Advanced Foundation Engineering
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Lecture – 7
Shallow Foundation: Bearing Capacity I

So, last class I have discussed about various soil exploration processes and then previous week also I have discussed different in-situ tests to determine the soil properties. Now, this class I will start the shallow foundation bearing capacity or the bearing capacity of the shallow foundation and then I will discuss about the settlement and then finally I will discuss the design of the shallow foundation.

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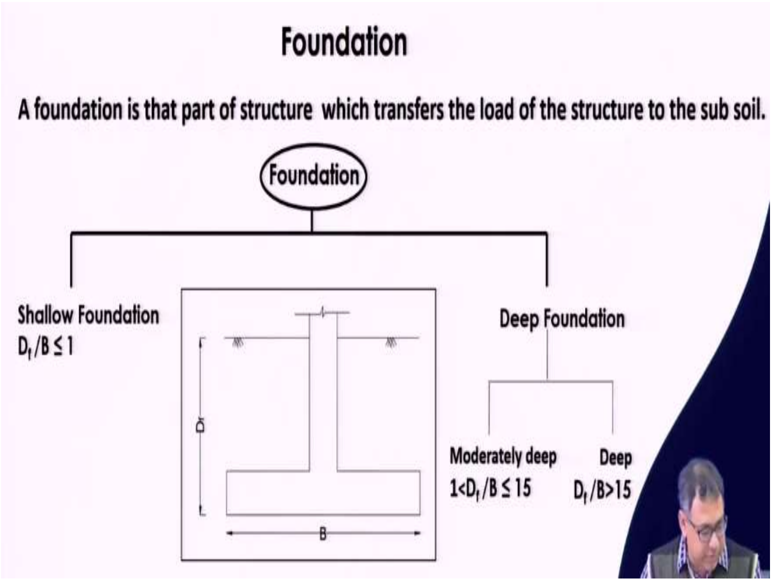

Now, generally the foundation can be divided into two parts, shallow foundation and the deep foundation. So, we can say it is a shallow foundation when the depth of the footing or the foundation is less than or equal to width of the foundation. So, this is the width *B* and this is the depth of the foundation. Now, deep foundation can say moderately deep if the depth is less than or equal to15 times the width and if it is more than 15 times of the width then it is called deep foundation.

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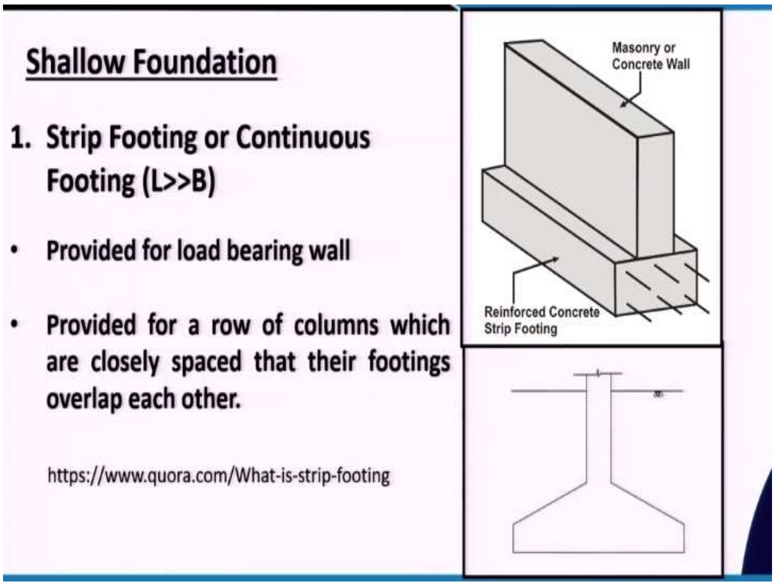

So, shallow foundation can be different types. It can be strip footing or the continuous footing. Strip footing means where the length is much larger than the *B* for retaining walls. So, this is the retaining wall where the length is much larger than the *B* that type of foundation is called a strip foundation or continuous foundation. So, it can be for load bearing wall.

It provides for a row of columns which are closely spaced and that their footings overlap with each other. Sometimes if your columns are very closely spaced so that their footing will overlap each other, then we can provide a combined footing whose length will be very much larger than the width of the footing.

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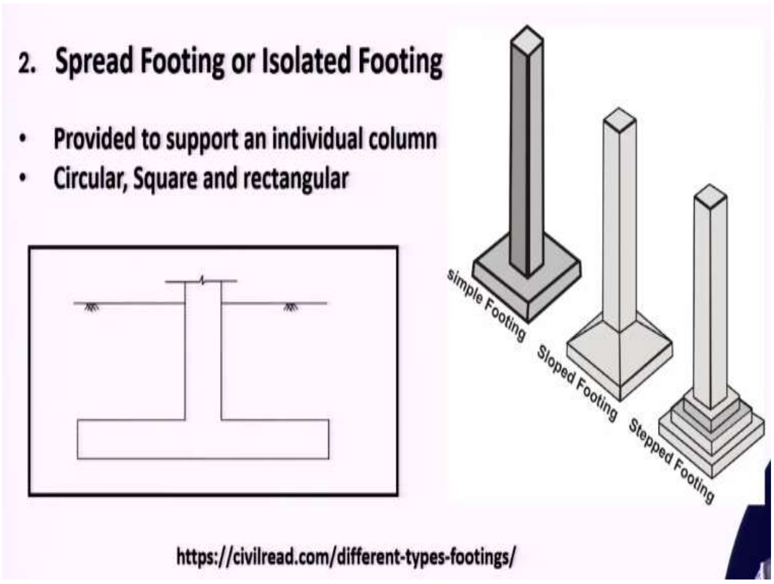

Then it will be spread footing or isolated footing. Isolated footing means here one footing will be placed below one individual column so that can be square, that can be circular that can be rectangular also.

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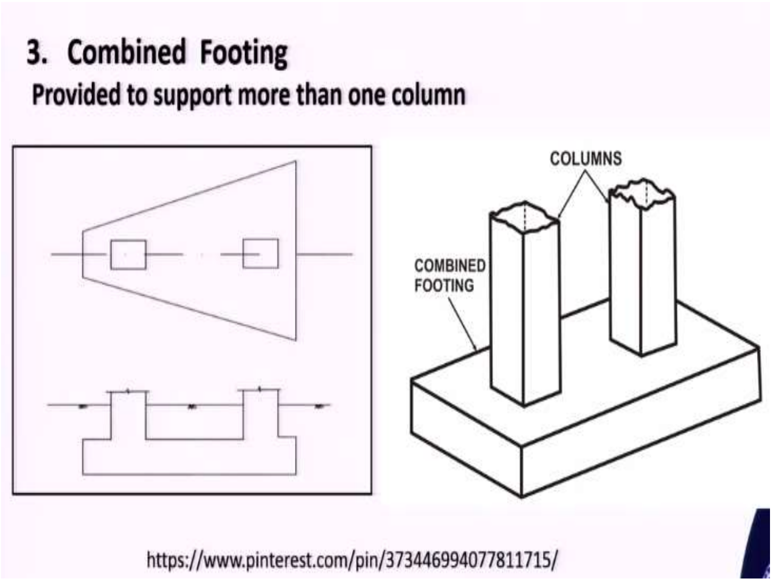

So, it can be a combined footing also where two or more columns are very closely spaced so that their foundation will overlap. So, in such case we provide a combined footing considering these two or three columns, then that type of footing is called combined footing.

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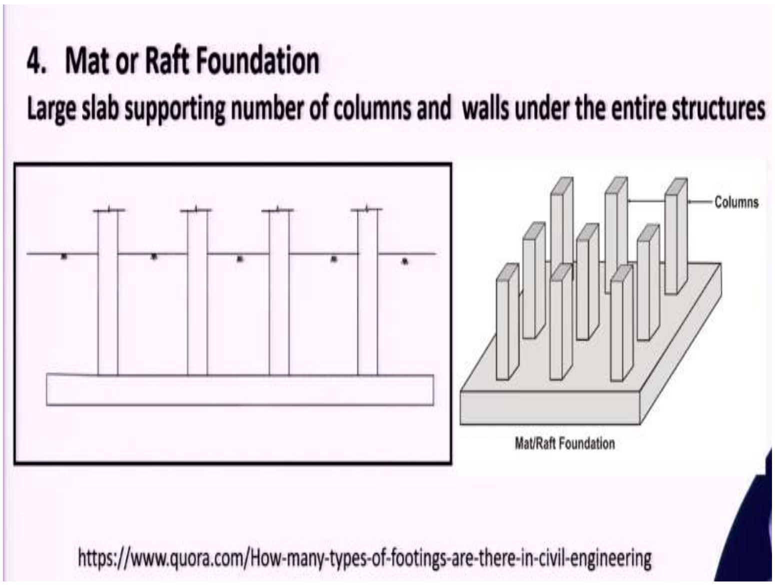

And sometimes we provide one single footing for the entire structure considering all the columns under one single footing, so that is called raft foundation okay.

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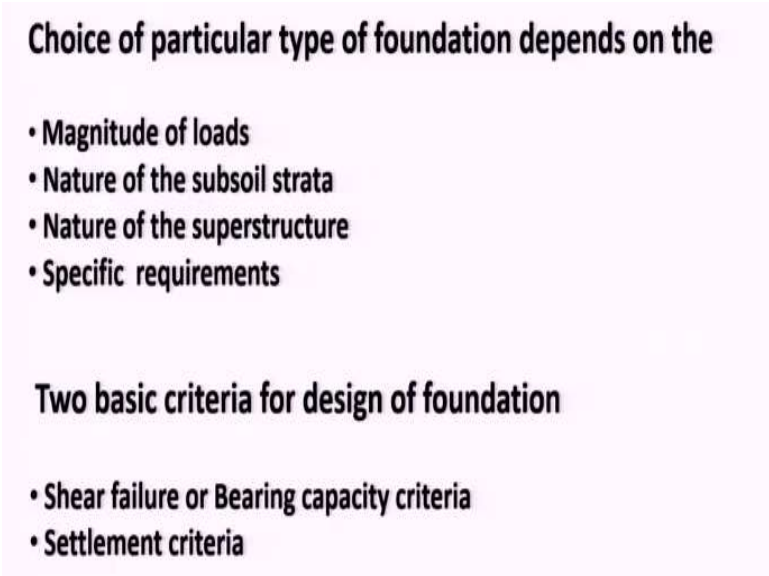

So, now the choice of particular type of foundation depends on the how much load is coming, what are the soil properties, then which type of structure we are constructing and if we have defined a specific requirement or not. So, during the design; we have two basic criteria, one is settlement and one is bearing capacity. I mean the settlement of the foundation should not be excessive and the load that is coming on the foundation and finally the load coming on the soil should not be more than the stress that soil can take.

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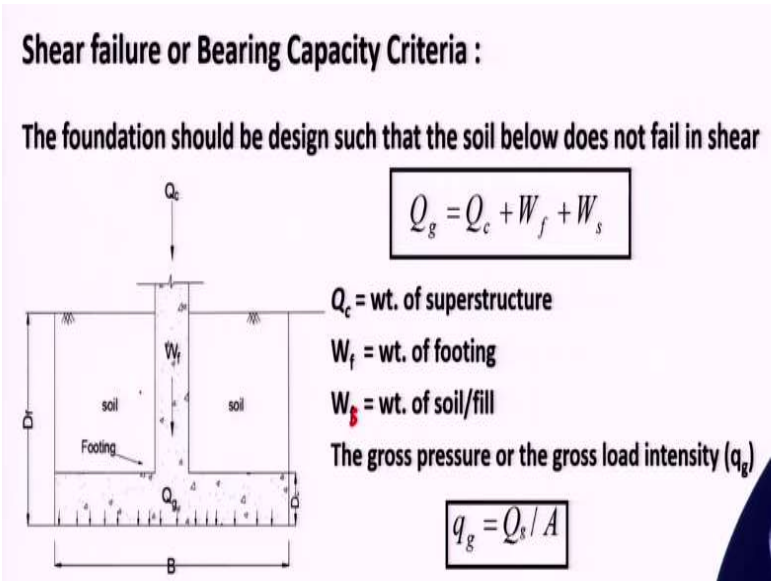

So before I go to the bearing capacity, there are different terminologies that we should know one is called gross load intensity that means the total load, the load that is coming from the superstructure, then the load of the foundation, W_f and then the load of the soil or the fill, W_s. So, this fill or, the soil or filled soil load the foundation along with the column this load.

And the total load which is coming to the column from the superstructure or the Q_c, the foundation load and the soil load, the total load and divided by the area of the foundation that is called the gross load intensity.

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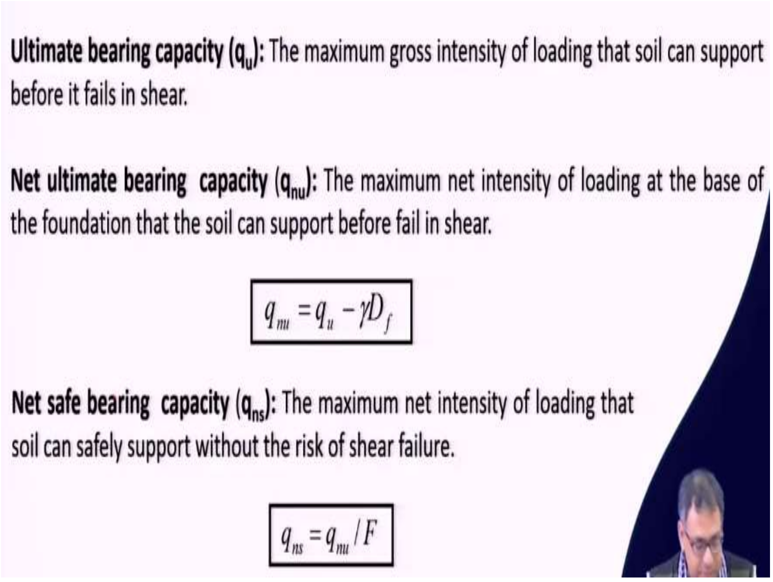

Then ultimate bearing capacity, the maximum gross intensity of load that soil can support is called the ultimate bearing capacity and net ultimate bearing capacity that means we have to subtract the surcharge or the soil pressure that means $\gamma \times D_f$. So that $\gamma \times D_f$ = the surcharge, so that is the net amount of pressure that we can apply to the soils because the soil surcharge is already there.

So, that means, the net one that we can apply is γD_f, D_f is the depth of foundation and γ is the unit weight of the soil. Then the net safe bearing capacity, if I apply the factor of safety because when we are doing a design we have to apply the factor of safety, so then that is called net safe bearing capacity and this factor of safety varies from 2.5 to 3. Now, we can apply the factor safety with the ultimate bearing capacity also.

In that case this will be called the gross safe bearing capacity okay. Net safe bearing capacity is net ultimate bearing capacity divided by factor of safety and gross bearing capacity or gross safe bearing capacity is net ultimate bearing capacity divided by factor of safety $+\gamma D_f$.

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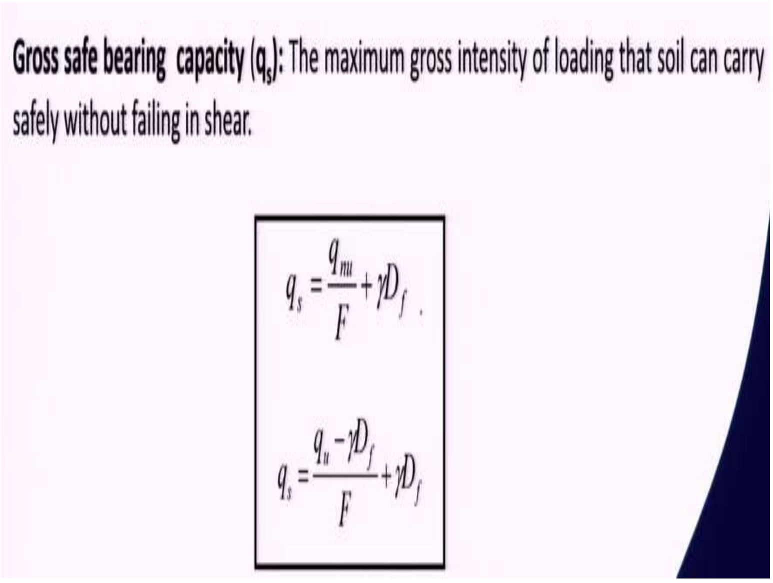

So that means finally this gross safe bearing capacity, we have to apply the net ultimate bearing capacity divided by the factor of safety + γD_f. So that means as we can say that directly if I apply the factors of safety with the ultimate load, so that will not be treated as gross safe bearing capacity. So, the gross bearing capacity actual definition is that net ultimate divided by the factor of safety $+\gamma D_f$.

That means we do not need to apply the factor of safety below that γD_f, only you have to apply the factor safety for the external load that is coming, so you just remember that. I mean gross safe bearing capacity means the net ultimate divided by factor of safety $+\gamma D_f$ because here we are just not applying the factor of safety for the soil surcharge.

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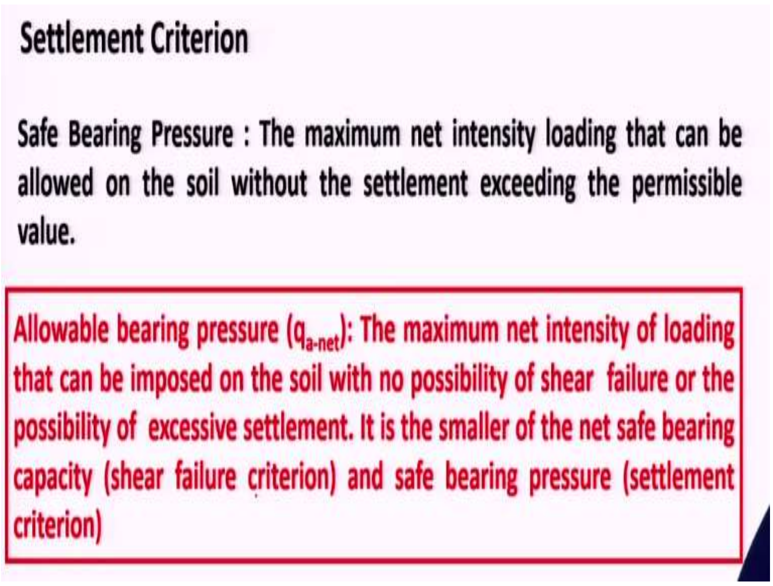

Then the safe bearing capacity, ultimate safe bearing capacity and allowable bearing capacity two things. Safe bearing capacity is in terms of settlement criteria. The previous definitions were in terms of bearing capacity criteria. Now in terms of settlement criteria, the safe bearing pressure is the maximum net intensity of loading that can be allowed on the soil without the settlement exceeding the permissible settlement.

That means how much load I can apply on the soil so that there will not be the exceeding of the permissible settlement of the foundation. That means in every design you have to put a permissible settlement, so we can apply that much of load such that the settlement of the foundation should not be more than the permissible foundation settlement. So, remember that in the bearing capacity calculation, we are applying the factor of safety.

But here this permissible settlement value is given and we have to determine the safe bearing capacity or the bearing pressure with respect to that permissible settlement, so no need to apply additional factor of safety because it is in terms of permissible settlement, so already that safety factor is there. So that means we have one safe bearing pressure and another in terms of settlement and another in terms of bearing capacity.

So, minimum of these two will give us the allowable bearing pressure that means how much load we can allow on the foundation, so that will be the minimum of the load that is satisfying the settlement criteria as well as the bearing capacity criteria. So, that is why the maximum net intensity of load that can be imposed on soil with no possibility of shear failure or possibility of the excessive settlement.

That means it is the smaller of the net safe bearing capacity and the safe bearing pressure. So, it is the smaller of net safe bearing capacity, we will calculate the net safe bearing capacity that means net ultimate bearing capacity divided by a factor of safety and we will calculate the safe bearing capacity in terms of settlement criterion. The smaller of these two will give you the allowable bearing pressure.

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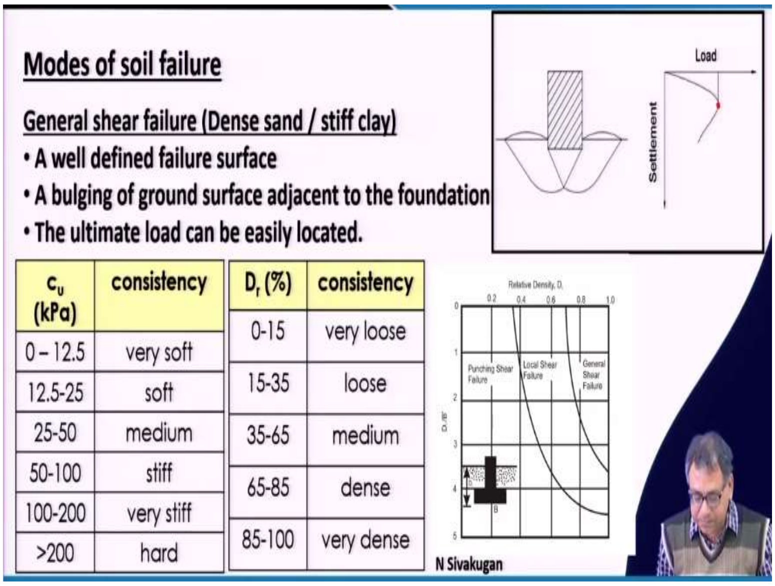

Now the modes of soil failure: How the soil will fail under foundation? There are three types of shear failure. One is the general shear failure, one is the local shear failure, another is the punching shear failure. Now, general shear failure occurs mainly in dense sand or stiff clay. Now when we can say it is a dense sand when we can say it is a stiff clay, then from this table I can get those values.

That means, I can get this dense sand if its relative density is 65% to 85%. From this curve also I can see that it is the D_f / B for shallow foundation, so for one, so this range is around 35% to 70%. So, in this range, there will be local shear failure and general shear failure will be more than 70%. So, here also we can see that general shear failure is in dense sand, so this is 65% to 85%, so more than 70% around.

So, from this chart also, we can see depending upon the D_f / B and these are the different ranges and this is the relative density x axis. So, we can say that if the relative density is more than 70% there will be a general shear failure, if the density is in between 35% to 70%, there will be local shear failure. If it is less than 35%, then there will be punching shear failure. So, you can see that for loose and very loose sand relative density is less than 35% and there will be punching shear failure.

So, how we can see what is the characteristics of this general shear failure? We will get a well-defined failure surface below and outside the footing, then we will get a bulging at the ground surface adjacent to the foundation and ultimate load will get a peak of load settlement plot and we can easily identify the ultimate load of the foundation.

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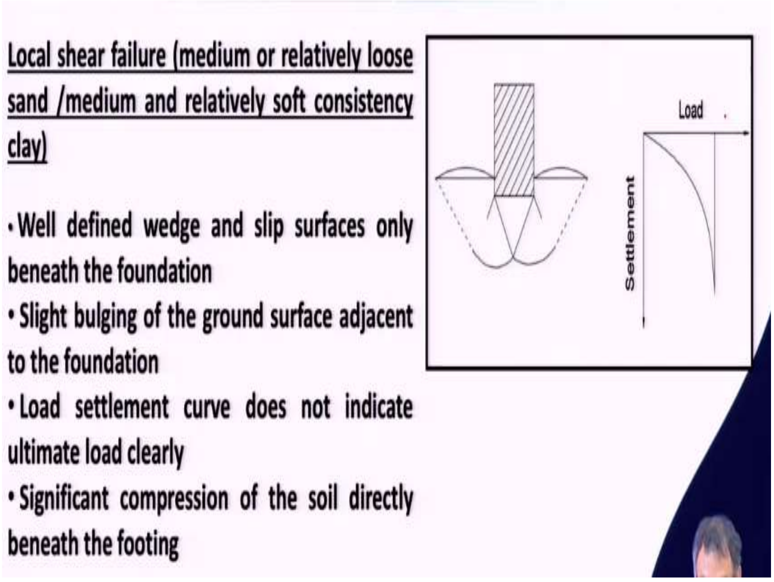

But for the local shear failure, it will occur as I mentioned for medium or relatively loose and medium and relatively soft consistency clay. Then we will get well defined failure surface beneath the foundation only, not outside the foundation. We will get a slight bulging outside the ground surface adjacent to the foundation and load settlement curve will not give a peak value and so we will not identify the failure load very easily. And we will get the significant compression of the soil just below the foundation.

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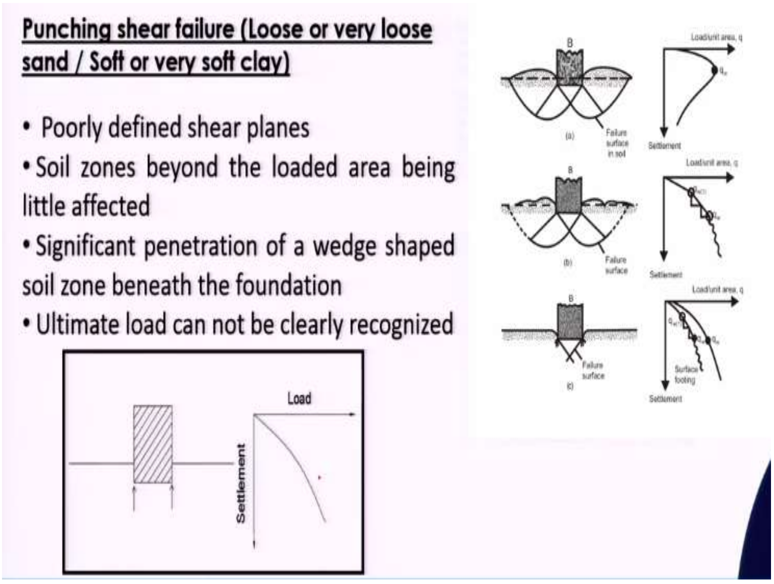

And then for the punching shear failure, so this is also different types of failure surface, this is for different type of cases. As I mentioned this is the general shear failure, this is the local shear failure, this is the punching shear failure. So, in punching shear failure, this is poorly defined shear plane and soil zone beyond the loaded region will not be significantly affected or little bit effect will be noticed.

And there will be significant penetration of the wedge shaped soil zone beneath the foundation. So that means, there will be significant penetration below the foundation and ultimate load cannot be clearly recognized. Here also we will not get a definitive peak, so ultimate load will not be clearly recognized.

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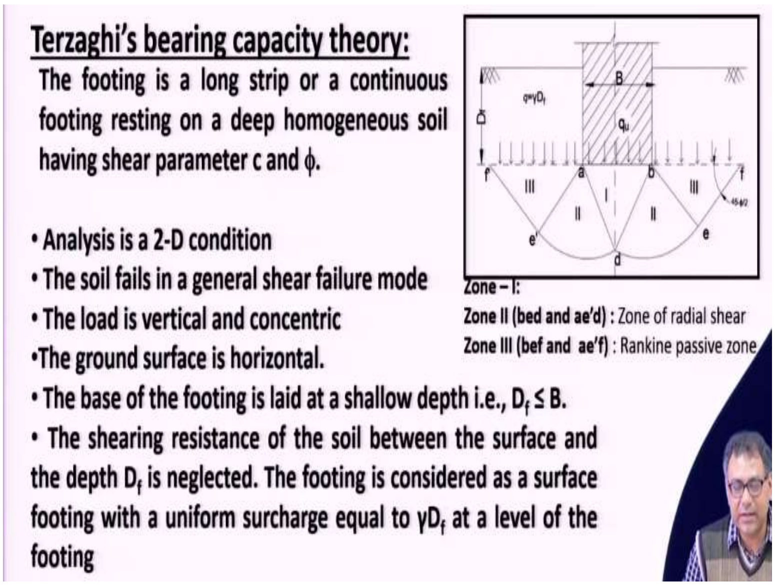

So, the first bearing capacity theory was proposed by Terzaghi. So, this is the advanced foundation engineering part, so I will not go in detail how this Terzaghi's equation is obtained, this has already been discussed in the foundation engineering course. So here, I will discuss what are the additional parts or what I can discuss or I can give you the idea about the additional part or some additional things those are not discussed in the foundation engineering course.

But for the continuation purpose, I will discuss about all the bearing capacity theories in brief and then I will discuss what the additional things in this course. So, this Terzaghi's bearing capacity theory is basically valid for strip footing okay and it is originally developed for the general shear failure mode. So load is vertical. It is acting at the center of the footing and ground surfaces are perfectly horizontal.

So, it is valid for the depth of the foundation equal to or less than the width of the foundation. Now, the shearing resistance of the soil above the foundation base that is from the base and in between base and the ground surface is neglected, but it is considered as a surcharge which is acting on the base of the footing and you can see the assumed failure surface is not touching the ground surface.

It is extended up to the base of the foundation. So that means you remember that it is valid for strip footing, originally it was developed for the strip footing under general shear mode that means it is valid for dense sand and the stiff clay. Then its load is perfectly vertical and there is no eccentricity, it is acting at the center of the foundation only and the ground surface is horizontal and it is valid if the depth of the foundation is less than or equal to width of the foundation.

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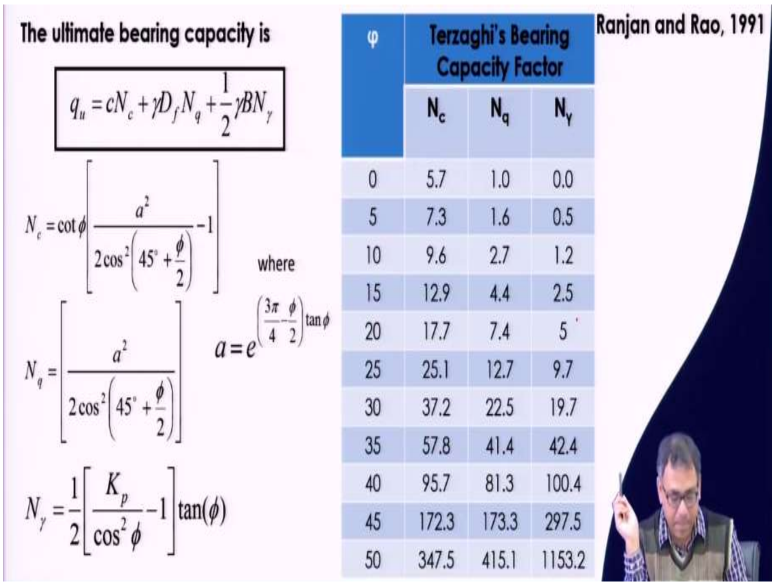

So, finally this expression is proposed that is the ultimate load carrying capacity of the foundation is $cN_c + \gamma D_f N_q + \frac{1}{2}\gamma B N_\gamma$, where N_c, N_q, N_γ are the bearing capacity factors that can be obtained by this equation. So, here, N_c, N_q, N_γ are the function of ϕ, friction angle of the soil and c, the cohesion of the soil and γ is the unit weight of the soil and B is the width of the footing, D_f is the depth of the foundation.

And there are two gammas you can see one is the γ in the second term and the γ in the third term. So, for the second term γ or the unit weight is the unit weight of the soil between ground and the base of the footing and the third term γ or the unit weight is the unit weight of the soil below the foundation okay. And there is a table also, by this table we can also get the bearing capacity factors N_c, N_q, N_γ corresponding to different ϕ values.

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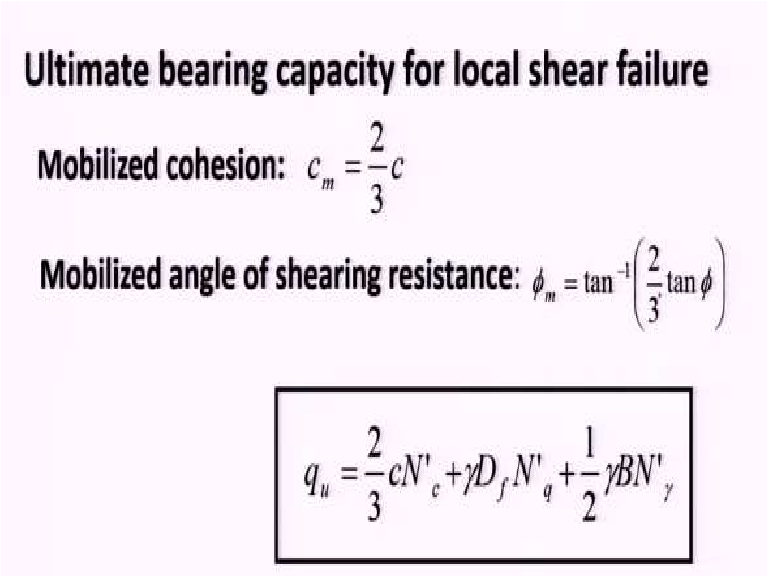

So, now originally this theory is developed for the general shear failure, but even for the local shear failure also further modification is suggested. Now, if you want to determine the local shear failure then you has to reduce the cohesion, c value by two-third and you have to reduce the ϕ value by using this equation. So, now, what we will do is this is the ϕ value of the soil, now that I will reduce and I will get ϕ_m by using this equation.

Now, by using the table corresponding to ϕ_m, we will determine the bearing capacity factor but not for ϕ. So, that means for ϕ_m we will determine the bearing capacity factors and that bearing capacity factor is mentioned here as N'_c, N'_q, N'_γ.

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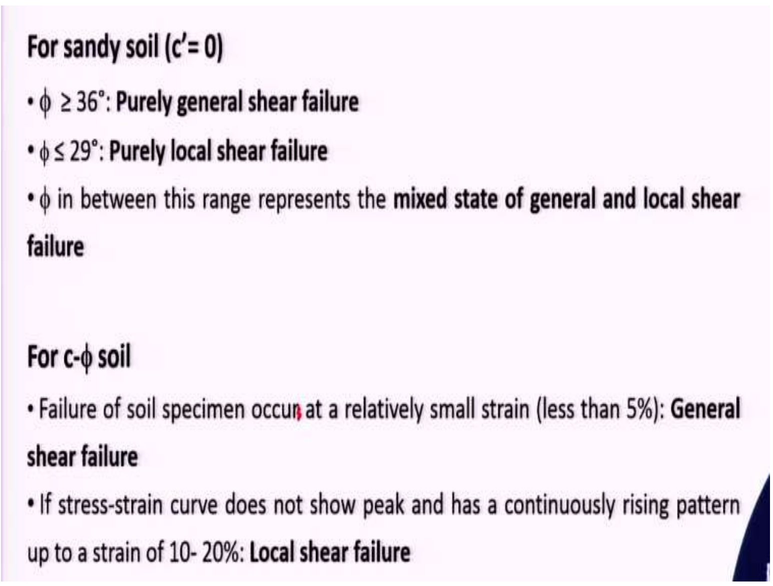

Now, when we can say this soil will fail in local shear failure or general shear failure? If the ϕ value ≥ 36°, then it is the general shear failure. If ϕ value ≤ 29°, then it is local shear failure. If it is in between that then this will be a mixed state of general and local shear failure. So, in such case we have to determine the bearing capacity by interpolating the values from general shear to local shear case.

So that I will discuss one example problem, but this is for sandy soil where this cohesion is 0. Now, if the soil is c-ϕ soil, then for cohesive soil also we can identify that if the soil is soft, then, there will be punching shear failure and if it is moderately soft or the medium consistency, then it will be local shear and if it is the stiff soil it will be general shear failure, but if it is a c-ϕ soil, then if the ϕ value is say less than 29°.

And so now there is no possibility there will be a local shear failure because in such case you have to see the load distribution curve, load versus settlement plot. Now, it says that if the failure of soil specimen occurs at a relatively small strain, then there will be general shear failure. That means in such case from the lowest settlement plot or the stress-strain plot if we see that the failure of soil specimen occurs at a relatively small strain within 5%, then that is general shear failure.

And if the stress-strain curve does not show any peak even up to 20% strain, then we can say this is a local shear failure okay. So, during the problem it will be mentioned whether it is a local shear failure or general shear failure. So, those things will be mentioned in the problem for c-ϕ soil. But for the sandy soil by identifying the ϕ value we can judge whether there will be local shear failure or general shear failure and based on that you have to solve the problem for the sandy soil.

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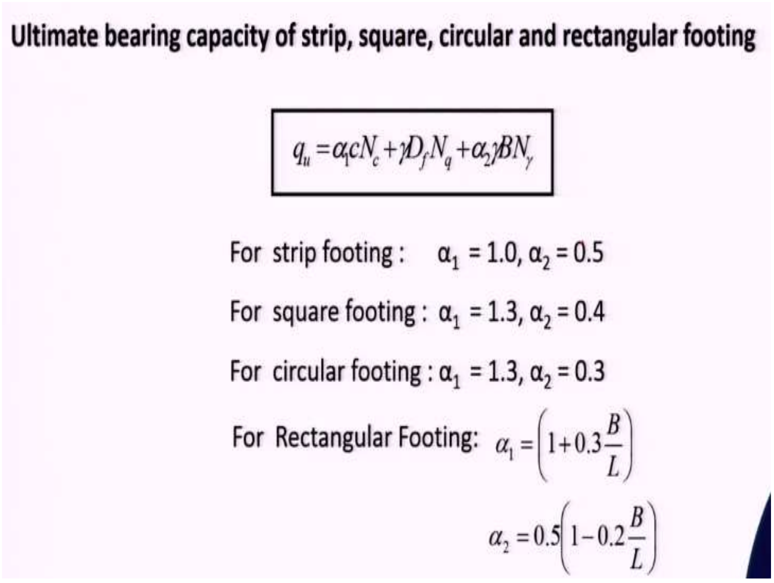

Now later on this equation, which is originally valid for strip footing is modified for the square, rectangular and circular footing also and this is the correction or the modification factor. Now, there are two factors, α_1 and α_2. α_1 is 1.0 for the strip footing and α_2 is 0.5 for the strip footing. Now, for square footing, α_1 is 1.3, α_2 is 0.4. For circular footing α_1 is 1.3**,** α_2 is 0.3.

For rectangular footing α_1 is $1 + 0.3\frac{B}{L}$ and α_2 is $0.5\left(1 - 0.2\frac{B}{L}\right)$ where B is the width of the foundation, L is the length of the foundation.

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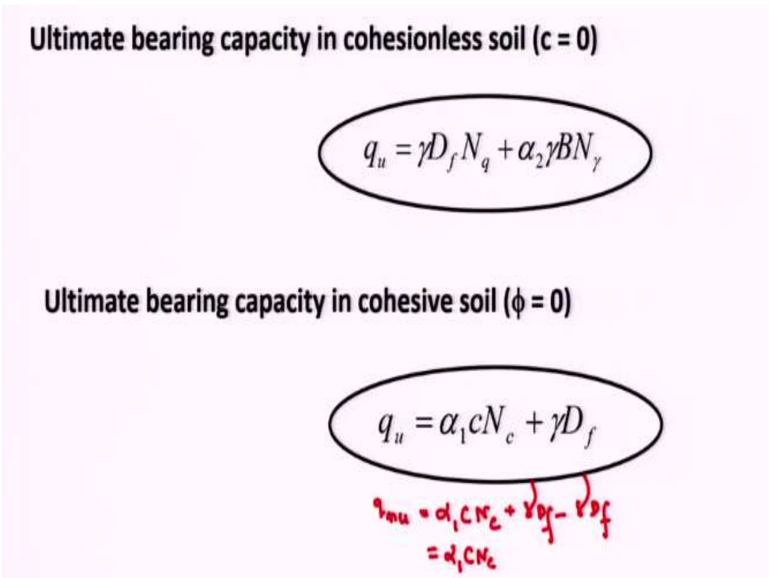

Okay, so now this is the case for two extreme conditions that means when $c = 0$, another is $\phi = 0$. So, $c = 0$, the first term will vanish because your c is 0, there will be only second term and third term and if the c = 0, then we can see the ultimate bearing capacity of the soil is function of D_f as well as width of the foundation. That means for sandy soil, the ultimate bearing capacity of the soil is function of the depth of the foundation as well as the width of the foundation.

But if the ϕ = 0, then as per Terzaghi's bearing capacity factor you can see for ϕ = 0 this N_q = 1 and N_γ = 0. So, third term will be 0. So in the second term also we will get that $\alpha_1 c N_c$ and γD_f. So, ultimate bearing capacity is a function of depth, but not the width. So that means width has very negligible effect on the ultimate bearing capacity if the soil is a cohesive soil.

But if you want to calculate the net ultimate, that means q_{nu} then this will be $\alpha_1 c N_c + \gamma D_f - \gamma D_f$ because the net ultimate, so ultimately $\alpha_1 c N_c$. So, for net ultimate it is not also the function of the D_f of the foundation okay. So, that is important thing for the cohesive soil.

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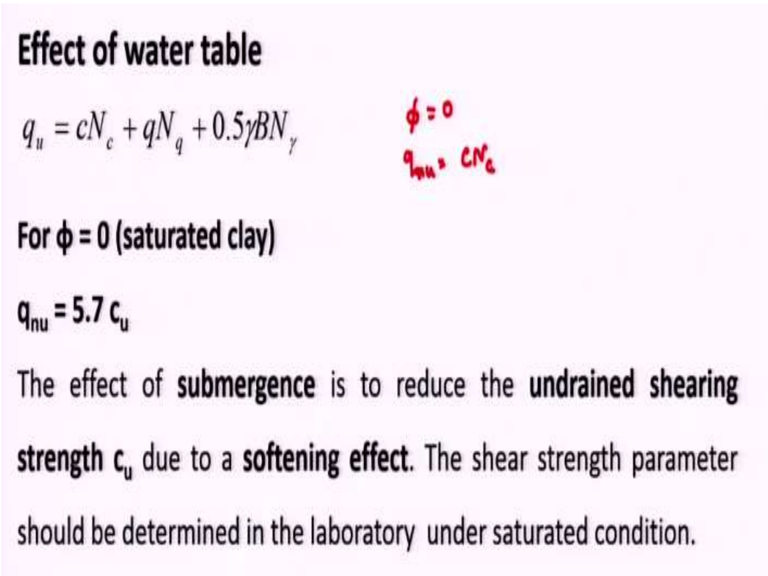

Now, we can include the water table effect also because in original developed equation, water table effect was not incorporated. So, we can include the water table effect also that is $cN_c + \gamma D_f N_q + \frac{1}{2}\gamma B N_\gamma$. So, because if the soil is clay soil, the net ultimate bearing capacity what for your ϕ = 0, so qN_q and cN_c or there will be an alpha term. So that means there is no unit weight.

So then how the water table will make an impact on these values because the water table position may change the cohesion value also because the effect of the water table if the soil is submerged then it reduces the undrained shearing strength of the soil due to softening effect. So that is why it is always better to determine the strength parameter in the lab under saturated conditions. So that means that will give us the worst condition.

So, if we determine the strength parameter on the saturated condition, so there we will get the cohesion value that will give such as that in the field when the soil is under submerged condition, So that way it will affect the bearing capacity that will be cohesion value.

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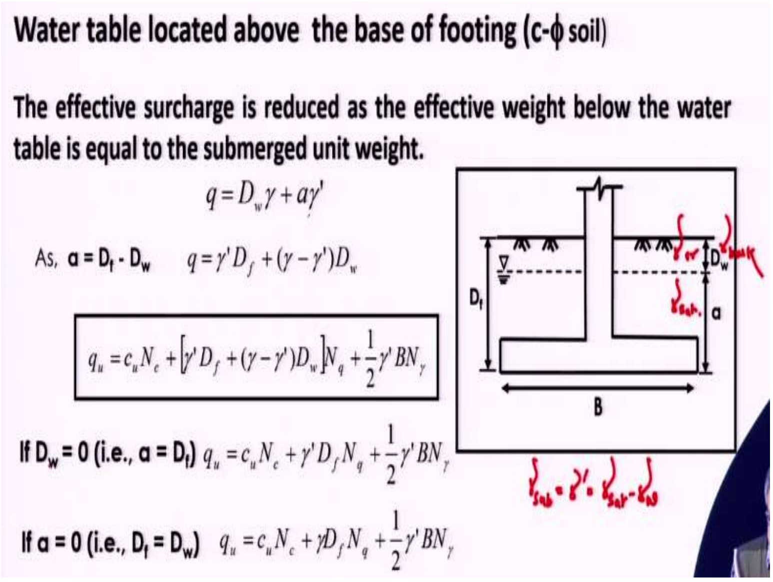

But if it is a c-ϕ soil or the ϕ soil, then this water table effect will be in the unit weight of the soil because we have two unit weights. Now in the two cases, if the water table is above the base of the foundation and another is below the base of the foundation. In the first case if the water table is above the base of the foundation, then the third term γ will be always the γ_{sub} or the γ' which is equal to γ_{sat} - γ_w.

γ_{sat} is the saturated unit weight of the soil and γ_w is the unit weight of the water, so it is always that. But above the water table then we can use this expression that means if I can say this is γ or γ_{bulk} and this is γ_{sat} then above the water table you have to use the γ or γ_{bulk} and below the water table you have to use that γ_{sat}.

So that means this will be the thickness or the depth of the water level from the ground surface into γ or γ_{bulk}+ the remaining depth of the foundation $a \times \gamma'$. So, this γ you have to put in the second term. And if your $D_w = D_f$ I mean the table is at the base of the foundation that means your $a = 0$, then the first term will be γ or γ_{bulk} and the second unit weight which is in the third term will be γ_{sub}.

And if the groundwater table is at the ground surface, then both the γ will be γ_{sub} or γ'. So if the water table is at the ground surface, so that will give us the lowest bearing capacity.

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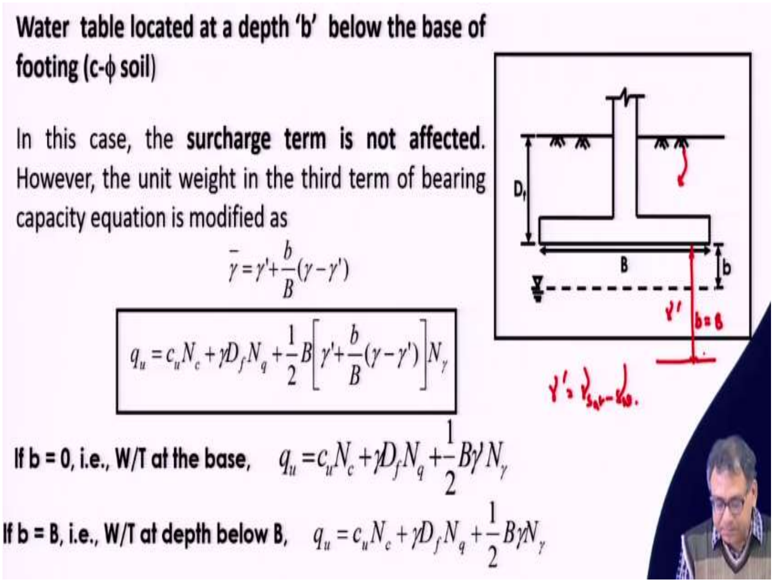

If water table is below the base of the footing, then we have to use this equation and here again the $\gamma' = \gamma_{sat} - \gamma_w$. So, I will use this expression for γ_{sat} and γ is the unit weight of the soil above the water table and this is the γ_{sat}, γ' and this is the equation that is given by which we can determine the bearing capacity by incorporating the water table effect.

Now that if the water table position is below at a distance of B from the base of the foundation, so there is no effect of water table. So for example, if the $b = B$, that means the width of the foundation, then on q_u there is no water table effect. So that means we have to consider the water table effect up to which the water table position is within the width of the foundation from the base of the footing.

So, that means up to which the position of the foundation, position of the water table is within the width of the foundation from the base, then we have to consider water table effect. Now if the position of the water table is beyond the width of the foundation from the base, then no need to consider the water table effect.

For example, we will consider the water table effect if my $b = B$. So if it is beyond that, then no need to consider the water table effect.

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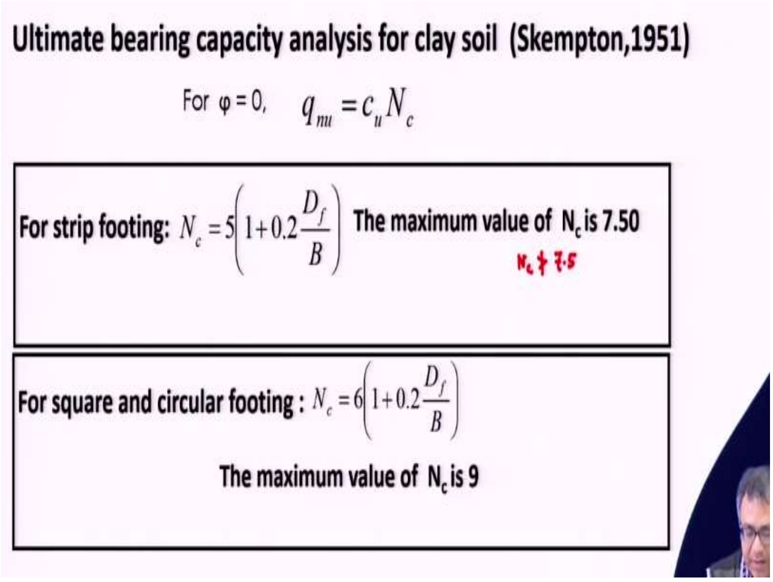

Now, the next bearing capacity equation that is ultimate bearing capacity equation proposed by Skempton and it is valid for clay soil okay and this equation is valid for any depth because in the Terzaghi's set equation is valid for when $D_f \leq B$, but it is applicable for any depth. So, this is the net ultimate bearing capacity is q_{nu} and obviously for $\phi = 0$ so this will be $c_u N_c$ and c_u is equal to undrained cohesion.

So, N_c for strip footing I will get by using this equation with a maximum value at 7.5. That means for this case N_c cannot be greater than 7.5. For square and circular footing, this is the expression, but N_c should be limited to 9.

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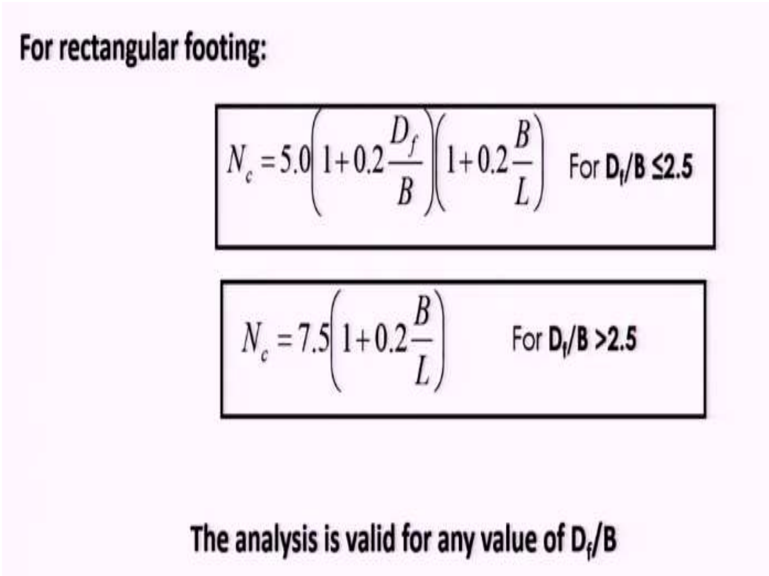

And for the rectangular footing, the first expression is valid if $D_f \le 2.5$ times of B and it is valid for $D_f > 2.5$ times of the width of the foundation. So, this is the expression for the rectangular footing, but remember that this is applicable only for the clay soil.

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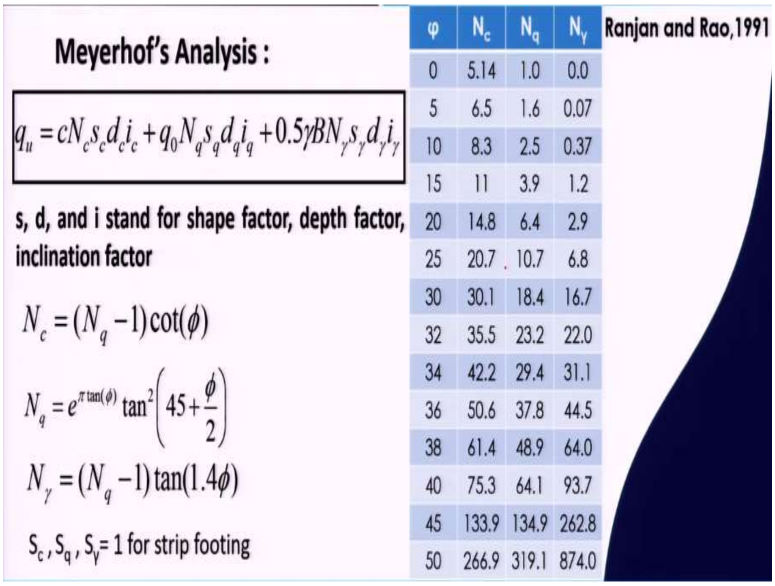

φ	N_c	N_q	N_γ
0	5.14	1.0	0.0
5	6.5	1.6	0.07
10	8.3	2.5	0.37
15	11	3.9	1.2
20	14.8	6.4	2.9
25	20.7	10.7	6.8
30	30.1	18.4	16.7
32	35.5	23.2	22.0
34	42.2	29.4	31.1
36	50.6	37.8	44.5
38	61.4	48.9	64.0
40	75.3	64.1	93.7
45	133.9	134.9	262.8
50	266.9	319.1	874.0

So, now the next one is the Meyerhof's bearing capacity equation and then Hansen and then Vesic and then our IS code has recommended bearing capacity equation. So, in the next class, I will discuss these four bearing capacity equations that means Meyerhof, Hansen, Vesic and IS code and what are the differences between these theories that also I will discuss in the next class.

Because in Terzaghi's bearing capacity equation, you can see that it is valid for only vertical load. There is no option to incorporate the inclination of the load in the bearing capacity. It is valid only if the load is acting in the center. There is no option to incorporate the eccentricity of the loading. Then it is valid for a base which is perfectly horizontal. If the base is tilted, then how we can determine the bearing capacity?

So those things will be discussed in later section of this course by using the other bearing capacity theories proposed by other researchers. Thank you.