuss about the piles in cohesive soil which is a free headed pile and a short pile.

As per Broms's theory if this is the ground surface, I now have a pile which is a short pile subjected to lateral load, H_u, this pile is subjected with an eccentricity, e from the ground surface that means, the lateral load is acting at a distance of e above the ground surface. So, now this is the length of the pile L. So, now as per Broms's theory as it is a short pile. So, pile will rotate about a point within the pile.

So, this is the rotation of the pile. So, it will rotate about a point within the pile. So, this is the deflection pattern, and this is the ground surface. Now, based on that, the soil pressure distribution will be something like this. So, this is the point. So, you can see the pile is rotating, the short pile under cohesive soil it is rotating about a point within the pile. So, upper portion of the pile is moving towards the soil. So that means upper portion of the pile will give the passive resistance because it is moving towards the soil from left to right.

So, in the upper portion there will be a passive resistance that will also act from right to left. But below the point of rotation the distribution will be totally opposite. Now the lower part, the pile is moving from right to left. So, the reaction or the passive resistance of the soil will act from left to right, so that I will write here. So, I will draw here. So, this is the point. So, below that there will be distributions like this. And above that there will be distribution like this.

And Broms has suggested that there will be 0 soil resistance at a distance of $1.5d$ from the ground surface where d is the diameter of the pile. Because if you see the actual distribution that distribution is or that value is very small. So that is why it is mentioned that it is recommended that the top portion $1.5d$ there will be no soil resistance and then a soil pressure or the resistance and then there will be a uniform resistance.

Because you can see it is for the cohesive soil, this soil resistance is more or less uniform after a certain depth. So, here Broms has assumed or recommended that from top $1.5d$ portion there will be no resistance after that there will be uniform resistance and as expected above the point of rotation, the resistance will act from right to left and below the point of rotation it will act from left to right and this is the pressure distribution diagram.

So, if we can write that, this is the point at a distance of f where maximum bending moment within the pile is observed. So that maximum bending moment will be at the point F, so after that it will go like this. So, at the point F there will be maximum bending moment. So, I can write this is M_{max} which is at a distance of f or total which is this is $1.5d$. So, total will be $1.5d + f$ from the ground surface and this distance is $\frac{g}{2}$ and this is also $\frac{g}{2}$ this is not in scale.

So, this one is total, I can write this distance is g. So, total length of the pile is L, which is equal to $1.5d + f + g$. So, this is an equation, the total length is $1.5d$ up to which there will be no soil reaction then $+f$ at that point there will be a maximum bending moment then $+g$ is the rest of the portion. So, total L, I can write $1.5d + f + g$. So, now, for the short pile this is the pressure distribution, bending moment and the deflection pattern.

So, I can write this is soil reaction and this is I can write bending moment. So, if I take, if I want to determine what will be the H_u value, H_u is acting laterally. But if I look at the soil reaction diagram then $\frac{g}{2}$ this part and the $\frac{g}{2}$ the upper part these two will cancel out. So, the H_u will get from the f, up to the f portion only. So, I can write that H_u will be equal to because this $\frac{g}{2}, \frac{g}{2}$ will cancel out.

So, this will be equal to and another thing that I want to say that from this diagram, this uniform portion varies from $8c_u$ to $12c_u$. So, Broms has recommended that this value is $9c_u$ and then we can multiply with d, so, $9c_u d$ is in kN/m. So, this stress I can represent per meter that means, if I multiply with the diameter of the pile. So, it will be kN/m.

Similarly, this one is also $9c_u d$, so 8 to 12 is general range and Broms has recommended that we can take a uniform soil reaction of $9c_u$ and d is multiplied along the length of the pile except top $1.5d$ portion where the soil reaction value is 0. So, I can write the H_u will be that $9c_u d \times f$ because $9c_u d$ is the pressure distribution $\times f$, f zone it is acting because $\frac{g}{2}, \frac{g}{2}$ is cancelled out, so that region or that area within the f distance is giving us all the resistance or the lateral load capacity of the pile.

So, this is the equation number 2. So, ultimately, I want to calculate the H_u. What will be the value? So, next if I take the moment, maximum moment. So, M_{max}, so what is M_{max}? So, M_{max} is acting at F point at the distance f from that zero-pressure point. So, maximum if I take the moment at this point, F point and then I can get that the maximum moment will be how much? So, that will be $H_u \times (1.5d + f + e)$.

Because this $H_u \times (1.5d + f + e)$ that is acting and then the upper portion there will be a soil reaction. So, minus soil reaction area $9c_u df$ and I am taking moment from this point. Why should you say this is the F point? I am taking moment from this F point because where the moment is maximum, I am determining the maximum moment. So, $f \times$ this area divided by, it will act as a center, $f \times \frac{f}{2}$.

So that is the maximum moment if I take the moment at point F, I am taking the moment above the point F. So, this is M_{max}. So, if I simplify this equation, I can write that M_{max} is equal to, see after simplifying these equation I can write $M_{\max} = H_u \times (1.5d + f + e)$ and this $H_u = 9c_u df$, so $-H_u \frac{f}{2}$. So, finally I can write this is $H_u(e + 1.5d + 0.5f)$, this is $f - 0.5f$, so this will be $+0.5f$. So, this is equation number 3.

So, there will be a maximum moment we can calculate at the point F, so this is the value. So, I can calculate maximum moment in another way also, by taking the moment for lower part of F. So, because this will also give me the maximum moment. So, I can write that for the lower part that $9c_u d \times \frac{g}{2}$, this is the area and then the lower part total will be $\frac{g}{2}$ then plus $\frac{g}{4}$ that is for this spot then minus$\frac{g}{4}$.

So, $\frac{g}{4}$ and $\frac{g}{4}$ will cancel out. So, because what I am doing, I am taking the moment, maximum moment and for the lower part of the F. So, this is the lower part we have two rectangular soil reaction area for height $\frac{g}{2}$ each and both are acting in opposite direction. So that is why I am taking the lever arm will be for the lower portion will be $\frac{g}{2} + \frac{1}{2} \times \frac{g}{2}$.

So that is $\frac{g}{4}$ then $-\frac{1}{2} \times \frac{g}{2}$, so that will be $\frac{g}{4}$, for the upper part and the lower part. So, finally, this value is $2.25dg^2c_u$, so this is also $M_{\max}$. So, there will be four equations. So, now, what are my unknowns? My f is unknown, g is unknown, $M_{\max}$ is unknown, H_u is unknown, four unknowns are there, *d* is diameter of the pile is known, length of the pile is known.

So, *f* is one unknown. So, what are those unknowns, *f* is one unknown, g is one unknown, H_u is one unknown and $M_{\max}$ is another unknown. So, we have four unknowns and we have four equations. So, once we solve these four equations, we will get the ultimate load carrying capacity of the pile H_u then we get where the maximum moment will come and then what is the value of g and then maximum moment $M_{\max}$ also we can calculate.

So, this way after solving this whole equation we can get what will be the H_u value. H_u is ultimate lateral load carrying capacity of the pile. So, next one I will discuss that this is for the short pile, but short pile remember that $M_{\max} \ngtr M_y$ that mean M_y is the yield moment of the pile.

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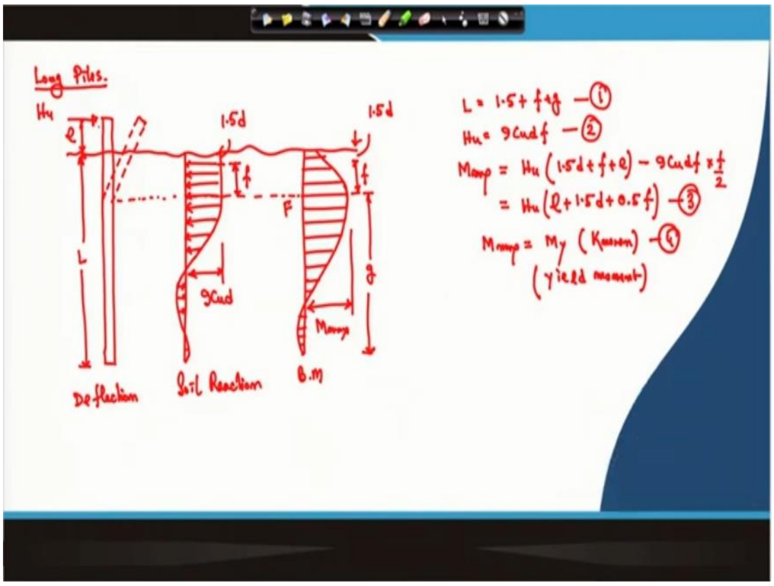

So, for the long pile what will happen? This is for the long pile; previous one is for the short pile. And for the long pile same if I take the ground surface, this is the ground surface and we have a pile which is a long pile. Here also H_u is acting at a height of e and here again this is the L length of the pile. So, here the total pile will not rotate because as the pile is long. So, lower part of the pile will be very rigid, it will not move like the short pile.

So, what will happen the upper part of the pile will move and after certain point if we apply more H_u then there will be a break or yield of the pile at a point and that will happen if that developed moment within the pile is greater than the yield moment of the pile material then this yielding of the pile will occur at a point. So that point is this point where there will be a yielding of a pile and at this point maximum bending moment will develop.

So, at this point maximum bending moment will develop this is the bending moment diagram and definitely this is $M_{\max}$, maximum moment and definitely if $M_{\max} > M_y$ then there will be a breakage or yielding at this point within the pile. So, we can draw the soil reaction. So, again for the soil reaction top $1.5d$ portion there will be 0 stress then uniform stress up to that point then the stress will change, and this will be the soil reaction for this long pile.

So, I can write this value is again that uniform portion value is $9c_u d$ and this distance is again where the maximum moment is acting is F, so f is this one and this one is $1.5d$. So, this is the deflection for the long pile, this is the soil reaction, and this is the bending moment. Now, for the long pile I can write that previous equations can be valid. Which are the previous equations?

Because equation number one is valid here also, because here or I can write a different equation but here also equation number one is valid where this is g. So, this is equation number one is valid here, equation number 2 is also valid here, because we can assume that this portion and the lower opposite portion are counterbalancing these forces. So, this portion are balancing these forces and then this top portion is only giving the H_u, equation 2 is valid.

Equation 3 is also valid but equation 4 is not valid here because we cannot write equation 4 here. So, we can write equation one, we can write equation 2, we can write equation 3. So, what are the equations that are valid here? So, this equation one, so that mean for the long pile $L = 1.5d + f + g$, so I am writing again 1, 2, 3, 4 so, one is valid. Again, as I mentioned that this top portion reaction is equal to H_u and the bottom portion the positive negative side we are assuming that they are balancing each other.

So, the equation 2 is also valid. So, equation 2 we can write that means $H_u = 9c_u df$, so this is also valid. Then you can take the maximum moment value at point F, so this is point F. So that will be equal to again we can write $H_u \times (1.5d + f + e) -$ this one, $9c_u df \times \frac{f}{2}$, so that is also valid. So, this value is coming out to be this value is H_u, so this is H_u, H_u then $e + 1.5d + 0.5f$. So, this is also valid.

What are the unknowns? Again, f is unknown, g is unknown, H_u is unknown, M_{max} is unknown. So, there are 4 unknowns, but there are 3 equations because equation 4 is not valid here for the long pile because in the equation 4 lower part we cannot take that type of moment expression because it is not uniform, distribution of soil reaction is different as compared to the short pile. So, equation 4 is not valid.

So, there are 3 equations for the long piles. But we have 4 unknowns. So, we need one more equation and that equation for the long pile that in particular this case, we have to consider that M_{max} is equal to yield moment. So, this is the yield moment of the pile and moment of the pile and which is the known value. So, based on the which type of pile section we are taking, whether the material of the pile this yield moment is known, so that means this yield moment is known and that is giving us the fourth equation.

So that means, these 4 equations are here and if the maximum moment which is induced in the pile is greater than yield moment then the yielding will occur, so that we do not want. So, we have to restrict that maximum bending moment to be equal to the yield moment. So that means, we can go up to this yield moment. So, $M_{\max}$ should be equal to yield moment and that will give us the fourth equation and yield moment is known for a particular pile.

So, then we have 4 equations and 4 unknowns or now as the $M_{\max} = M_y$ and M_y is known. So, we can say we have 3 unknowns and we have 3 equations. So, we can solve and we will get the H_u value. So, this is for the long pile and both the pile, short piles and long piles are in cohesive soil and they are free headed pile that means we have not applied any fixity on the pile head.

So, in the next class I will discuss that how we can develop similar type of equation for the fix headed pile when pile is within the cohesionless soil and then based on these equations already charts are developed. So, we can directly use those charts and then we can design or we can calculate what would be the ultimate load carrying capacity of the laterally loaded pile. So, ultimate lateral load carrying capacity of the pile. Thank you.