Advanced Soil Mechanics
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Lecture - 29
Interpretation Triaxial Test - CU

Welcome back all of you so, in the last lecture, we have been discussing about the interpretation of triaxial test and we have finished UU test and UCS. In today's lecture, we will see the interpretation of consolidated undrained CU test.

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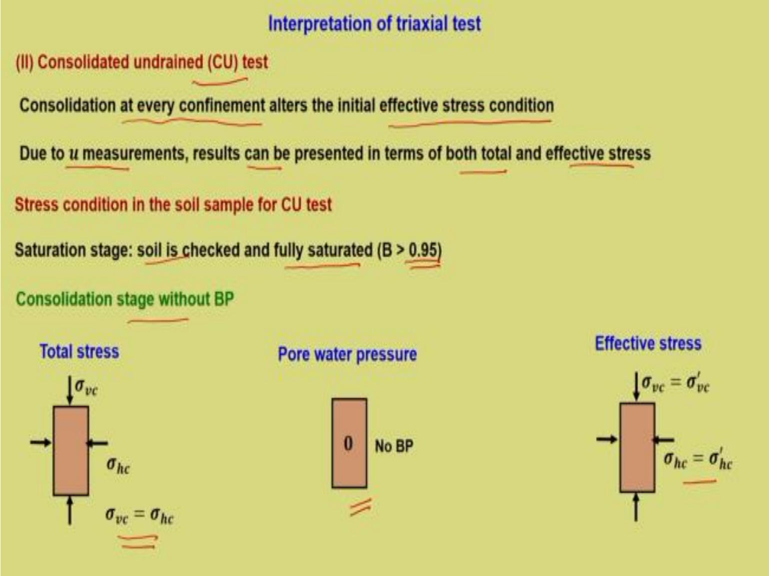

So, let us start the consolidated undrained CU test. Now in this as different from UU test we have to understand that the consolidation at every confinement alters the initial effective stress condition, what does this mean? We need to understand because while learning this we might not have paid much attention to what is the implication of consolidation? Now, what happens during consolidation we are conducting the test at least maybe 3 different confinements of σ_3 values.

And at every σ_3 for CU test, we allow drainage to happen and the consolidation to occur. Now, this consolidation alters the initial state of the sample, which was not happening for UU test and when the initial state alters definitely the strength of the soil will differ. Now, what is the significance of this statement? When the strength of the soil differ is in terms of Mohr circle, the diameter will keep changing, which was not the case for UU test that is the significance of what is meant by consolidation at a given cell pressure.

Now, the second part of this test that is the shearing part is at undrained condition. Now, during undrained condition, pore water pressure will develop and the same is measured in this particular test. So, due to this, u measurements we can present the result in terms of both total as well as effective stress. Now, just like we discussed about the stress condition in the soil, for UU test we will see what is the stress condition in CU test.

So, first is saturation stage again for each of these tests, we will repeat these because for completeness and for clear understanding. So we need to ensure that the B parameter is greater than 0.95 to ensure that it is fully saturated. So the next stage is consolidation now consolidation can be brought about or saturation can be brought about by the application of back pressure as well and we may also not opt to take the back pressure.

So there are 2 conditions of consolidation where back pressure is used where back pressure is not used. So first let us see a consolidation stage without back pressure. So, in the figure for confinement application a particular sample is denoted with is σ_{vc} that is the vertical stress for confinement, c denotes confinement and σ_{hc} is the horizontal stress for confinement that is σ_{hc}.

Now, there can be isotropic or anisotropic consolidation in general, conventional triaxial testing we always opt for isotropic consolidation because this is more simple and easy to understand. Anisotropic consolidation would also induce some sort of shearing because there is a difference in stress. So, here we are talking about a condition where $\sigma_{vc} = \sigma_{hc}$ which is an isotropic consolidation.

Since it is a consolidation stage, drainage valve will be opened and we do not expect any pore water pressure to develop. So the pore water pressure will be equal to 0 because of consolidation stage. If there is some residual pore water pressure, we need to account for that will be the initial pore pressure that is soon after it is mounted. So, in this consolidation stage, since the drainage valve is opened, pore water pressure is equal to 0 and hence we have $\sigma_{vc} = \sigma'_{vc}$ and $\sigma_{hc} = \sigma'_{hc}$. So, that is consolidation stage without backpressure.

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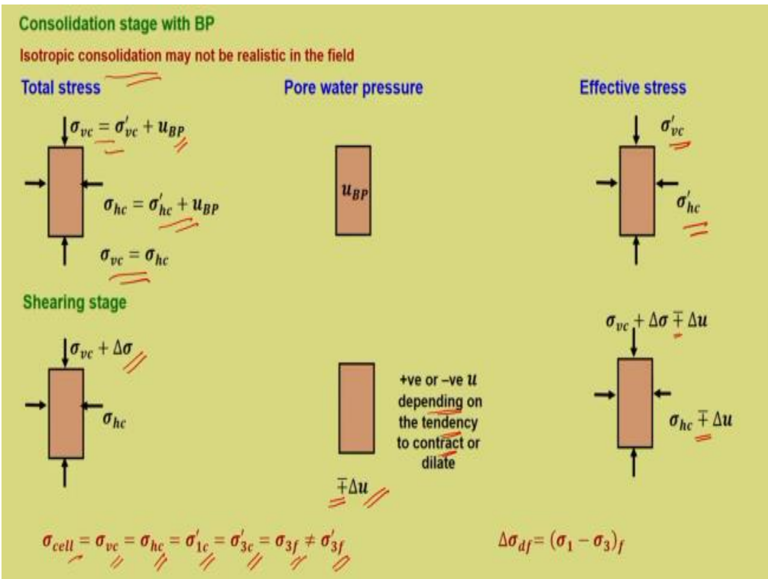

Now, let us see the consolidation stage with back pressure. So, whatever we are doing this isotropic consolidation this may not be actually realistic in the field because in the field always an isotropic consolidation happens because you have an overburden because of this overburden will there will be lateral earth pressure lateral pressure is not always equal to vertical pressure.

Hence, what we are adopting in triaxial testing we need to understand that there is some deviation from the reality and hence, but they still go ahead because this is very easy to understand and follow and there is no shear which gets induced. So, total stress what did we understand in backpressure? In backpressure both the cell pressure and the back pressure is increased simultaneously. So, it is more like a static pore water pressure that is what is denoted here.

So, σ_{vc} is raised by u BP and σ_{hc} is also raised by u BP and but here it is isotropic consolidation and the pore water pressure within the soil is also increased by back pressure. So, u BP will be the back pressure pore water pressure so, what has happened u BP is increased outside and there is an increase in inside also, so, net effect is 0. So, effective stress is σ'_{vc} and σ'_{hc}. Now, in the previous case also that is when back pressure is not applied, there also the σ'_{vc} and σ'_{hc} is the same.

So, we are not altering the initial effective stress condition. So, once the consolidation is completed, that means, there is no more drainage of water happening then the next stage is shearing stage and this is done under undrained condition. So, here we are increasing by $\Delta\sigma$

that are the stress difference or whatever is the actual stress which is imparted to the sample that is $\Delta\sigma$. Now, this results in an increase in or increase or decrease there is both positive and negative of pore water pressure during shearing stage.

So, during shearing stage there is either positive or negative pore water pressure. Now, why this positive or negative pore water pressure we can see that it depends on the tendency of the sample to contract or dilate let us say that there is a volume change which is permitted for this particular sample during volume change, what happens to this soil during shearing we have seen this in our previous lecture that this sample will have a tendency to either compress, or it to dilate.

So, that is the volume change in this case volume change is not permitted so, that translates to pore water pressure. So, a dilating sample will try to exhibit negative pore water pressure or decrease in pore water pressure. Whereas, a compressing sample at low sample which tends to compress will achieve positive pore water pressure because drainage is not permitted it translates to pore water pressure. So, hence, the effective stress will be $\sigma_{vc} + \Delta \sigma \pm \Delta u$.

So, the sign depends upon the behavior during shearing similarly, for σ_{hc} so, this is the stress condition of the sample during consolidation and during shearing stage. Here there is also important aspect which we need to understand which we know but it is better that we confirm this again and again. So, $\sigma_{cell} = \sigma_{vc} = \sigma_{hc}$ (isotropic consolidation) $= \sigma'_{1c} = \sigma'_{3c}$ provided pore water pressure is 0 and $\sigma'_{3c} = \sigma_{3f}$ that is only in terms of total stress.

But since the shearing stage is undrained there will be pore water pressure that gets generated. So, definitely final cell pressure is going to be different that is final effective cell pressure that is σ'_{3f}, which is $\sigma_{3f} \pm \Delta u$. So, that is why this is not same and the final deviatoric stress at failure will be $\Delta\sigma_{df} = (\sigma_1 - \sigma_3)_f$.

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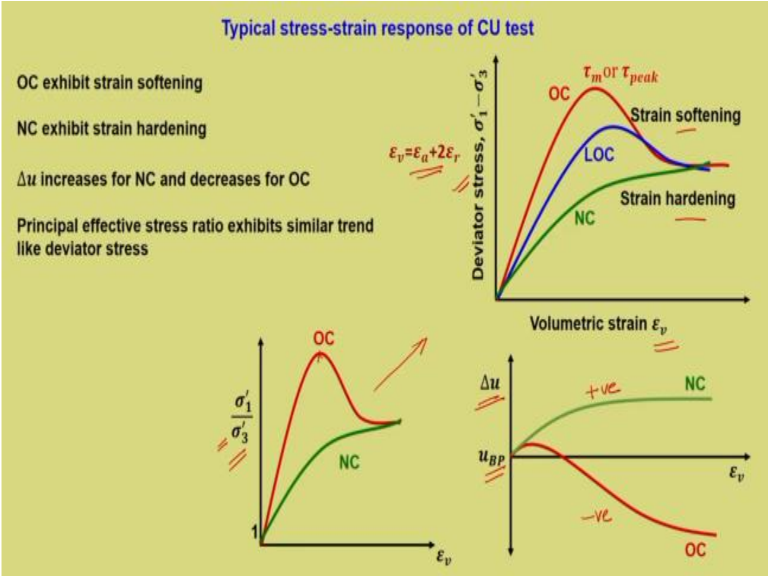

Now, let us see the typical stress strain response of CU test. Now, we have already discussed in our previous lecture about a typical stress strain response. Now, there is nothing different from that, when you consider UU, CU, CD test, but it is important for every stage of the test that we repeat this and reaffirm that this is what is the stress strain response? Why this is important is this knowledge is very much important for your subsequent modules.

So, there is no harm if we hear this maybe 1 or 2 times more, so, that, things and the concepts will be pretty clear. So, here it is deviatoric stress versus volumetric strain and a typical OC, NC and LOC curves are given this we have seen previously here it is plotted in terms of volumetric stream, one can do that in terms of actual strain as well and volumetric strain is $\epsilon_v = \epsilon_a + 2\,\epsilon_r$. So, what is happening at typical OC has a peak and NC does not exhibit a peak and here it is strain softening here it is strain hardening.

Now, in this case, instead of volume change, we have changes in pore water pressure and you if it is under back pressure, then the port water pressure starts from the back pressure and for NC there will be positive, so, this will be positive and that is NC and for OC after a small initial adjustment, it will get to negative pore water pressure. So, that is what is going to happen it may reach negative, but what it means is that it is reducing the pore water pressure is reducing from back pressure.

So, depending upon the amount of OCR that means, how over consolidated the soil sample is maybe it is heavily over consolidated. So, definitely it may reach to a negative pore water pressure. So, this, the same figure is plotted in terms of principal stress ratio. This also we have seen before as a very important aspect in terms of maximum stress obliquity, so, σ'_1 / σ'_3 versus ϵ_v.

It gives the same pattern as that of the deviatoric stress pattern only thing is the peak it may not be exactly at that particular point because of σ'_1 / σ'_3 please note it is in terms of σ'_1 / σ'_3 that is effective stress ratio. Here in the case of deviatoric stress ratio $\sigma'_1 - \sigma'_3 = \sigma_1 - \sigma_3$ it is same. So, in the ratio maybe there will be some difference here and there.

So, that is why the trend is same, but it may not be exactly the same here it is starting from 1 why because it we are starting from an isotropic stress condition. So, OC exhibits softening behavior NC exhibit strain hardening Δu increases for NC and decreases for OC principal effective stress ratio exhibit similar trend like deviatoric stress.

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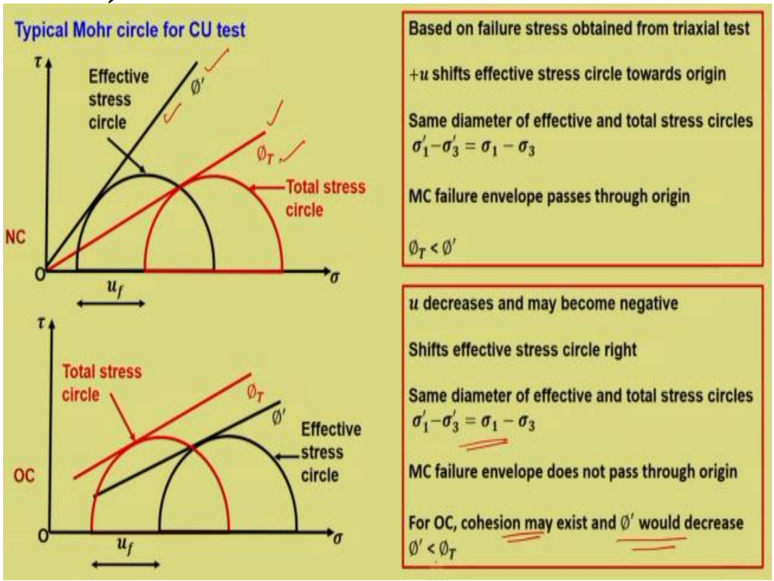

Now, let us see the typical Mohr circle for CU test in the case of NC and OC. So, for the NC case, the total stress circle that is at the end of the test like once the test is completed, we obtain the failure stress then we try to plot the Mohr circle. So, the total stress circle is indicated and a failure line for total stress is indicated that is ϕ_T. So, they have already measured pore water pressure and measurement of pore water pressure is invariably necessary in the case of CU test.

So, once we know u_f that is a pore water pressure at failure, one can plot the effective stress circle so, this is the effective stress circle. Now, if we draw the failure envelope that is given by ϕ' now, what is the implication of the two tangent lines? Let us see, based on failure stress obtained from triaxial tests, we have plotted this plus u, because you shift the effective stress circle towards origin.

Because we are minusing from the total stress, same diameter for effective and total stresses, because $\sigma'_1 - \sigma'_3 = \sigma_1 - \sigma_3$ MC failure envelope passes through origin now, this is a very important information, which you have to keep in mind, let us say that you are dealing with normally consolidated clays and if we have certain wrong notion that clays are always cohesive material, then we tend to question the fact that why there is no cohesion and there is only friction which may be sometimes difficult to understand.

We need to understand that all soils are granular in nature and it can mobilize friction. Now, what happens to a normally consolidated material? A normally consolidated material it can undergo fast volume change and here in fact, it is in terms of pore water pressure because volume change is not restricted. So, you tend to have only frictional component for normally consolidated clays and we do not tend to have cohesion for this particular soil and hence, the failure envelope of CU for NC passes through origin.

So, that we need to keep in mind and ϕ_T is less than ϕ'. Now, let us try to understand whether this is really important or not whether ϕ_T that is the frictional angle corresponding to undrained condition is it relevant or not. In fact, it is not relevant the reason is Mohr Coulomb failure envelope is always defined in terms of effective stress. So, only this particular failure envelope is important and we generally do not use ϕ_T because the undrained strength is different.

Now, we will keep repeating this you will hear the statements at least 4, 5 times throughout this module and we need to clearly understand this particular fact. So, for OC, the total stress circle is given as follows and ϕ_T is drawn and you can see that it does not pass through origin. So, here since the soil has the tendency to dilate the pore water pressure will be less so, it will tend to be negative and hence, we will have effective stress circle moving towards the right and the failure envelope drawn as ϕ'.

So, u decreases and may become negative shifts the effective stress circle towards right same diameter same explanation. MC failure envelope does not pass through origin for OC which means that the cohesive component may exist now, this may be due to cementation this may be due to apparent cohesion, it is not very clear since the particles are already stiff, because it is over consolidated and the stress which is applied is less than the over consolidation.

The pre consolidation stress the material tends to act like a stiff material and the particles are sufficiently close. So, this would exhibit in terms of some sort of cohesive intercept that you get. So, for OC cohesion may exist, and ϕ' would decrease. Now, ϕ' decrease means in terms of NC and OC do not think that OC will have a lower strength it is not like that. So, when you plot the envelope for both, then we will try to we will be in a better position to understand. So for OC question may exist ϕ' would decrease that is ϕ' is less than ϕ_T, again ϕ_T does not have much meaning.

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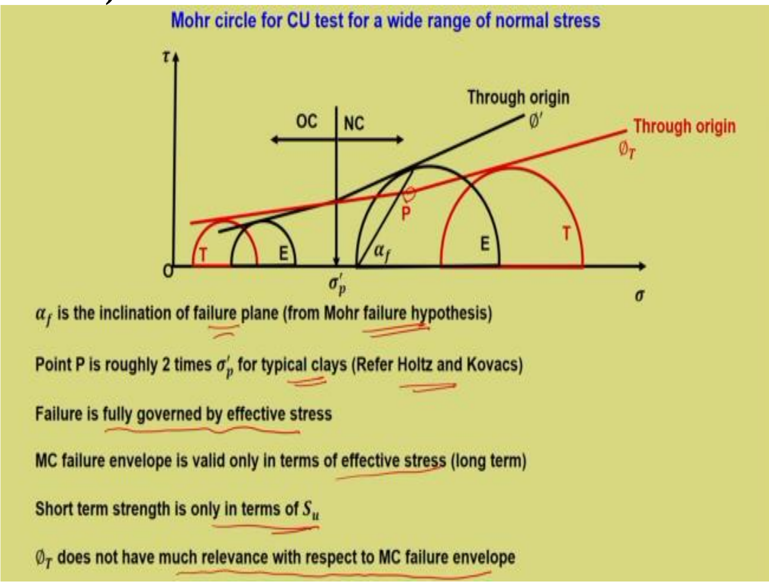

Mohr circle for CU test for a wide range of normal stress. Now just we will try to understand what is the kind of Mohr circle when we consider a wide range of consolidations stress or normal stress? So, τ versus σ: Let us first draw the pre consolidation pressure σ'_p is the pre consolidation pressure, which divides the behavior into OC and NC. So, let us say the total stress circle for NC, which gives ϕ_T and this passes through origin effective stress circle.

And the envelope the failure envelope, which is denoted by ϕ', this also passes through origin. Now for what is α_f? α_f according to Mohr failure hypothesis is the inclination of failure plane which is nothing but 45 + ϕ' / 2 and that is as per the Mohr failure hypothesis. Now, total stress envelope for OC is T and if you draw it, you can see that there is a kink or there is a discontinuity at this point P.

Now, this point P is roughly 2 times σ'_p for typical clays and this information is obtained from Holtz and Kovacs. The original paper is different. If you are interested to find out more, you can always refer to this book and cross refer the literature. The effective stress circle for OC is drawn and the failure envelope is drawn in both these cases there will be sort of cohesive intercept.

Now failure again, this part is I am telling this again repeated and I am intentionally repeating these statements. So, that it is pretty clear as to what we tend to understand. So, and this understanding again it is important for accumulating your further understanding. So, failure is fully governed by effective stress. MC failure envelope is valid only in terms of effective stress that is long term, short term strength is only in terms of undrained cohesion.

So ϕ_T does not have much relevance with respect to Mohr Coulomb failure envelope. Now, what is the relevance we will not talk about ϕ_T much the reason is for failure defining the failure bound we tend to use only effective stress. And hence Mohr Coulomb failure envelope in terms of effective stress only is important.

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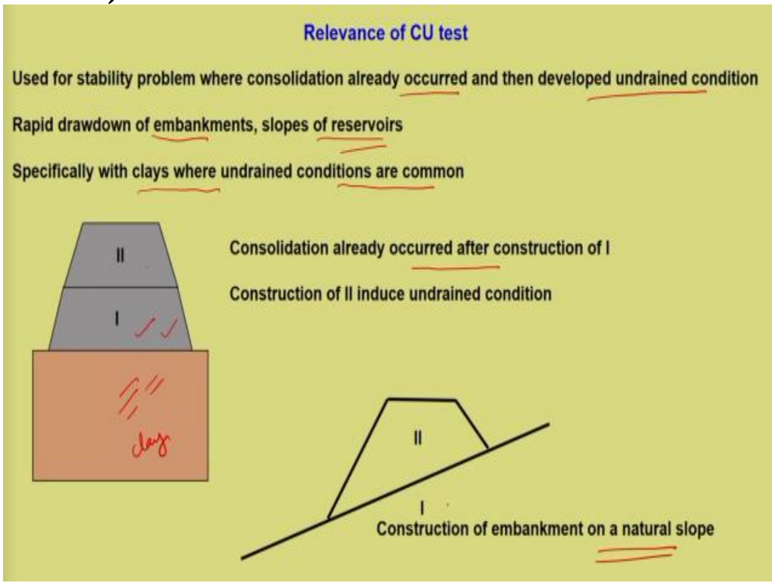

Now, what is the relevance of CU test it is used for stability problem where consolidation already occurred and further developed an undrained condition. For example, there is a typical case of an embankment construction. So, this let us say this is clay and consolidation already occurred when you construct it this particular one, so is the kind of staged construction, the entire height of the embankment is not constructed in one go first this part is constructed and it was left for some time before the second part got constructed.

So, this particular clay would have undergone some amount of consolidation maybe it might have undergone a complete consolidation depending upon the clay properties, then comes the construction of 2 and this construction of 2 induces again a undrained condition provided clay is saturated. Now, this is a typical case of CU condition some other conditions are rapid drawdown of embankments, slopes of reservoir. Now when there is full of water and then there is a rapid drawdown that is happening that induces more effective stress.

And this additional effective stress is going to cause an undrained condition within the core of the dam. So I am not going to the details of it. I just need to understand that these conditions do exist and it is close to CU conditions. And this is very true with clays where undrained conditions are common. And other cases case where such a case can occur is when you are constructing an embankment over a natural slope. So in case of certain developments, if it is done, then this can undergo a kind of CU response.

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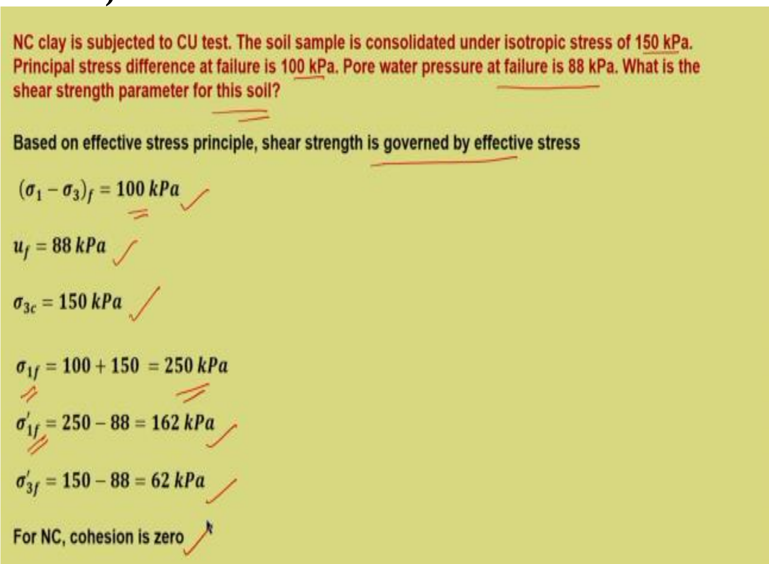

Let us just try to see quickly what is the significance of what we have just understood? NC clay is subject to CU test. The soil sample is consolidated under isotropic stress of 150 kPa. The principal stress difference at failure is 100 kPa. What is meant by principal stress difference that is deviatoric stress at failure pore water pressure at failure is 88 kPa. What is the shear strength parameter for this soil?

Nothing is told about back pressure so, we will not get into that. But we will assume that the pore water pressure is the final pore water pressure at failure and whatever it is it is all inclusive.

Now, based on effective stress principal, shear strength is governed by effective stress what is given σ_1 - σ_{3F} is 100 kPa, u_f is 88 kPa, σ_{3C} is 150 kPa. So, this much is given and these are in terms of total stress.

So, σ_{1f} that is from this particular equation one can find out what is σ_{1f} that is equal to 250 kPa you are just adding σ_{3C} to it and σ'_{1f} is minus pore water pressure that is 162 kPa, σ'_{3f} = 62 kPa and for NC cohesion is 0. Now, think of a situation that we do not understand this particular point like for NC there is no cohesive intercept then it becomes difficult to solve this problem. So, now, we know that NC does not possess cohesive intercept.

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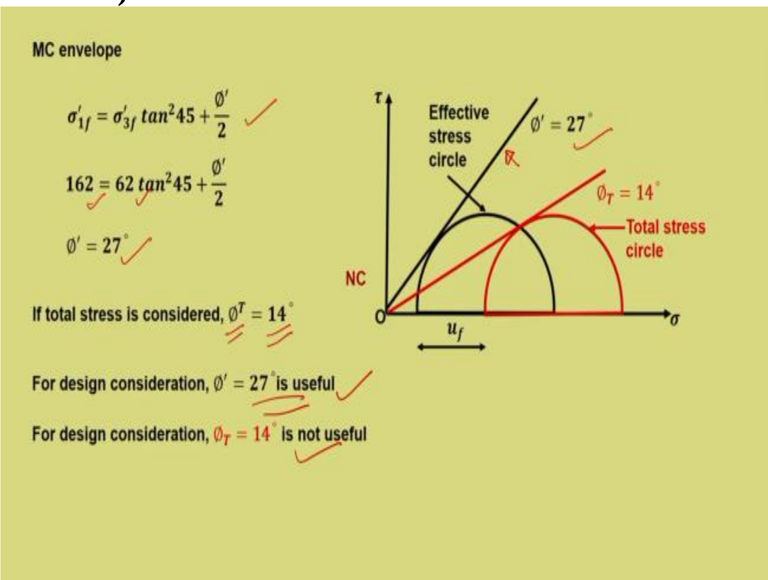

So, that is equal to 0 if that is equal to 0 then one can always write the Mohr Coulomb failure envelop $\sigma'_{1f} = \sigma'_{3f} \tan^2 45 + \frac{\phi'}{2}$. Substituting the effective stress condition into this equation, we can get $\phi' = 27^0$ and that is plotted as show in the figure and the line touching the circle is the bound now, only 1 Mohr circle is there if you have more or 3 Mohr circles as we do for the axial testing.

And average line which is tangential to 3 of the Mohr circles gives the failure bound or Mohr coulomb failure bound or failure envelope, we can also obtain the value of ϕ that is ϕ_T if you substitute the total stresses in the same equation, which is not relevant, but if you substitute you will get 14^0 and that is what has been plotted in the figure. Now, that is the differences u f for design consideration 27^0 is useful and this $\phi_T = 14^0$ may not be useful, I am telling in terms of the failure criterion and the failures on the strength parameter.

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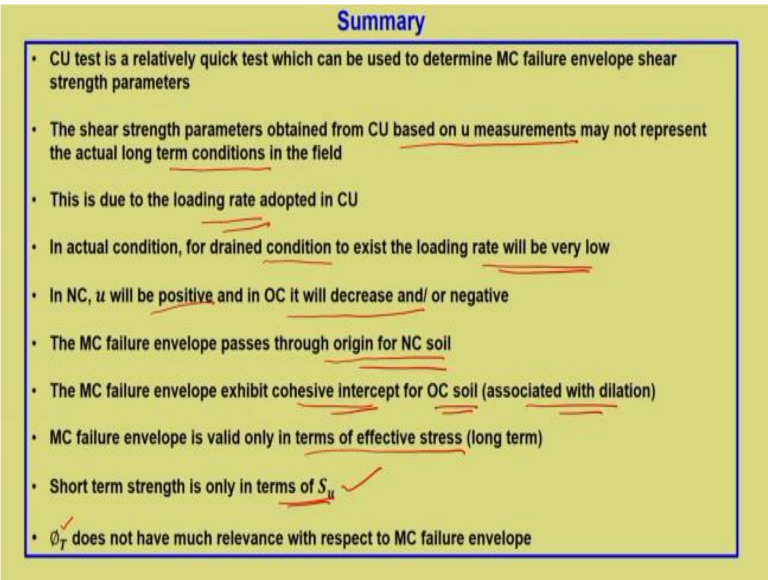

So, CU test is a relatively quick test, which can be used to determine Mohr Coulomb failure envelope shear strength parameters. So, what we are doing here is we know that for clays drainage is poor and it takes weeks or maybe even months for completing a consolidated drain test, if we are conducting it with a condition that pore water pressure does not generate. So, practically it is not possible for conducting a drained test in clays whose permeability is less.

So, in that condition, we have CU test where it is still faster, why because the shearing stage is undrained, but, there is a problem associated with it, which is like in CU test, the rate of shearing is faster, I mean the second stage the rate of shearing is faster and which is different from a normal field case or a CD case. Now, we also need to understand that the rate of shearing considerably influences the strength. Hence, what we get from CU that is from CU we do the test get the result in terms of effective stress.

This effective strength parameter closely simulates but we need to understand that it is not exactly what is expected in the field. The shear strength parameters obtained from CU based on u measurements may not represent the actual long term conditions in the field is exactly what I just told. Because in the field it takes time in what manner it is getting loaded and in what rate it is getting loaded. And in what rate the pore water pressure is dissipated.

And it gets to drained condition these things are quite, quite different from what we simulate in the lab. And that is the reason why we need to understand like, we will use CU parameters effective strength parameters. But we need to understand that there will be some sort of deviation what we are trying to explicitly state is the uncertainties involved in these tests one should not be. So, confident that we have got this particular value and this is the final it is not so, a lot of inherent uncertainties associated with each of these parametric values.

Now for engineering purposes, we need a design value based on which we can design various structures which are founded or maybe the design the foundation or various other applications. So, we need to understand that these are representative values and not really true values and because of these hidden factors involved and this has something to do with the loading rate. And we have already explained this in actual condition for drain condition to exist the loading rate will be very low in NC, u will be positive and in OC it will decrease.

And tend to negative value the Mohr Coulomb failure envelop passes through origin for NC this is important and the Mohr Coulomb failure envelope exhibit cohesive intercept for OC soil you please note that I have used the term cohesive intercept. So, this does not mean that again it is a true cementation there is a kind of value which you obtain because of the OC condition this is associated with dilation.

Mohr coulomb failure envelope is valid only in terms of effective stress which is long term short term strength is only in terms of S_u probably you will hear the statement once more when we discuss the next interpretation which is ϕ_T. Because I find that or I understand that this is very important to clearly get into your mind that undrained condition the strength is mostly in terms of S_u, ϕ_T that is the total strength parameter which you obtain from the total stress does not have much relevance with respect to Mohr Coulomb failure envelope.

So that is all for the interpretation of consolidated undrained test. We will see about the interpretation of consolidated drain test in the next lecture. I again, request the participants to be patient, those who know these particular concepts very well and those who have been τght these particular concepts very well. For them, it may look like it is getting repeated. But for me, these particular aspects are extremely important for all the participants to clearly understand this, so that the understanding of the subsequent modules will be easy. So that is all for now. Thank you.