Soil Structure Interaction
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Lecture - 2
Bearing Capacity of Soil

Last class, I have discussed about various soil exploration techniques and the scope of disturbed sample and undisturbed sample usage along with the different design criteria for a shallow foundation. In this class, I will discuss about the bearing capacity and how to determine the bearing capacity of soil. So as I discussed, there are different terminology for the bearing capacity calculation listed: ultimate bearing capacity, the net ultimate bearing capacity, gross safe bearing capacity, net safe bearing capacity. The net safe bearing capacity is very important. Ultimately we will determine the net safe bearing capacity and then, then the safe bearing pressure in terms of settlement criteria. So, the smaller value of net safe bearing capacity and the safe bearing capacity in terms of settlement criteria will give the allowable bearing pressure.

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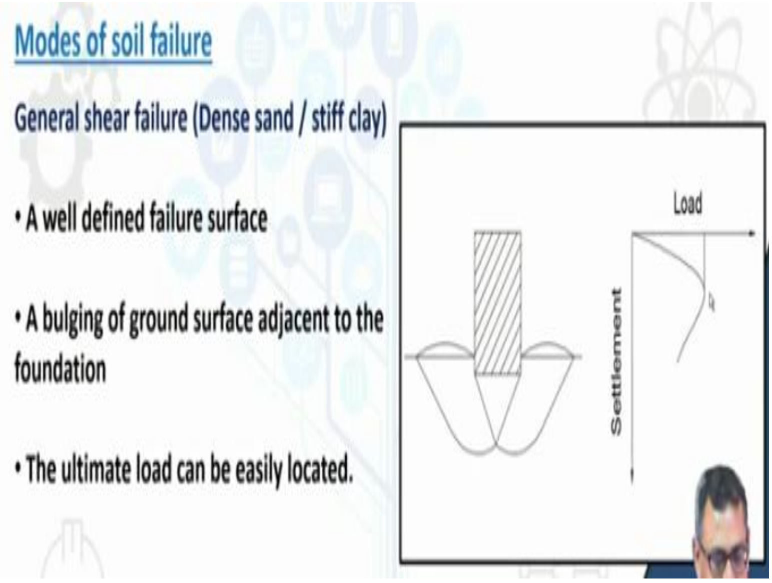

Now, we will discuss about the different modes of soil failure. When a load is applied on soil, it may fail in different modes which depend upon the type of soil. There are 3 types of failure modes as: general shear failure, local shear failure and punching shear failure. General shear failure occurs in dense sand or stiff clay. A definite failure surface develops within the soil that fails in general shear failure. There would be significant amount of bulging on both sides of the foundation and the ultimate load can be easily determined. The load versus settlement graph gives a definite peak.

That means, the load settlement curve initially increases and then decreases giving a particular peak value. This peak value will give us the ultimate load of the foundation which is easy to locate.

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c_u (kPa)	consistency
0 – 12.5	very soft
12.5-25	soft
25-50	medium
50-100	stiff
100-200	very stiff
>200	hard

D_r (%)	consistency
0-15	very loose
15-35	loose
35-65	medium
65-85	dense
85-100	very dense

These are the different conditions to identify a soil as soft or medium or stiff as mentioned earlier, the general shear failure is applicable for stiff clay or dense sand. The undrained cohesion for a stiff soil would be between 50 and 100 kPa. If the undrained cohesion is within 0 to 12.5 kPa, then the soil is called very soft, 12.5 to 25 is for soft, 25 to 50 is for medium, 50 to 100 is for stiff, 100 to 200 is for very stiff and then if c_u is greater than 200 it is called hard.

Similar to consistency of different types of soil, there is a term called relative density which is usually applicable in granular soils. Relative density is the term by which one can understand the density status of the soil in the field. That means, for a soil in a very loose condition, the relative density should be between 0 and 15. But, for a dense soil where the general shear failure usually occurs, the relative density should be in between 65 and 85. The relative density values for a very dense soil would be 85 to 100 and for medium soil, 35 to 65%. So, if the relative density of a soil is determined, we can predict the type of failure the soil may undergo and for clay, this can be done by determining the consistency of it.

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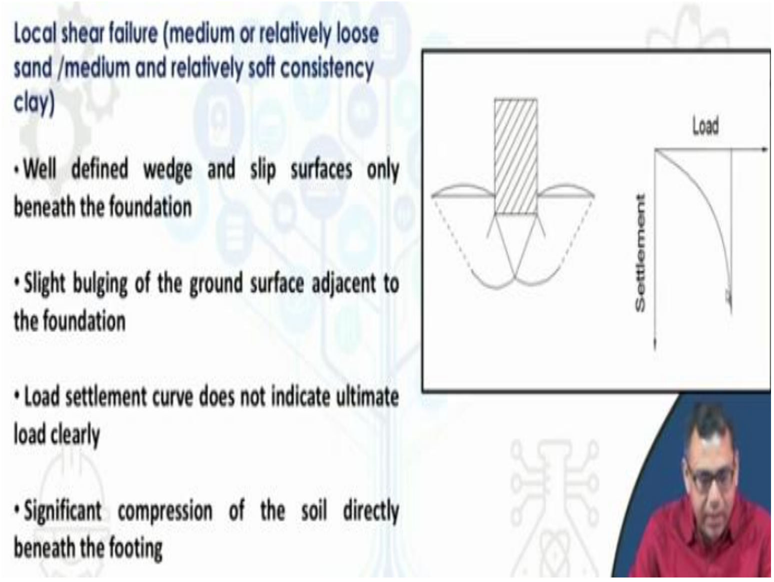

Local shear failure occurs in medium/relatively loose sand or medium/relatively soft clay. In case of a local shear failure, well defined wedges and slip surfaces will only be found beneath the foundation, and not on the sides of the foundation. Although, there would be a slight bulge in the ground surface adjacent to the foundation, it is not as significant as compared to the general shear failure. Besides, the load settlement curve does not indicate any ultimate load clearly. That means there would be no definite peak of the load settlement curve, as the curve increases initially and becomes almost parallel to the settlement axis. Another characteristic of the local shear failure is that the soil directly beneath the foundation undergoes significant compression.

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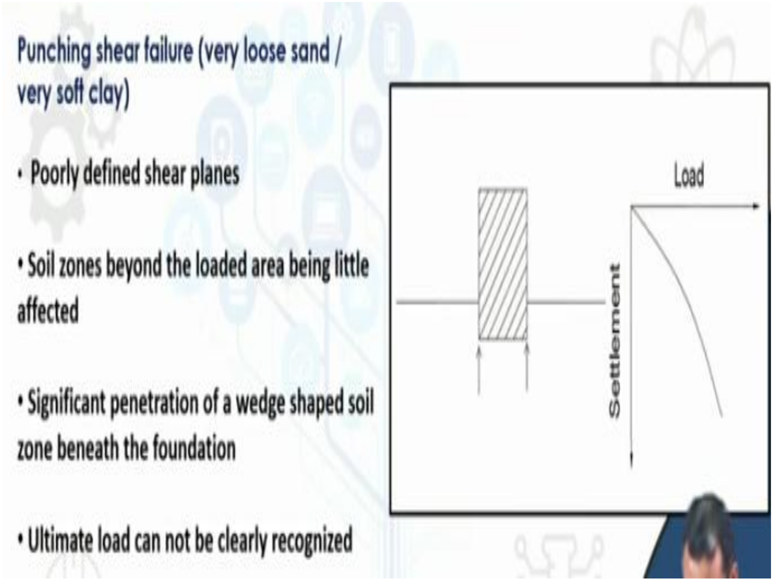

Next in the failure modes is punching shear failure which occurs in very loose sand and very soft clay. Here, there would be no definite failure surface even below the footing. The soil zones beyond the loaded area will not be affected, which means there would be no bulging or a very little effect would be noticed. Significant penetration of the wedge shaped soil zone beneath the foundation can be expected which in turn results in significant penetration of the foundation, but within the footing zone. So, the ultimate load cannot be clearly recognized in the local shear failure.

These are the different failure modes that may occur in various types of soil.

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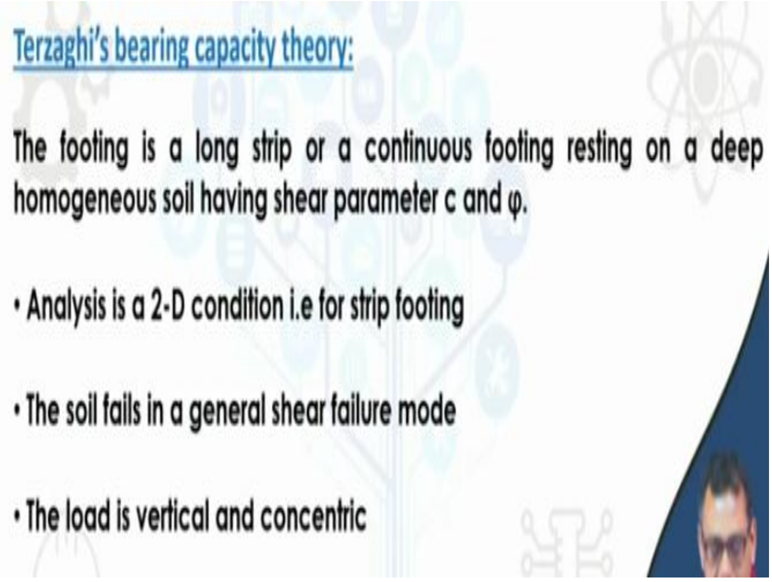

Based on the observations discussed so far, the first bearing capacity theory was proposed by Terzaghi which is very popular. This equation is generally used to determine the bearing capacity of soil. When Terzaghi derived this bearing capacity theory, he assumed or he derived this theory for strip footing or the continuous footing and it is assumed that the soil is homogeneous which fails in general shear failure. Terzaghi's bearing capacity was initially developed for dense soil and stiff clay where the general shear failure will occur, so that there will be a definite failure surface below and beyond the loaded region. The load is considered perfectly vertical and acting at the center of the footing.

These are the conditions or assumption in Terzaghi's bearing capacity theory.

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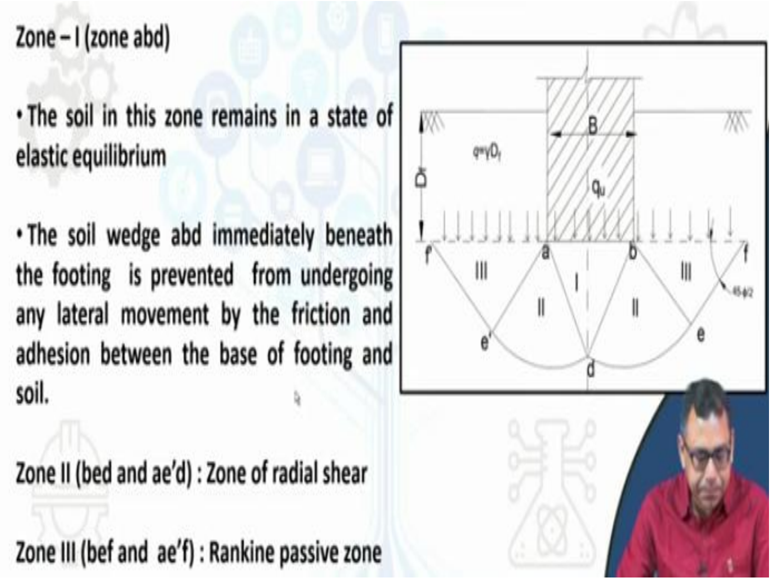

Terzaghi assumed 3 different zones: a triangular portion, zone-1 and a curved portion, zone-2 and again there would be a straight line portion, zone-3. The zone-1 is called the state of static equilibrium. The zone-2 is the zone of radial shear and zone-3 is called the Rankine passive zone. Here, the effect of soil on the bearing capacity is taken as a surcharge effect.

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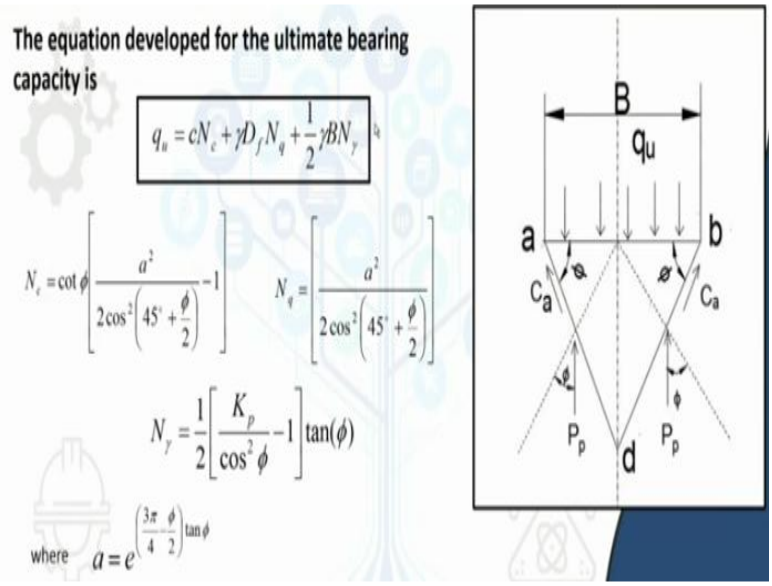

The different forces acting on the wedge and then finally these expressions are proposed. There are 3 terms in this equation: the first term is cN_c; the second term is $\gamma D_f N_q$ and the third term is $\frac{1}{2}\gamma B N_\gamma$. N_c, N_q N_γ are the bearing capacity factors. The expressions for the bearing capacity factors are given in the slide and as it is evident, they are a function of ϕ, friction angle. The factor, 'a' is also a function of friction angle, ϕ. Note that this equation was developed and is valid only for a strip footing.

As a summary of defining all the terms of the equation:-

N_c, N_q N_γ are the bearing capacity factors

c is the cohesion of the soil

γ is the unit weight of the soil

D_f is the depth of foundation

B is the width of foundation

The first term in the bearing capacity equation considers the contribution due to cohesion. The second term is $\gamma \times D_f$ which is nothing but the surcharge of the soil above the foundation level. The third term is the contribution due to the unit weight of the soil below the foundation.

There are two unit weights (γ) in the equation which means that for a homogeneous soil, the same γ can be used for both the terms. But ideally, the second term γ is the unit weight of the soil above foundation level (from the ground level to the foundation level) and the third term γ is the unit weight of the soil below the foundation level.

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φ	Terzaghi's Bearing Capacity Factor		
	N_c	N_q	N_γ
0	5.7	1.0	0.0
5	7.3	1.6	0.5
10	9.6	2.7	1.2
15	12.9	4.4	2.5
20	17.7	7.4	5
25	25.1	12.7	9.7
30	37.2	22.5	19.7
35	57.8	41.4	42.4
40	95.7	81.3	100.4
45	172.3	173.3	297.5
50	347.5	415.1	1153.2

Terzaghi had also given in tabular form, the different bearing capacity factors (N_c, N_q N_γ). Values are given for different ϕ values ranging from 0 to 50º of soil. For a ϕ value of 0º (purely cohesive soil), the N_c value is 5.7, N_q is 1 and N_γ is 0.

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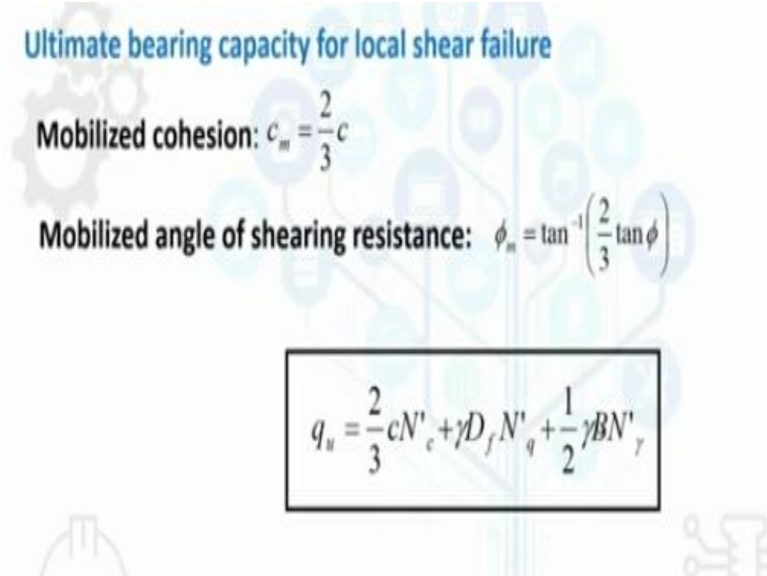

Terzaghi's bearing capacity expression was initially applicable only in case of general shear failure, but it can also be used for local shear failure condition by modifying the c and ϕ values. This modification includes reducing the c value to two-thirds of the original value $\left(c_m = \frac{2}{3}c\right)$. The mobilized angle of shearing resistance (ϕ_m) is given by: $\varphi_m = \tan^{-1}\left(\frac{2}{3}\tan\varphi\right)$ So, instead of using ϕ and c, the mobilized values, c_m and ϕ_m should be used. So, for the equation in case of local shear failure, the bearing capacity factors would be chosen based on the new ϕ value. The ultimate bearing capacity in this case will be: $\frac{2}{3}cN_c' + \gamma D_f N_q' + \frac{1}{2}\gamma B N_\gamma'$. So, N_c', N_q' and N_γ' means that it is for local shear failure and the bearing capacity factors are determined based on ϕ_m but not ϕ.

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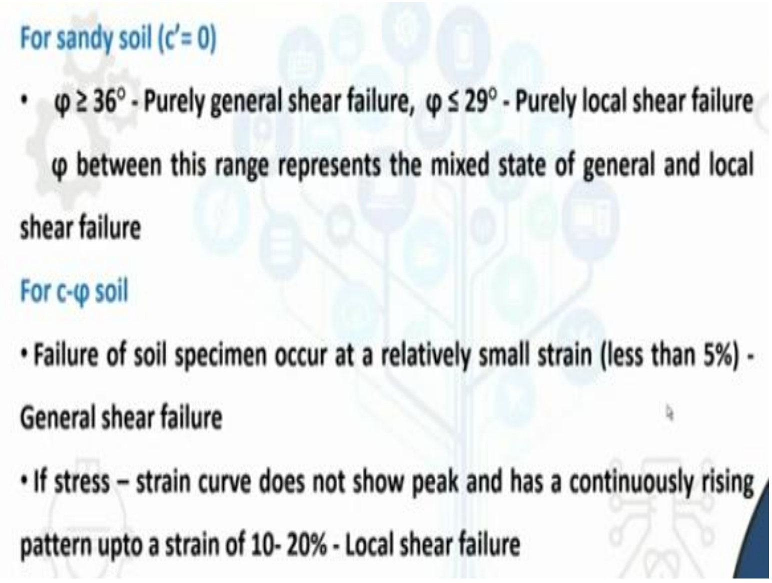

The next question is that when to consider general shear failure and when, local shear failure. There is a guideline given for this purpose. If soil has its friction angle, $\varphi \geq 36^{o}$ then the soil is expected to fail by general shear failure, and if $\varphi \leq 29^{o}$, local shear failure is likely to occur. If the ϕ value lies in between 29^{o} and 36^{o}, a mixed type of failure may be encountered. So, if $\varphi \geq 36^{o}$, directly we can use the N_c, N_q, N_γ, the original Terzaghi's bearing capacity factors as well as equation. If $\varphi \leq 29^{o}$, the ϕ and c values should be modified.

For example: if $\varphi = 29^{o}$, convert it to φ_m which would be equal to: $\tan^{-1}\left(\frac{2}{3}\tan 29^{o}\right)$.

Then based on that ϕ_m, determine the bearing capacity factors, which will be N_c', N_q' and N_γ'. If the P value lies between 29^{o} and 36^{o}, linear interpolation should be done to determine the bearing capacity factors. In case of a c-ϕ soil, the mode of failure cannot be decided either by the ϕ value or c value alone in which case, an analysis of the load settlement curve of the soil would be required.

If the stress-strain curve or the load settlement curve does not show any peak and has a continuously rising pattern up to a strain of 10 to 20%, then we will go for the local shear failure. If the curve indicates failure of soil specimen at a relatively small strain, less than 5%, then we will go for general shear failure.

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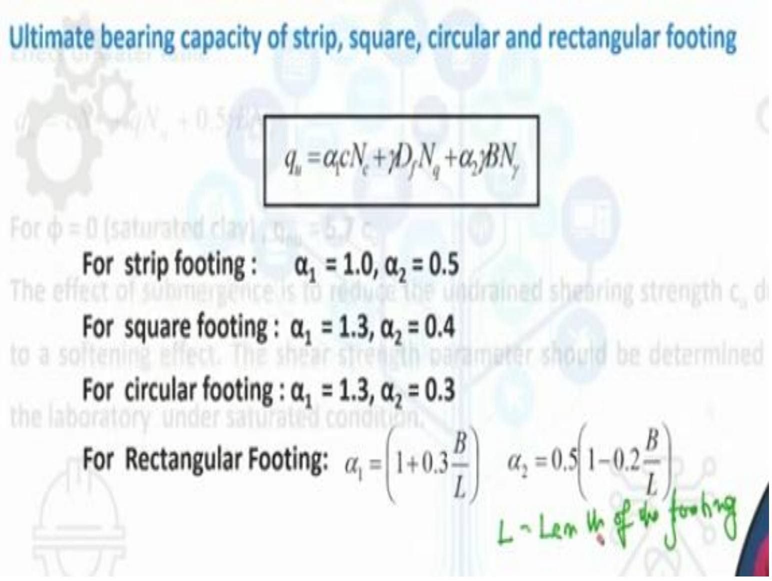

Originally Terzaghi's equation was applicable only for strip footing, but later on it has been modified and now it can be used for square footing, circular footing or rectangular footing but only with the application of certain correction factors. Two correction factors are introduced: α_1 and α_2 where, α_1 is applied for the first term ($\alpha_1 \times cN_c$) and α_2 is applied for the third term.

Now, for a strip footing: α_1 and α_2 will be half because in the original expression, it is ($1/2 \times \gamma$ B N_q). For a square footing, α_1 and α_2 will be 1.3 and 0.4 respectively. For a circular footing, α_1 and α_2 will be 1.3 and 0.3. For a rectangular footing, α_1 will be $\left(1+0.3\frac{B}{L}\right)$ and α_2 will be $0.5\left(1-0.2\frac{B}{L}\right)$ [B is the width of the footing and L is the length of the footing]

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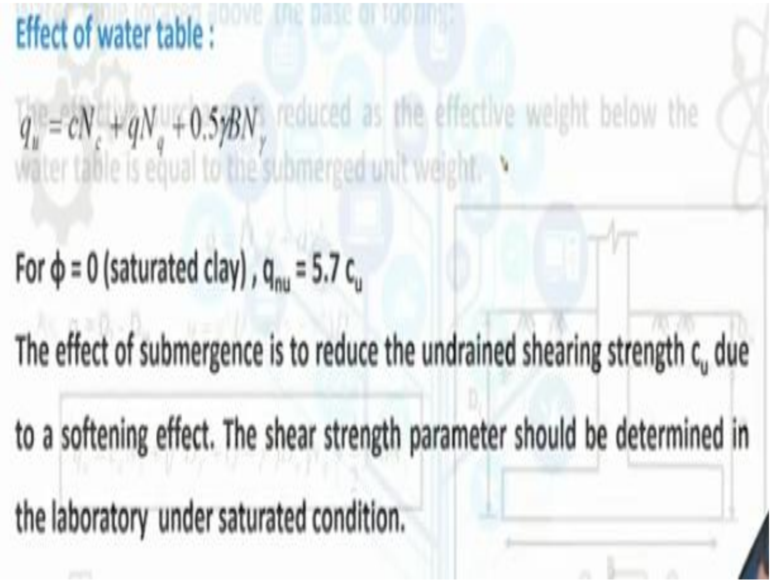

The next aspect to be considered is the water table effect because in Terzaghi's original equation, the water table effect was not introduced. But when a foundation is being designed, the water table should be taken into consideration. Now how we will incorporate the water table effect?

When bearing capacity is being worked out for a saturated clay ($\phi = 0$), the N_γ would be zero and $N_q = 1$. So, the third term in Terzaghi's equation would be zero and q_u would be equal to $(cN_c + q)$. But the net ultimate bearing capacity is: $q_{nu} = q_u - q$ (where, $q = \gamma \times D_f$). So, q_{nu} would be equal to c_uN_c. But if $\phi=0$, N_c will be 5.7 which makes $q_{nu} = 5.7N_c$.

So for a saturated clay ($\phi = 0$), net ultimate, q_{nu} will be $5.7c_u$.

The effect of submergence on soil is to reduce the undrained shearing strength, c_u due to softening effect. The shear strength parameters should be determined in the laboratory under saturated condition. Remember that whenever soil is under submerged condition, its cohesion or the strength will reduce. So when it is needed to determine the properties of clay or any soil, it should be done under submerged condition or the saturated condition.

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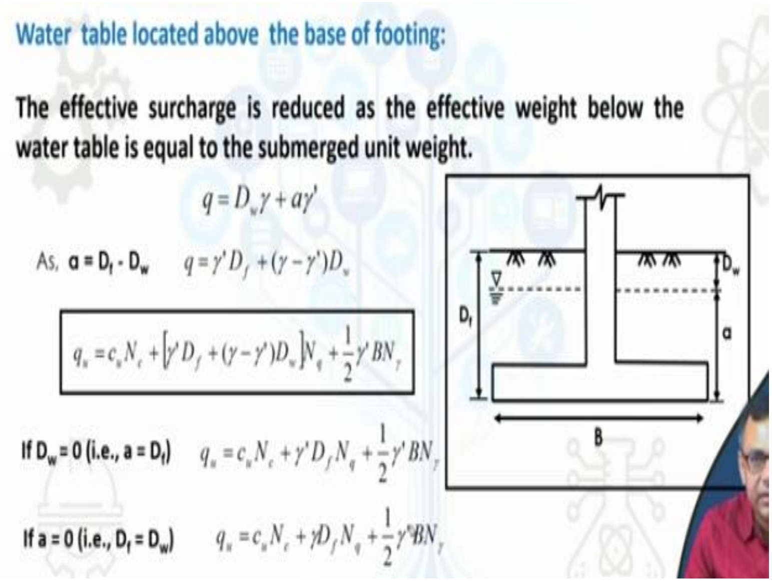

The effect of water table is actually introduced in Terzaghi's equation by using the effective surcharge in the calculations. This implies using a reduced surcharge as the effective weight below the water table is equal to the submerged unit weight.

As we are using the effective stress of soil we should know of total stress and effective stress. When a load is applied on soil, the soil skeleton takes some portion of the stress and the water takes some portion of the stress. Due to this, pore pressure will be generated in the soil. The effective stress is the stress taken by the soil skeleton only. That means, we can express effective stress as: total stress minus pore water pressure. $(\sigma' = \sigma - u)$

From the figure: D_w is the position of water table below the ground level;

D_f is the depth of foundation and

B is the width of foundation.

The soil above the ground level is not in submerged condition, but the soil below the ground level is submerged condition. Initially when there is no water, q = $\gamma \times D_f$. Now with the water table, q will be ($D_w \times \gamma$ + a×γ'). Now what is γ'? γ' is basically the effective unit weight of soil.

At a point at a depth of 'h' from ground level with water table at the ground level, effective stress will be: total stress, (γ × h) – (γ_{water} × h). $(\sigma' = \gamma h - \gamma_w h)$

where, γ is the unit weight of soil (here, as the soil is in submerged condition, γ is $\gamma_{saturated}$ or γ_{sat}) and γ_{water} is the unit weight of water.

Now, effective stress, $(\sigma' = (\gamma - \gamma_w)h) \Rightarrow (\sigma' = \gamma' h)$

γ' is the submerged unit weight of soil (may be referred to as γ_{sub} sometimes).

The same concept is used here, that here ($D_w \times \gamma$ + a×γ'). As the soil below water table will be submerged condition, γ' is used here and 'a' is the height, so: (a× γ'). Although initially, both were γ and this may be different γ_s according to the condition. It may be γ_{bulk} above the water table or γ_{sat}, (saturated unit weight). γ_w is the unit weight of the water, generally taken as 10 kN/m^3. Sometimes, you may find in some problems that γ_{bulk} will be equal to γ_{sat} and in some cases, these two can be different. You can refer to any soil mechanics book for the detailed derivation of this equation. Also, there would be detailed explanation about γ_{bulk}, γ_{sat}, γ_w and γ_{sub} or γ'.

If γ_{sat} and γ_{bulk} are different, then two different values will be given for: unit weight of the soil above water table and the saturated unit weight of the soil below water table. Finally, the equation for q will be: (γ × D_w) + (a × γ_{sub}).

If I substitute a = (D_f - D_w), the expression changes to: $q = \gamma' D_f + (\gamma - \gamma')D_w$ (D_w is the height of the water table from the ground). Now, substitute the value of q in the bearing capacity equation: $q_u = c_u N_c + [\gamma' D_f + (\gamma - \gamma')D_w]N_q + \frac{1}{2}\gamma' B N_\gamma$.

Here, as the water table is above the footing base, the third term will be definitely γ_{sub} or γ'. If the water table is at the ground level, the second term would also be γ' along with the third term. As, here it is not at ground level, we have to modify it in this way.

The next case we will discuss is if a = 0, that means water table is at the base of the foundation and D_w will be D_f. Now the second term γ will be γ_{bulk} because there water table is not present, but the third term γ will be γ_{sub} because third term γ represents the oil below the footing base which is in totally submerged condition. So, third term will be γ_{sub} or γ'.

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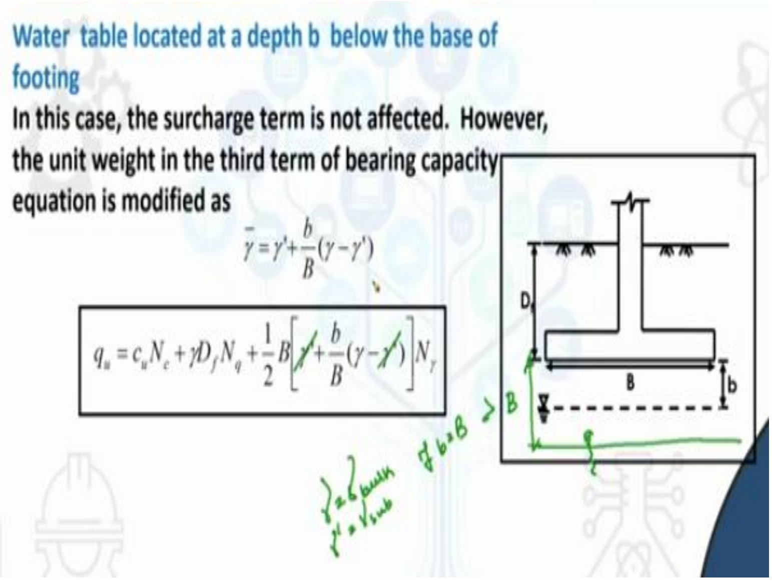

The next case is when the water table lies below the footing base. If the water table position is below the footing level at a depth which is greater than or equal to the width of foundation from the footing level, then the water table effect need not be considered. But, if the water table is located within a distance B from the base of the foundation, then our expression will be: $q_u = c_u N_c + \gamma D_f N_q + \frac{1}{2}\left[\gamma' + \frac{b}{B}(\gamma - \gamma')D_w\right] BN_\gamma$. The γ in second term would be γ_{bulk} or simply γ as the water table is not affecting the soil above the foundation.

So instead of using only γ, we should be using $\left[\gamma' + \frac{b}{B}(\gamma - \gamma')D_w\right]$. Usually if only γ is given, it means that it is the bulk density, γ_{bulk} and sometimes γ' may be written as γ_{sub}. In the last equation, if b=B (b is the depth of water table from base of the footing), this equation turns to the original bearing capacity equation indicating that the water table effect need not be incorporated.

In the next class, I will discuss about another condition where load is inclined and not acting at the center. In that case, how to determine the bearing capacity expression, bearing capacity of the foundation will be discussed in the next class. Thank you.