Advanced Foundation Engineering
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Lecture-23
Shallow Foundation: Settlement-I

So, in this lecture, I will start the next topic that is the settlement of the foundation because I have discussed about the soil exploration, then the bearing capacity of the foundation, then we will go for the settlement of the foundation because as you know that the two design criteria for the foundation design are the bearing capacity and the settlement. So, I have discussed the different bearing capacity theories.

And different cases like inclined loading, eccentric loading, then the layered soil case, the effect of soil compressibility, then tilting base case, then the sloping ground case. So, all the cases are discussed in the bearing capacity part and I have also discussed which theory you should use for what condition, and then I solved the example problems to show you how you can incorporate those theories.

So, now today I will start the second part that is the settlement of the foundation, how you can calculate a settlement of a foundation, but before I start that part, I will just discuss one small part that is remaining that is the fourth case for the layered soil bearing capacity. So, first I will discuss that fourth case and then I will go for the settlement part. So, now, I go for the case 4.

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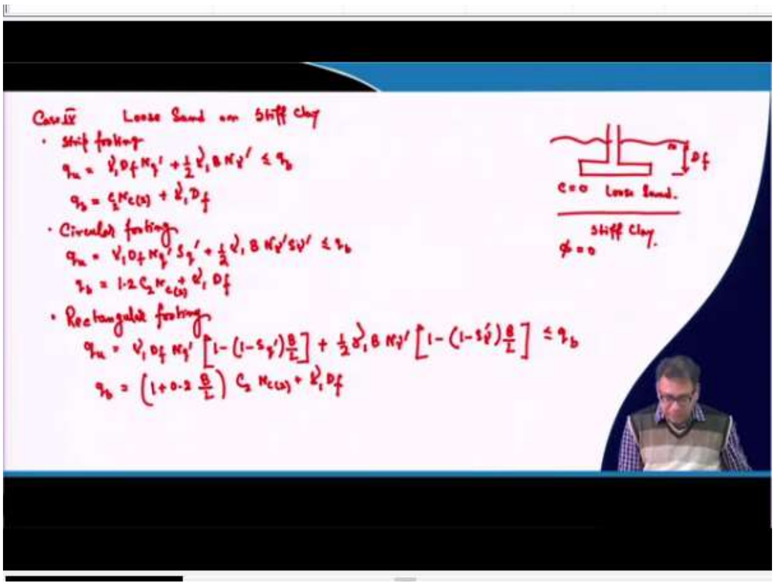

So, in the case 4 of that layered soil where the loose sand and stiff clay. So, loose sand and the stiff clay, that means here your top layer is the weaker layer and the bottom layer is stronger, in all the previous three cases always the bottom layer is the weaker layer and the top layer is the stronger layer but it is the opposite case. So, in such case I will give the expression for three different footing conditions that means the strip footing, your rectangular footing and then circular footing.

And if you have the equation for the rectangular footing you can get the equation for the square footing also. So, now first one is the strip footing. So, in this case q is given as $\frac{1}{2}\gamma_1 BN_\gamma'$. Now what is this particular case? This is the foundation, this is the ground surface and this is my stiff clay and this is loose sand. So, here $c = 0$ for top layer and $\phi = 0$ for bottom layer.

So, now, in previous case where this was simply the opposite that means, the stronger layer is on the top and the weaker layer is at the bottom. So, a punching type of failure was considered there, but here the stiff layer is at the bottom. So, this stiff layer is considered as a rigid layer. And then in this case the failure in most of the cases will be in the top layer. So that is why the bearing capacity of the top layer is $\frac{1}{2}\gamma_1 BN_\gamma'$ +, because this is the third term basically.

So, I should write the second term first, then the third term. So, the second term is $\gamma_1 D_f N_q'$. So, this is D_f, this is the first layer then + third term $\frac{1}{2}\gamma_1 BN_\gamma'$. So, the first term is 0 because c

= 0, then the second term and the third term are given. So, this is the $q_u \le q_b$ because, definitely that cannot be more than the bearing capacity of the bottom layer because in previous 3 cases that should not be greater than q_t because in that case the stronger layer was the top layer. So, it should not be greater than q_t.

But now in this case the stronger layer is the bottom layer, so it should not be greater than q_b. So, now, what is q_b? Now q_b will be equal to now, if this is the case then this is $c_2 N_{c2} + \gamma_1 D_f$. So, q_b is considered as $\gamma_1 D_f$ because as I mentioned here the H part is not considered. So, now, if you consider the $\gamma_1 (D_f + H)$ then you have to subtract that H from the main equation. So, that is not given.

So, that is given in q_b term. So, H term is not considered. So, that is why it is $c_2 N_{c2} + \gamma_1 D_f$, because that H term is already incorporated within the bearing capacity equation. So, this is the equation for the strip footing. Now, for the circular footing the equation will be $q_u = \gamma_1 D_f N_q'$, then this shape factor is introduced s_q', then it is same $\frac{1}{2}\gamma_1 B N_\gamma'$, then s_γ'.

So, N_γ', s_q' and s_γ' are the shape factors and that should be less than q_d and then $q_b = 1.2 c_2 N_{c2} + \gamma_1 D_f$, same as the strip footing only the factor 1.2 is introduced in first term. Now I can write the equation for rectangular footing. So, this is q_u. This is half, let me write the second part first, then I will write the first part.

The same as $\gamma_1 D_f N_q'$. Now, the shape factor again we have to apply and that is $1 - (1 - s_q') \times \frac{B}{L}$. Then the third term that is $\frac{1}{2}\gamma_1 B N_\gamma'$, then $1 - (1 - s_q') \times \frac{B}{L}$, that should be less than q_t and $q_b = \left(1 + 0.2\frac{B}{L}\right) c_2 N_{c2} + \gamma_1 D_f$. So, in this way I can calculate the bearing capacity for the fourth case, where the strip footing, circular footing and rectangular footing. Now, how I can calculate N_q', N_γ' and s_q', s_γ' from this chart.

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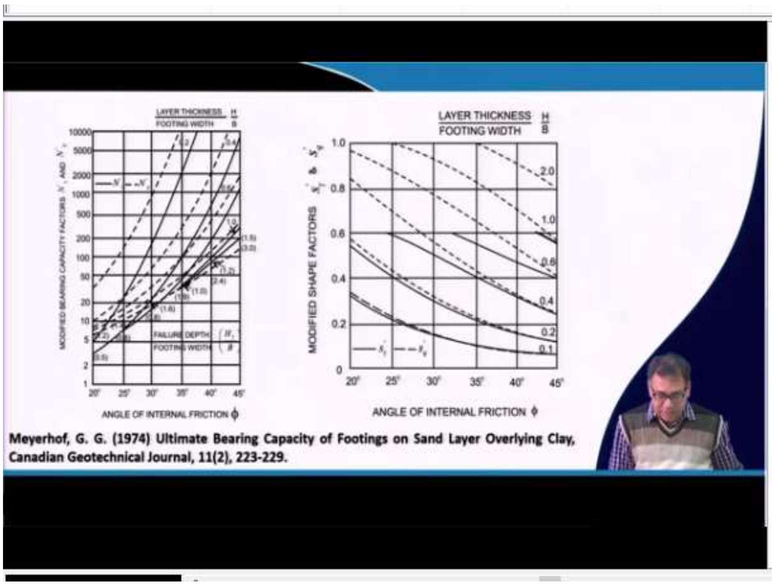

So, these tw charts will give you the bearing capacity factor as well as the shape factor, for example, since this dotted line is giving N_q' and the firm line is giving N_γ'. So, these are the values of $\frac{H}{B}$, H is the thickness of the layer. So, this is $\frac{H}{B}$. So, this is H. This is the B, width of the foundation. So, if I know these $\frac{H}{B}$, then this is the internal friction angle obviously of the top layer.

Then the value of $\frac{H}{B}$ is 0.2, this firm line is given for N_γ' and this dotted line is given for N_q', these are the values. So, this is for different fiction angle, this is 2 for 0.42, this is 0.4, then 0.6, then this line is 1 and this dotted line is also for 1, then this firm line is up to 1.5 and dotted line is 3. So, that means $\frac{H}{B}$ firm line is given 1.5 and dotted line is given up to 3.

So, these are the values. So, from here you will get the modified bearing capacity factor. So, these are called modified bearing capacity factors. So, from this chart you will get the N_γ' and N_q' and similarly, you will get the s_q' and s_γ' by using this chart. Again this is $\frac{H}{B}$ and the firm line is giving for s_γ' and the dotted line is giving s_q'.

This is for 0.21, 0.2, 0.4, 0.6 1 and 2. So, these are for different friction angle values. So, this way you will get the modified carrying capacity factor and modified shape factor to incorporate in the fourth case that is if the top layer is loose sand and the bottom layer is stiff clay, then how you can calculate the bearing capacity? So, these charts you can use and you will put this chart in the equation which is given.

And then you will get the maximum bearing capacity or the bearing capacity of the two-layered case and you see that these are the equations. So, now, one thing before we finish this part, one thing I also want to mention that in my previous class also when I solve the bearing capacity this two-layered case equation for here I am taking loose sand and soft clay. So, all these terms.

So, basically, if the soil is loose or medium loose, if it is soft or medium consistency clay, then always this general shear failure will not occur. So, there is a possibility that there may be a local shear failure, but the equation that I used during the bearing capacity calculation I use all the cases even if when I put the foundation directly on the loose sand or the weaker soil.

If I consider all the terms or the bearing capacity factor those are proposed for general shear failure. So, that will be used for all the bearing capacity factors proposed for the general shear failure even though the soil is weak and I put the foundation directly over there. But actually when this theory was developed, no such recommendation is given that what to do if the soil has a local shear failure.

Now, one thing I have mentioned that I had given the compressibility effect part, if those data are available, then you can check whether you need any compressibility corrections or not for your case, your soil case, if you need that, then you put those corrections here. If you have those data, you put those corrections here and then you incorporate the soil compressibility effect also.

Because that is important, because here we are taking all the soils are not the stronger soil, some weaker soil also. But these recommendations are not given here in original theory. So, that means you have to collect those data and you have to check whether some soil compressibility effect is there or you have to put those corrections. That is one way or another when some researchers have suggested when the soil is weak soil.

Though instead of taking full c you take $\frac{2}{3}c$ which is recommended by Terzaghi for the local shear failure and $\tan^{-1}\left(\frac{2}{3}\tan\phi\right)$. So, you do that part also, because if you are sure that this soil is very poor soil, weaker soil and there will be a local shear failure possibility or this is basically just to reduce the bearing capacity.

If I take full c then I will get a higher bearing capacity obviously, but the soil is weaker soil and the bearing capacity equation or the factors that are using is valid for the stronger soil or general shear failure. So, to be on the safer side, shear strength parameters are reduced, that means by the recommendation given by Terzaghi. But actually in the original theory, this type of recommendation is not given.

So, I have taken full c value, full strength parameters I have given even in the assignment problems also I will mention that, you take full strength parameter values in the exam also you will take full strength parameter value, but you should know that to be on the safer side it is better during your design that you reduce this strength parameter value as given by Terzaghi's recommendation that is $\frac{2}{3}c$ or the ϕ value also you reduce according to that.

Because when you are putting foundation on the weaker soil directly specifically because we have to calculate q_t, basically you have to calculate q_b for the weaker soil. So, during basically q_b calculation, q_t calculation reduction is not required because q_t is your stronger soil. So, general shear failure will occur when I am talking about this is not the layered case I am talking about when you are calculating the bearing capacity individually for top layer and the bottom layer.

So, for the top layer it is okay, for the bottom layer bearing capacity calculation you reduce the system parameters or if you have the soil compressibility factors available or those data are available you can apply those factors also, depending upon what parameters are available, but for examples also I am taking full strength parameter in the exam and the assignments also you will take the full strength parameter.

But when you apply them in the real design, I would suggest that you can reduce it, but again it is engineer's choice, engineer's judgment whether he or she will take the full strength parameter or reduced strength parameter, but these are the facts that I have discussed.

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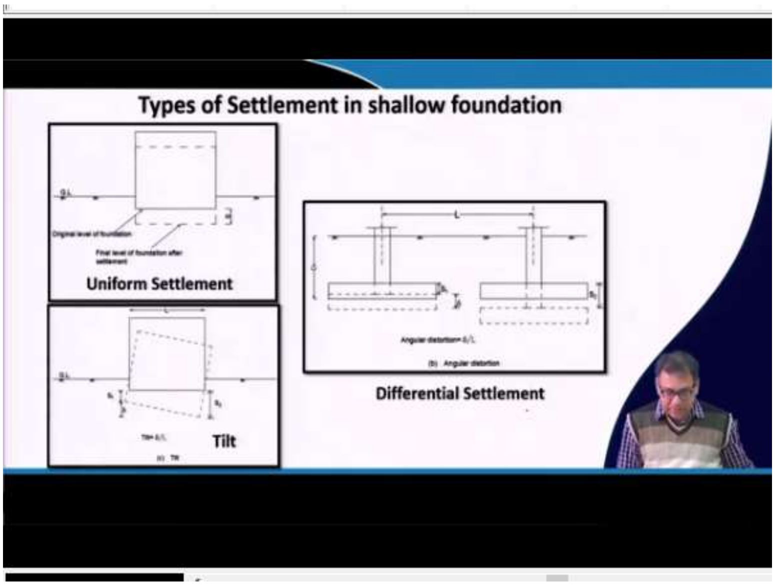

So, now, I will go to the next topic that is the settlement of foundation. So, now, as you know there are two design criteria, one is the bearing capacity, another is the settlement of the foundation. So, when we are talking about settlement of the foundation, so, the initial part definitely all these parts are covered in the foundation engineering course. So, that is why I will not go in detail in this part, those are already been covered in the foundation engineering course.

But for the continuation purpose I will explain them, so that there should be a continuation, I did it for the soil foundation bearing capacity also, I explained initially few things those are very common for foundation engineering course.

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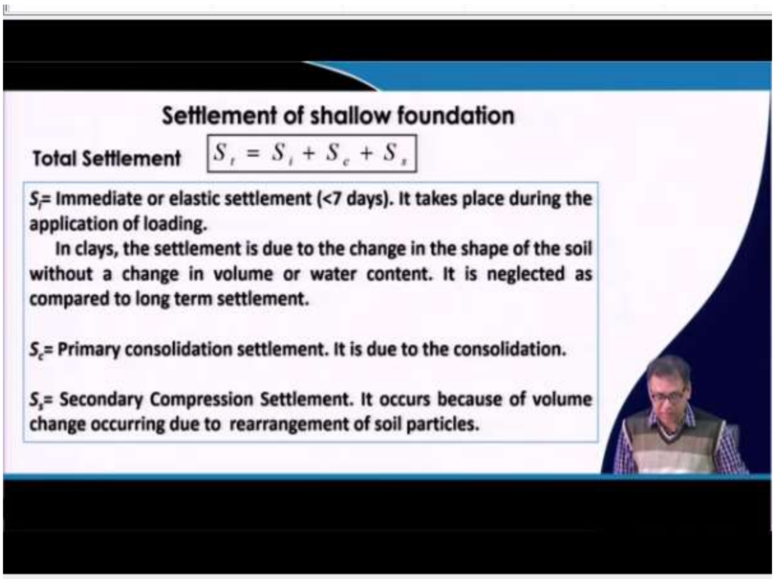

So, now those things I will explain in settlement part also. So, that means we have three major types of settlements that we have to check, the uniform settlement, differential settlement and tilt, what is the difference? In uniform settlement your old building will settle uniformly and in differential settlement suppose some column will settle more compared to the other columns.

So, that is called a differential settlement. And in the field, suppose one side of your building will tilt or will deform more compared to the other side of the building. So, that total building will tilt in towards a particular side where the deformation is more. So, that is called tilting, differential settlement and the uniform settlement. So, most of the design if suppose your soil parameters are not significantly varying in your site or your design or the load coming on each foundation are significantly different.

Or there is a huge variation in the load coming on the foundation, and then also you have to go for the differential settlement check and tilting check also**.** Otherwise, if the loading is more or less same coming on all parts of the foundation, then generally you only go for the uniform settlement, but if the design load is different for different columns and that difference is significantly very high then you have to go for other two checks also and the soil parameter variation is also significant.

So, in the settlement basically three types one is the immediate settlement, consolidation settlement and the secondary settlement or, basically, this is primary consolidation settlement and the secondary compression settlement. So, the immediate settlement basically is the elastic settlement that takes place during the application of loading. So, and this immediate settlement is very significant in case of sandy soil. In sandy soil most of the settlements are immediate settlements.

So, that means you will get the settlement within 7 days or even less than that, because in consolidation settlement which is primary settlement, for major settlement for the clay soil because in case of clay soil your permeability is less. So, when you apply the load pore water dissipation takes more time. So, that is why the consolidation is a very major settlement for the clay soil. And secondary settlement occurs due to volume change or due to the rearrangement of the particles. So, that is secondary compression settlement.

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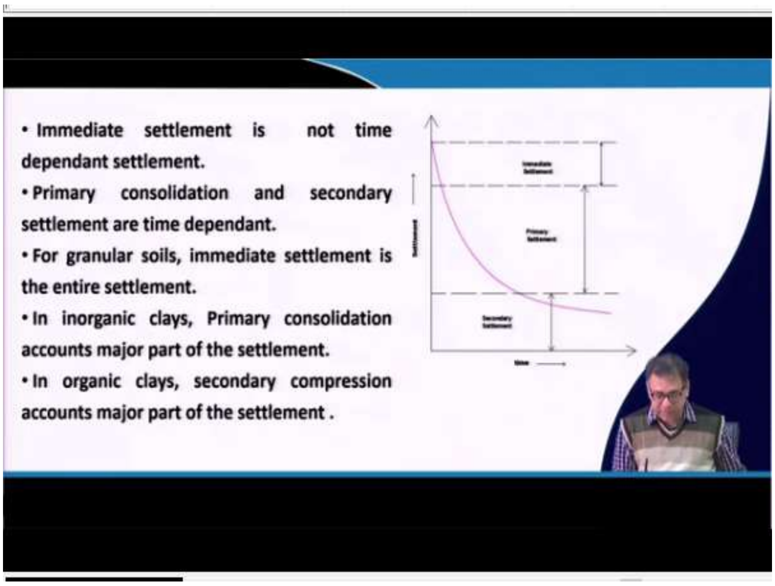

So, these are the different cases where I will get the immediate settlement or primary consolidation settlement or secondary compression settlement. For example, the sand as I mentioned in granular type of soil, immediate settlement is the majority of the settlement. For inorganic clay, primary consolidation is the major part of the settlement and organic clay, secondary compression is a major part of the settlement.

So, in this course, basically we will concentrate on the immediate settlement and the primary consolidation settlement. So, we assume that our soil is such that the secondary compression settlement will not be a major part. So, that is why we will consider only the immediate settlement and primary consolidation settlement.

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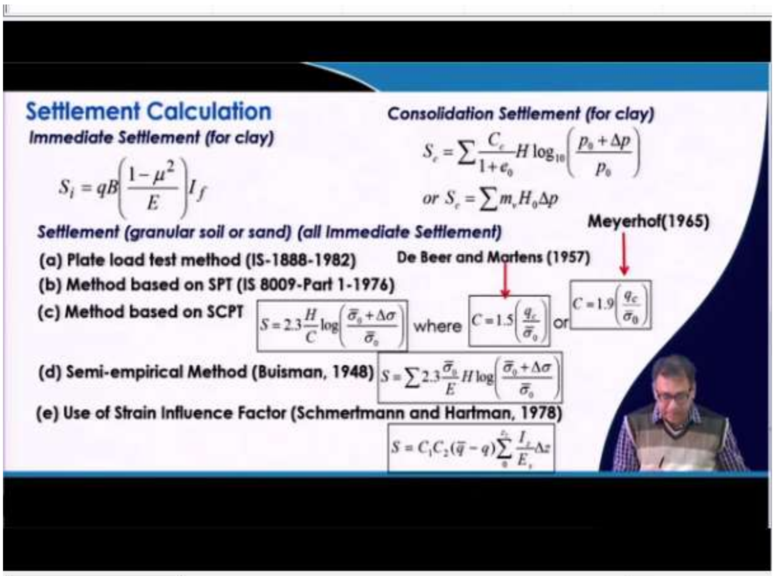

So, now, this is the typical chart or the slide where I have given all the methods, almost all are important methods which are used to determine the settlement of clay soil as well as the granular soil and I will discuss all these methods okay. So, that means the first immediate settlement for clay that I can calculate by using these equations. So, I will discuss what the different terms of these equations are.

And then I can calculate the consolidation settlement. So, first I will give you the immediate settlement, then the consolidation settlement and either I can use this top equation or I can use the bottom equation for the consolidation settlement. So, this is the primary consolidation settlement. So, if I add this immediate settlement and the consolidation settlement, then I will get the total settlement of foundation resting on the soil.

And for the granular soil as I mentioned the immediate settlement is a major part of the settlement. So, most of the settlement will take place immediately. So, these settlements can be mostly calculated by field test data. So, I can get these settlements directly from the plate load test method, I can get it from the SPT based method, then I can get it by the SCPT based method. I mean the static cone penetration test based method.

So, if I have the plate load test data, then I can calculate the settlement of the foundation. If I have the data of SPT then I will also get the settlement of the foundation. If I have data from the static cone penetration test, basically the cone resistance, Q_c then also I will get the settlement of the granular soil.

We can apply the semi-empirical methods also, that is the fourth one and then we can use the strain influence factor methods; that will also be discussed. So, these are basically five methods, the lower five methods can be applied to determine the settlement of granular soil, but for the immediate settlement for clay we can use the first equation and the consolidation settlement we can use the second equation.

And you can see the consolidation settlement and method based on SCPT and the semi-empirical method. So, these three are more or less same. So, that is why I will give an example problem to calculate the consolidation settlement only. So, in similar way you can calculate if you have the SCPT data, then you can calculate the settlement of the granular soil or you can use the empirical equation also by using these methods to calculate the settlement of a footing in sand.

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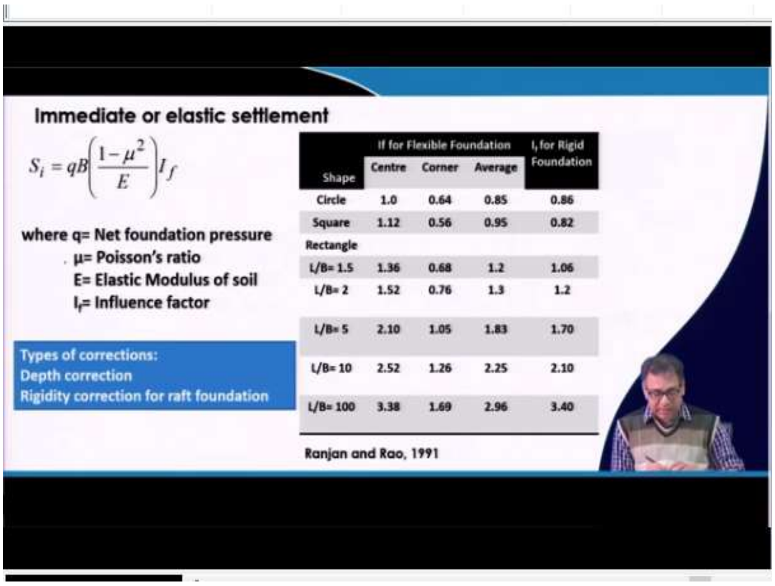

And so now, one by one I will discuss these total seven methods that I have mentioned here, two are for clayey soil and five for sandy soil. So, for the immediate or the elastic settlement, this equation is based on the elastic theory and this is the elastic settlement. Here, S_i is the immediate settlement and q is the net foundation pressure.

Net foundation pressure is acting on the foundation base, B is the width of the foundation, E is the elastic modulus of the soil, μ is the Poisson's ratio of the soil and I_f is the influence factor. And once I will get these things then because this theory is valid for the surface footing, but if your foundation is placed at a depth then you have to apply that depth correction.

So, what are the types of corrections that are required, two types of corrections are required, the depth correction or the rigidity correction. Now rigidity correction is required, if you have the influence factor table you can see this influence factor table this I_f value I can get from this table where it is given for flexible foundation and rigid foundation.

Now, for a flexible foundation or different types of foundations like circular, square, rectangular, which have different $\frac{L}{B}$ values 1.5, 2, 5, 10 and 100. Then it is for center, corner, and average. So, that means obviously the center one has more influence factor, the center one will calculate the settlement at the center. So, center one is giving more value.

So, center, then the corner and the average. So, now, if you take the flexible foundation I_f value to calculate the immediate settlement for rigid foundation, then we have to apply the rigidity correction and if you take the rigid foundation I_f value to calculate the settlement for immediate settlement for the clay, then this rigidity correction is not required, because we have taken the I_f for rigid foundation itself.

But in most of our design or basically I prefer to take the flexible foundation center I_f value then you apply a rigidity correction, what is that rigidity collection value. Now, if you look at these values that means for rigid footing and the center. So, I_f is 1 for flexible foundation, but only one I_f value is given for the rigid foundation and it is 0.86 because for rigid foundation it is not center, average, corner, because if it is a rigid foundation then it is expected that the foundation will settle uniformly, that is why only one factor is given.

But in flexible foundation it is not like that because in the center and the edge, there will be different settlements. So, that is why different values are given. So, now, for the square footing, it is 1.12 and it is 0.82, 1.1 1.36 1.06 1.5 to 1.2. So, if you see that the rigid footing influence factor is almost 80% of the influence factor of the flexible footing at center, you can see it is roughly 80%.

So, that is why as I mentioned, what I do that I take always in the calculation whether the foundation is the flexible foundation or rigid foundation. Generally a rigid foundation or isolated footing that means one foundation for one column is considered as a flexible foundation. So, if now, I generally prefer to take the I_f value at center of flexible foundation for all the cases.

Now, if it is a rigid footing, then I apply a rigidity correction factor which is 0.8. So, the rigidity correction factor is how much? The rigidity correction factor is 0.8. So, rigidity correction factor of 0.8 is applied, once you calculate this S_i by using the given value I am taking the influence factor at the center for flexible footing. Now, if it is flexible footing, then the rigidity correction is not required. If it is a rigid foundation, then you apply 0.8 with this calculated immediate settlement.

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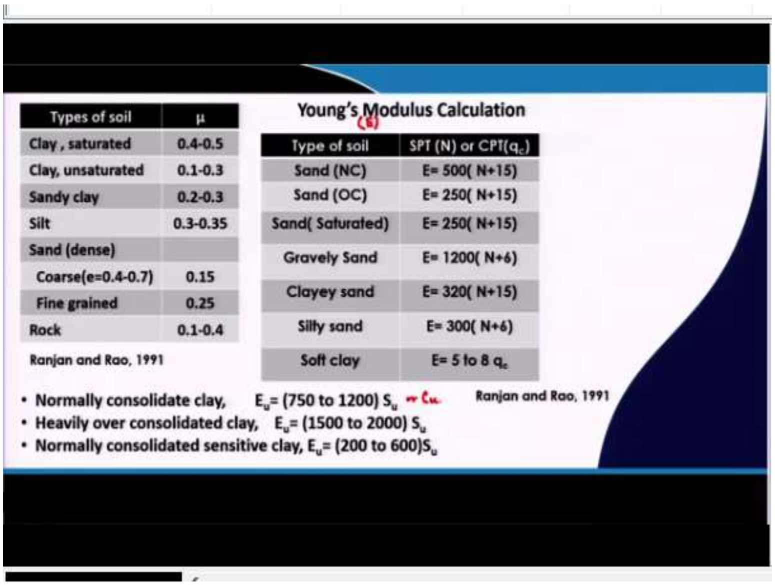

So, now, these are the tables by which you should know the E and μ value for the soil. So, these are the tables for different types of soil. So, from this table you can use directly E and μ values. So, if you do not have the values, then these tables will help you to take the appropriate E and μ values. So, this table is for the μ value and this table is for the E value or Young's modulus.

This is the E value table. So, this if you have the N value SPT then also you can calculate the E by using these correlations. If you have the Q_c value then also you can use this correlation to determine the E value and you can correlate with E this shear strength, s_u or c_u thar means the undrained cohesion also. If you know the undrained cohesion of the soil then by using these correlations also you will get the E value.

So, but these are the correlations and you can see some ranges are given. So, it is always better to have the particular E and μ value for that soil for which you are designing the foundation. That means you should have the E and μ values for that particular soil for which you are designing the foundation. So, these tables will give you a guideline but it is better always to have the actual E and μ values.

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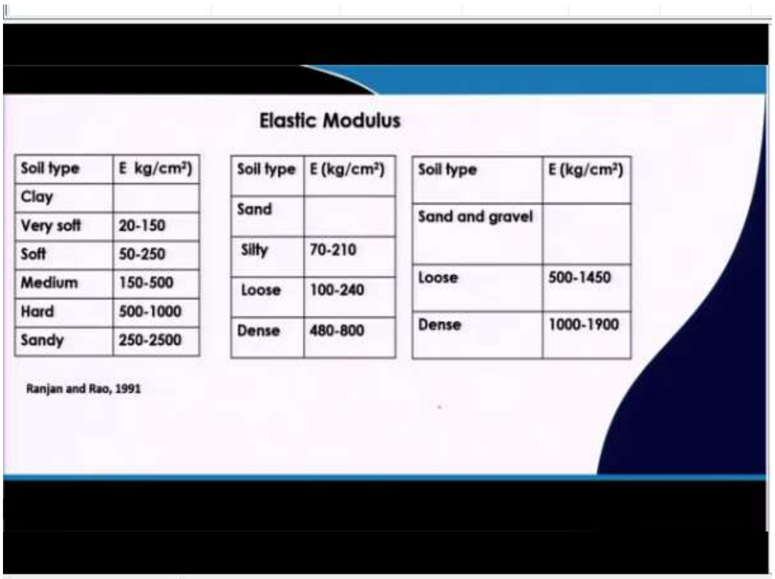

So, now, this is another table by which also you can get the elastic modulus for different types of soil.

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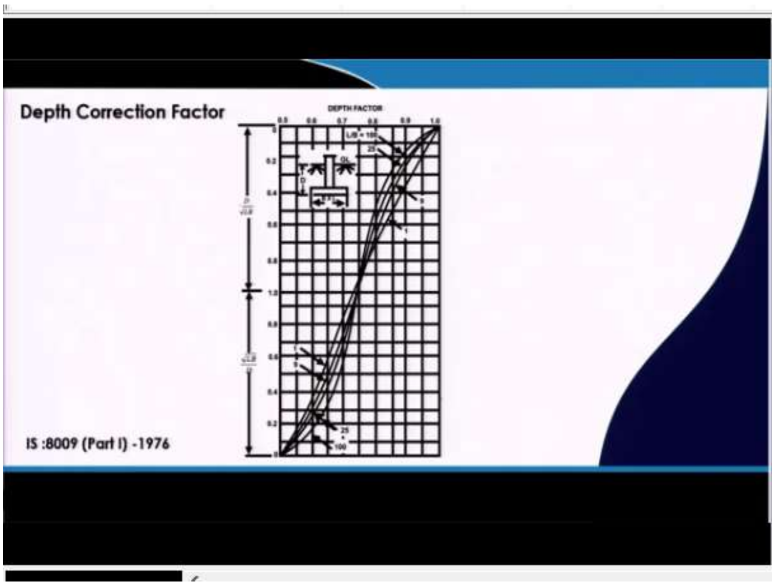

And then as I mentioned there is a depth correction factor. So, this is the rigidity correction factor I have discussed. Now, there is a depth correction factor. So, depth correction factor I can get from this Fox depth correction factor chart. So, along this x axis there is depth correction factor, y axis this $\frac{D}{\sqrt{LB}}$ and this is $\frac{\sqrt{LB}}{D}$, D is the depth of foundation.

So, generally the upper part of this chart is used for the shallow foundation design and the lower part of this chart is used for the deep foundation here. So, now, for the shallow foundation design most of the problems we will use the upper part, but when you calculate the settlement for the pile foundation, then we will use the lower part and this is a $\frac{L}{B}$, L is the length of the foundation, B is the width of the foundation.

So, these are the charts from which I will get the bearing capacity or the depth correction factor for this immediate settlement. So, that means I have discussed the depth correction factor and how you can get a value of E and μ. So, again I am mentioning that if you have actually a μ value that is always preferable, but if you do not have so, these tables will guide you to select the appropriate E and μ values.

So, this way I can calculate the immediate settlement. So, this will give you the immediate settlement for the clay soil. So, next class I will discuss the consolidation settlement of the clay soil and then the other settlements that settlement procedure to determine the settlement of the granular soil or the sandy soil. Thank you.