Advanced Soil Mechanics
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Lecture - 27
Triaxial Testing

Welcome back all of you, so in the last lecture we have seen a few aspects related to pore water pressure and its estimation. Next we will move on to shear strength determination with specific focus on triaxial testing, many of you would have already studied triaxial testing properly during your undergraduate. So, please take this as a revision of triaxial test because in the subsequent lectures we will rely a lot on triaxial test.

And its interpretation which is mandatory for understanding stress path and critical state soil mechanics. So, I cannot forego this topic even though it is start in UG and in addition we will be discussing a few additional points which is actually needed for this particular course. So, we will have a brief on what axial test is and what are its possibilities and then in the subsequent lecture we will see its interpretation.

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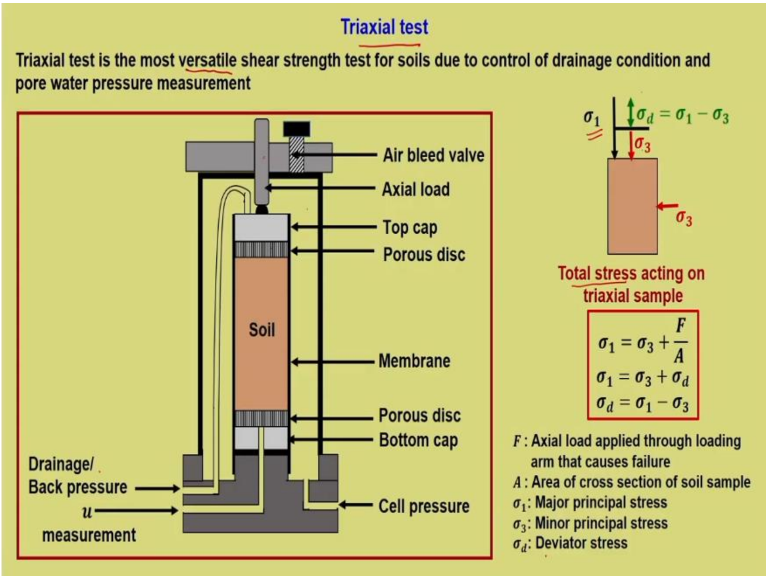

So, this is all about triaixal test. So, triaxial test is the most versatile shear strength test for soils due to control of drainage condition and pore water pressure measurement. Now in the field you have different possibilities a low permeable soil has the drainage capacity quite low which means to say when a load is acted upon on a low permeable soil you are likely to have undrained condition for substantial amount of time.

Similarly there will be development of pore water pressure. So, there will be undrained condition pore water pressure with time pore water pressure dissipation happens and at very large time what happens is and a completely drained condition would exist. So, we have the strength of the soil at its short term that is undrained condition what will be its strength and for a long term what will be its strength.

Now it is very difficult to define something called undrained shear strength because we know that based on effective stress principle the strength is entirely dependent on effective stress condition however soil will be possessing some amount of effective stress even under undrained condition and that is why we need to have the idea of pore water pressure and most of the effective stress condition which is relevant for the soil it is there right at the beginning.

Which is mostly associated with its initial state from where the soil has been sampled. So, for simulating different conditions the most versatile test that we have is a triaxial test. So, we will see quickly what traxial test apparatus looks like because that is needed to understand this particular aspect how it becomes versatile. So, this is the soil sample which is mounted in the triaxial cell. And on top of it you have porous disc which permits drainage of water from soil outwards when the loading happens.

And there are 2 caps one is the bottom cap and the top cap for delegating the load equally to the soil. Now we have the provision for applying cell pressure then there is a provision for recording pore water you are now by this time I hope all of you are familiar with u if I write only u It means pore water pressure, so pore water pressure can be measured and there are a provision for drainage of the soil sample.

And there is a provision for back pressure which is more or less in together with drainage condition. So, we have different outlets then the soil is housed inside a membrane, so that the soil is not able to interact with the water outside because cell pressure is delegated there will be water within this chamber. This is the ramp through which the actual load is delegated to the sample and there is an air bleed valve in order to allow the air to escape from this water.

So, when you fill this chamber with water for applying cell pressure the any entrapped air bubbles or dissolved air bubbles is forced further out through this air bleed valve. So, this is the overall setup of traxial test. So, when the stress is applied or when the load is applied on to the soil sample referring the figure. First is the confinement that you give σ_3 and then is the actual load which comes the top.

So that is denoted as σ_1 now in triaxial testing it is important to understand what causes failure. So, initially there was a confining stress σ_3 all round this stress will not partake in the process of failure because there is an isotropic stress condition as a mean stress condition where all round stresses are equal. Now this creates volume change but not shear stress within the soil this we have already discussed then what causes failure.

So, when you apply the load that is the ramb this load which is delegated to the actual this system. So that causes failure that induces shear within the soil this also we have discussed before. But what is exactly that is causing failure that is the deviator stress component which causes which induces a shear and that causes failure that is given by this. So, total stress which is the actual stress as well plus the confining stress which is acting on the top of the sample that is together the major principle stress.

Hence the deviator stress is nothing but $\sigma_1 - \sigma_3$ this is further explained hereσ_1 = σ_3 + the force which is applied through actual force that is applied through this ramp divided by area of cross section of the sample. So, σ_1 = σ_3 + σ_d. Hence σ_d = σ_1 - σ_3. So, F is the axial load applied through loading arm that causes failure. So, area of cross section of soil sample and σ_1 is the major principle stress σ_3 is the minor principle stress and σ_d is the deviator stress.

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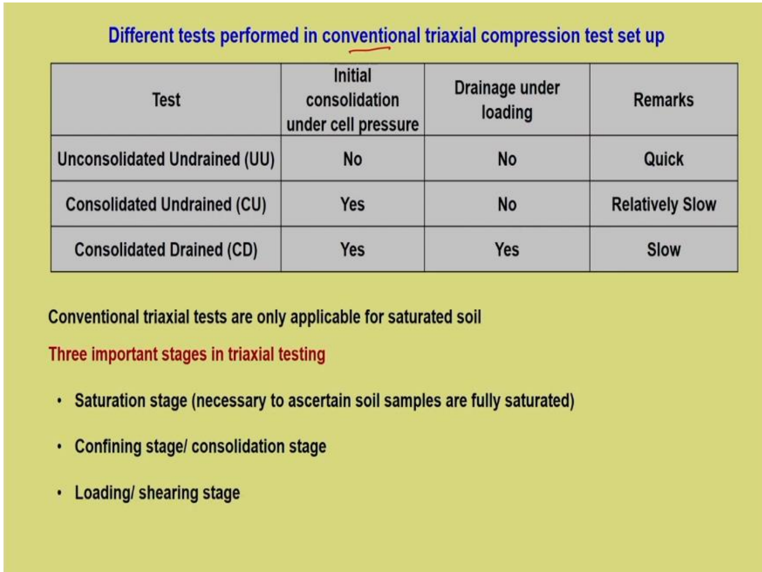

Now what are the different tests performed in conventional triaxial compression test setup. Now why I am using this term conventional means I am talking about the basic triaxial test equipment. Nowadays there are different variants of triaxial testing possible you have cyclic triaxial testing you have unsaturated the soil to triaxial testing there are stress but for traxial testing. So, there are different provisions which got added up for specific situations.

But I am talking about the very basic triaxial compression test. So, these are the 3 possible tests which one can do in triaxial compression testing which is unconsolidated undrained denoted by UU, consolidated undrained CU and consolidated drained CD now all the information are there in the name itself. So, there are 2 stages essentially with respect to loading. First is the initial consolidation phase which is acted upon by cell pressure.

So, initial consolidation under cells pressure and there is drainage and there is loading stage or shearing stage now whether there is initial consolidation under cell pressure for UU test no and whether drainage happens under loading. Loading means both cell pressure as well as the triaxial stress or the deviator stress, so there is no drainage which is happening. So, as it is mounted it may be saturated and then the load is applied without any drainage and consolidation.

So, consolidated undrained CU there is initial consolidation which means that there is some changes that is happening to this soil sample during the consolidation phase that is confinement is applied and then the drainage valve is open, so that water moves out and consolidation can happen whereas in the case of loading that is in the shearing stage it is not the drainage wall was closed and hence it is a complete undrained condition.

Then consolidation also happens that is drainage valve is not closed during confinement also it is open and during shearing also it is open and hence the there is volume change which is happening during both the stages. Now accordingly the first test is very quick because nothing you have to do you have to mount the sample saturate and then load it and hence the failure happens relatively faster.

CU it is relatively slow whereas CD is extremely slow by this is relatively slow and slow we will come to know a bit later as we discuss this test. So, conventional triaxial tests are only applicable for saturated soil. Now this aspect one need to understand very carefully some undergraduate students they do not appreciate this fact properly but we need to understand that for conventional triaxial test is only applicable for saturated soil alone.

The 3 important stages in triaxial testing the first one is the saturation stage we need to a certain that the soil samples are fully saturated if the samples are not fully saturated we need to perform the saturation. So, the first aspect is we draw the sample from the field for determination of shear strength and mostly these samples will be undrained. Now we cannot guarantee that the particular soil sample that we get from the field is saturated.

So, first we will check whether the soil is saturated if it is not then the first stage is to execute or to induce saturation in the soil sample then comes the confining stage or the consolidation stage and finally the loading or the shearing stage. So, these are the 3 important stages in to triaxial testing.

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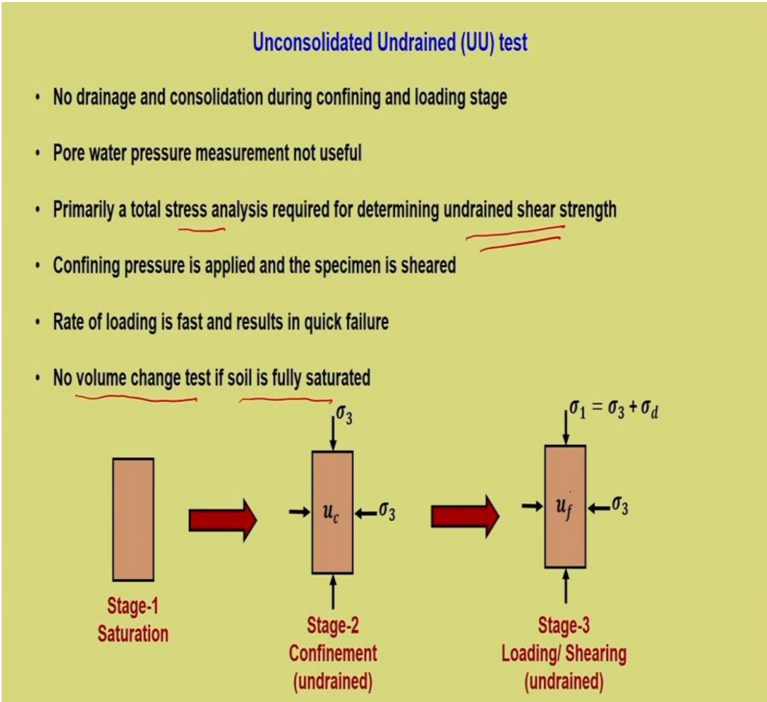

So, let us see the features of unconsolidated undrained test we are not going to discuss any results in this lecture we will understand clearly what are the possibilities of these tests, no drainage and consolidation during confining and loading states we have seen this now pore water pressure measurement is not useful. This is an undrained test what else is going to happen other than pore water pressure. But still one can always measure the pore water pressure in UU test.

But that is not going to be useful why? We will see this when we discuss about the results of UU test primarily a total stress analysis required for determining undrained shear strength. So, this is purely a total stress analysis and the second statement and third statement they are complimentary to each other. Because if there is no pore water pressure measurement use there if the pore water pressure measurement is not going to be useful.

Then it is apparent that we are not going to have the results in terms of effective stress. So, it is a total stress analysis and only useful for undrained shear strength confining pressure is applied and the specimen is sheared there is no waiting period because consolidation is not there. Rate of loading is fast and results in quick failure. No volume change test, so this is specifically and no volume change test if the soil is fully saturated.

So, these minute points one need to keep in mind why should I write if soil is fully saturated? A clue you will get when because you if you have gone through the lectures of pore water pressure what is the effect of partial saturation on B parameter. So, same thing is applicable here if there are air present in the sample then air will get displaced in the process. So, what is going to happen is if it is fully saturated whatever is the initial effective stress that remains same.

But if you allow any sort of volume change and that will alter the initial effective stress and once it is altered the strength also gets affected. So, that is the reason, so it is understood that there is no volume change which takes place. So, the stage 1 is saturation the stage 2 is confinement. So, we have the pore water pressure which is developed which is corresponding to the confinement sigma 3 you may choose to measure or you may choose not to measure it is not mandatory. But you see even if it is measured is not going to be useful in this test.

So, the loading stage is you are applying the deviator load through the axial provision which is there in the triaxial testing and hence the cumulative pore water pressure and the failure is u_f, so that is how it is.

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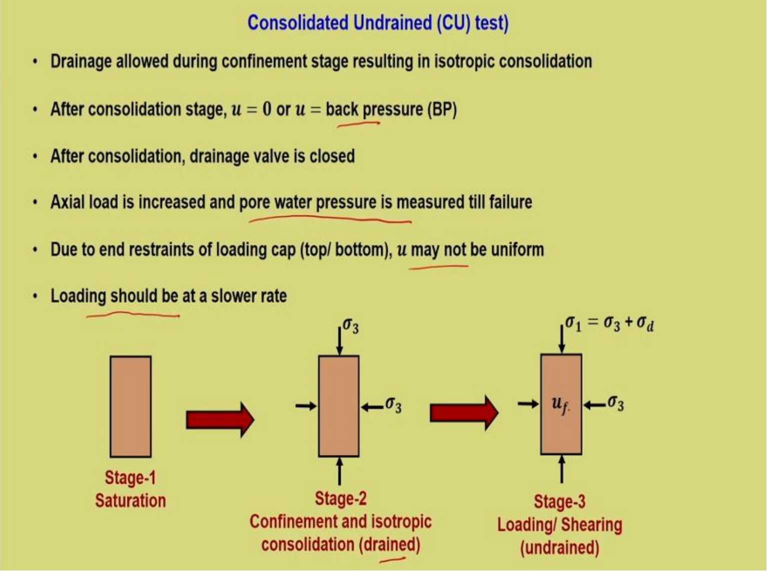

Next we will see consolidated undrained test, so we have drainage allowed during confinement stage resulting in isotropic consolidation yes we need to note here that the consolidation happens under isotropic condition after consolidation stage u = 0 or u = backpressure please hold on for some time we will discuss at length what is meant by back pressure ideally during consolidation the drainage valve is kept open. So, there will be no development of pore water pressure.

Hence at the end of consolidation stage pore water pressure will be 0 provided the drainage line is kept open to atmospheric pressure. Now there is some arrangement for applying back pressure which we will see soon and if it is, so then at the end of consolidation stage this particular pore water pressure in terms of back pressure do exist these are again some minor points but very important points you need to keep in mind for appreciating or understanding the development of pore water pressure.

How you determine the effective stress all these things are dependent on your understanding on what is pore water pressure what is back pressure how it is applied. So, these things become important. So, please pay specific attention on these points even though it may look very minor. So, after consolidation the drainage valve always closed axial load is increased and pore water pressure is measured till failure.

Now you can see here in CU test it is invariably necessary to obtain the pore water pressure only if you know the pore water pressure you can give the shear strength or you can represent the stress strain in terms of effective stress. And here it is extremely important that we need to have the effective stress strength parameters he was that is more relevant. Now due to end restraints of loading cap we have already seen in the initial figure there are 2 loading caps top and bottom.

And hence during the undrained loading pore water pressure generated may not be uniform within the soil sample. Just to avoid this non uniformity it is always ideal to have loading at a slower rate. Now you will appreciate why this particular test is relatively slow than UU test this is mainly because that the loading rate has to be slow. So that the pore water pressure development is there is a height applicable for the sample.

It is not like a consolidation sample there is an appreciable height. So, when the load is delegated it may not instantly equilibrate the pore water pressure may not instantly equilibrate. So, there will be a certain time lake that is what is known as u may not be uniform and after keeping for some time it will achieve a uniform value it is a hydrostatic stress, so it has to be equalized. So, stage 1 is saturation same as before stage 2 consolidation there is confinement and isotropic consolidation. So, it is a drained stage then the drainage valve is closed and the loading stage happens is the same as before but there will be development of pore water pressure that is u_f during the undrained stage and this u_f need to be known.

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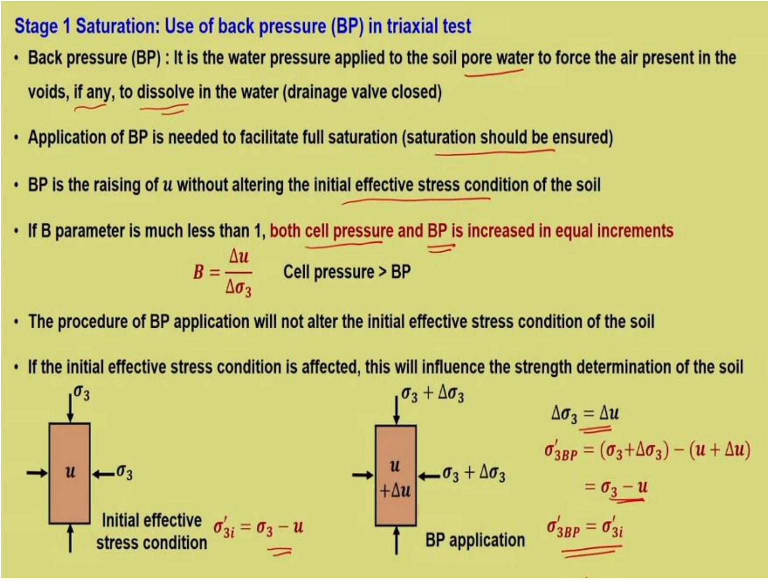

As I told in the beginning we will discuss a bit on what is back pressure in triaxial testing and this backpressure is applicable for all the 3 testing because back pressure is useful for saturation and saturation is mandatory for all the 3 types of tests, all the 3 types of triaxial testing. Now what is back pressure? It is the water pressure applied to the soil pore water. So, it this pressure goes within the soil sample to force the air present in the voids if any.

So, if it is fully saturated then most of the air voids will be filled with water. But in case it is not then it is the water pressure which will help the air bubbles which are present in the voids to dissolve in the water already there is water in the pose. So, the air is displaced from the voids and it dissolves in the water and in the process some amount of minor amount of water gets in and fills the pose.

Please make a note this process is without changing the effective stress condition or the initial state of the sample only what is happening is the air which is present dissolves into the water and will get displaced by water. So, water displaces the air and hence it achieves complete saturation which is a condition mandatory before consolidation or loading application of backpressure is needed to facilitate full saturation and saturation should be ensured.

So, it is the raising of pore water pressure without altering the initial effective stress condition of the soil. This is very important the moment it changes the effective stress then it is going to have its effect on strength. Now you will probably understand the importance of discussing pore water pressure. Now just before discussing this lectures we had on pore water pressure we discussed about A and B parameter there when we discussed we specifically told that B parameter is used for assessing soil saturation.

So that application will come here, so if B parameter is less than 1, so you check the B parameter what do you do for checking the B parameter you need to increase the cell pressure by some amount that is not substantially some small increment of cell pressure you give and measure the port water pressure and B is we know that it is $\frac{\Delta u}{\Delta \sigma_3}$ that is the during the confinement.

So, you measure both if it is substantial value then if it is much less than 1 it indicates that it is not saturated. If it is close to 1 it indicates it is saturated. So, both the if the parameter is much less than 1 which means that it is not saturated then both the cell pressure and the back pressure is increased in equal increments. Now back pressure is mostly along with the drainage line from where the pressure is delegated into the soil sample and that raises the pressure.

Now if cell pressure is not raised simultaneously there will be a kind of blowing out effect and that will destabilize the soil sample. And always we have to keep in mind that back pressure application should not be substantial. It also has to be done in small incremental stages. So, if the B parameter is less than 1 both cell pressure and back pressure is increased in equal increments. So, $B = \frac{\Delta u_c}{\Delta \sigma_3}$.

And we need to keep in mind that always the cell pressure is kept more than back pressure else there will be case of negative conditions. So, always the cell pressure is greater than back pressure. So, the procedure for back pressure application will not alter the initial effective stress condition of the soil, if the initial effective stress condition is affected this will influence the strength and determination of the soil. So, this is the condition when the confinement is applied.

So, the initial effective stress condition is $\sigma'_{3i} = \sigma_3 - u$. So, this is the initial condition of the soil now we will make an assessment of B parameter let us say it is substantially less than 1. So, you need to saturate the sample this much is understood. So, you apply the back pressure. So, when you apply the back pressure that is in terms of delta u that is increase there is an increase in cell pressure $\Delta\sigma_3$ and $\Delta\sigma_3 = \Delta u$, so it is equal increment.

So, back pressure is increased by Δu, so the cell pressure is also increased by $\Delta\sigma_3$, so that the effectively the condition remains the same. So, $\Delta\sigma_3 = \Delta u$. So, what is the effective stress condition for this backpressure application is

$$\sigma'_{3BP} = (\sigma_3 + \Delta\sigma_3) - (\mathrm{u} + \Delta u)$$

$$= \sigma_3 - u$$

$$\sigma'_{3BP} = \sigma'_{3i}$$

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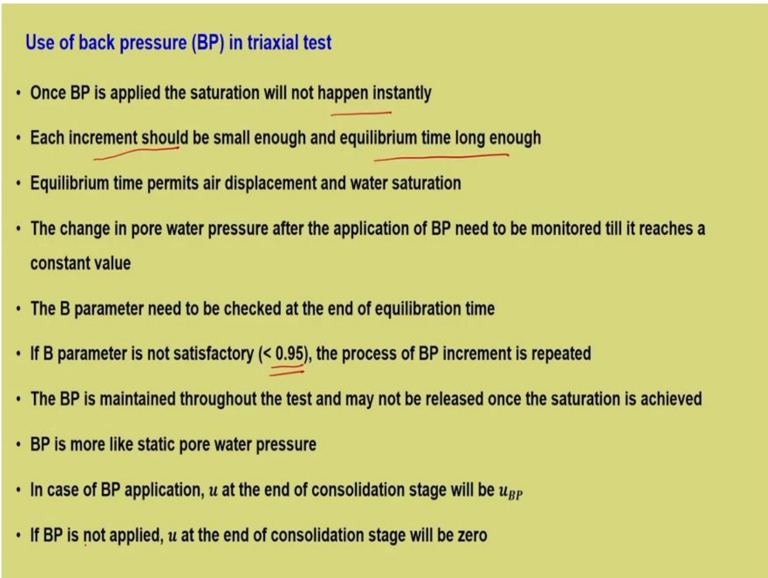

Uses of back pressure once the back pressure is applied the saturation will not happen instantly. This also we need to understand when a load is acted upon into the soil we say that immediately the water captures all the load yes this is true but there is a bit of time lake by the time it delegates to the entire soil sample. So that the back pressure is applied the saturation will not happen instantly.

It is not an instant response just because of this each increment should be small enough and equilibrium time should be long enough. So, we need to wait for some time and the increment has to be smart let us say that ultimately the backpressure application is around 200 kPa. So, always start with a small increment let us say 50 kPa and then wait for some time till it equilibrate.

How do you know it will equilibrate when you keep measuring the pore water pressure it becomes constant. So that indicates that the pore water pressure has almost equilibrated if it is still rising we have to wait for some time. So, this is what we need to keep in mind back pressure application is in small increments and that small increment has to be kept for sufficient time and that is known as the equilibrium time.

So, equilibrium time permits air displacement and water saturation the change in pore water pressure after the application of back pressure need to be monitored till it reaches the constant value the B parameters need to be checked at the end of equilibration time. So, once before the pressure equilibrate we know what is the incremental pore water pressure that has happened for an incremental rise in cell pressure or the back pressure back pressure application.

And cell pressure applications simultaneously we will measure Δu and $\Delta\sigma_3$ check the B value if B value is not satisfactory normally it is as a rule of thumb it is considered as 0.95. So, anything above 0.95 you can treat it to be saturated but if it is less than 0.95 is an indication that the saturation has to be made the process of back pressure increment is repeated. So, with 50 kPa it is not getting saturated and other 50 is added.

So, total back pressure now becomes 100 kPa is simultaneously the cell pressure is also increased. So, this process goes on the monitoring goes on the whole of the saturation process goes in an incremental manner till the B value achieved is around more than 0.95. So, the back pressure is maintained throughout the test and may not be released once the saturation is achieved. There is another important point like once the back pressure is applied.

So, It kept as it is once the B value is achieved it is not that we close it. So, this backpressure would remain or it may remain in the soil sample till the test is completed. So, back pressure is more like a static pore water pressure we have seen what is a static pore water pressure only the excess pore water pressure brings about changes or volume change in the soil mass or densification in the soil must this we have seen.

So, here back pressure will not change any such changes will not bring about any such changes. So, it is more like a static pore water pressure. So, in case of back pressure application, u at the end of consolidation stage will be u_{BP} that is there will be some amount of pressure already existing in the sample. If back pressure is not applied for saturation then u at the end of consolidation stage will be 0.

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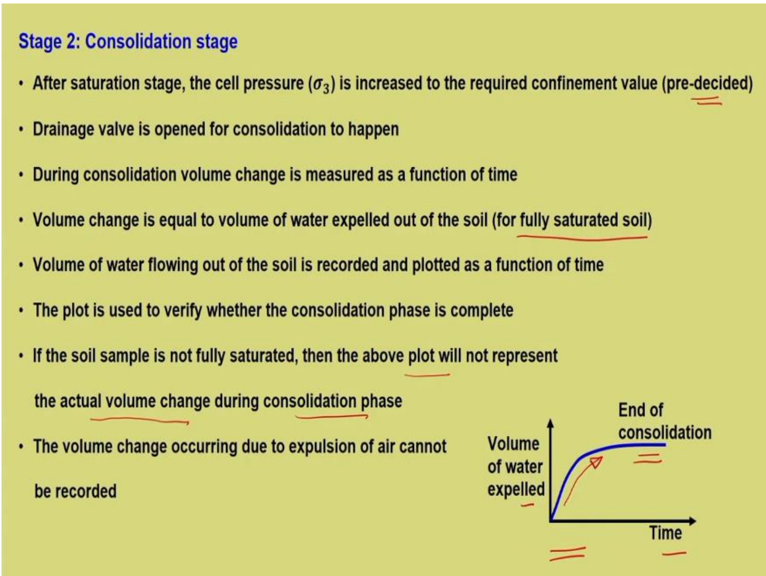

Stage 2 is the consolidation stage after saturation stage the cell pressure is increased to the required confinement value which is already pre decided by the person who is conducting the test the drainage valve is opened for consolidation to happen. Now none of this was relevant in UU test, so that we will possibly understand why this test is taking a lot of time consolidation is also not an instant response it takes time.

So, for under a given pre decided confining stress the consolidation is carried out and for that drainage valve is opened during consolidation volume change is measured as a function of time volume change is equal to volume of water expelled out of the soil for fully saturated soil again now you will understand why soil has to be fully saturated whatever volume change that happens during consolidation we need to capture that.

And for capturing that it is mandatory that the whole of the soil is fully saturated. So, whatever is the volume of water that gets expelled out that itself is equal to the volume change that is happening during consolidation the volume of water flowing out of the soil is recorded and plotted as a function of time as like given here. So, this is volume of water expelled and this is the time we can see that initially there is an increase in volume of water expelled.

And it slowly becomes constant for that particular amount of confinement which is applied. So, once it becomes constant we understand that the consolidation phase got completed the plot is used to verify whether the consolidation phases complete. So, if the soil sample is not fully saturated then the about this plot will not represent the actual volume change during consolidation phase why?

Because the volume change occurring due to expulsion of air cannot be recorded. Now let us say that there is some amount of air also present because of poor saturation. Now what will happen when the load is applied when the confinement load is applied for conducting the consolidation the air also displays and there will be a volume change associated with the displacement of air that volume change we cannot capture.

We can capture only from the volume of water which is getting expelled out which means to say that whatever has been represented by this curve is not complete if the soil is not fully saturated the volume of air we cannot measure that is the reason it is important that we need to have complete saturation and this particular curve is very important to decide upon the shearing stage like when it comes next. So, especially that will become important for drained shearing. So, this particular information becomes important.

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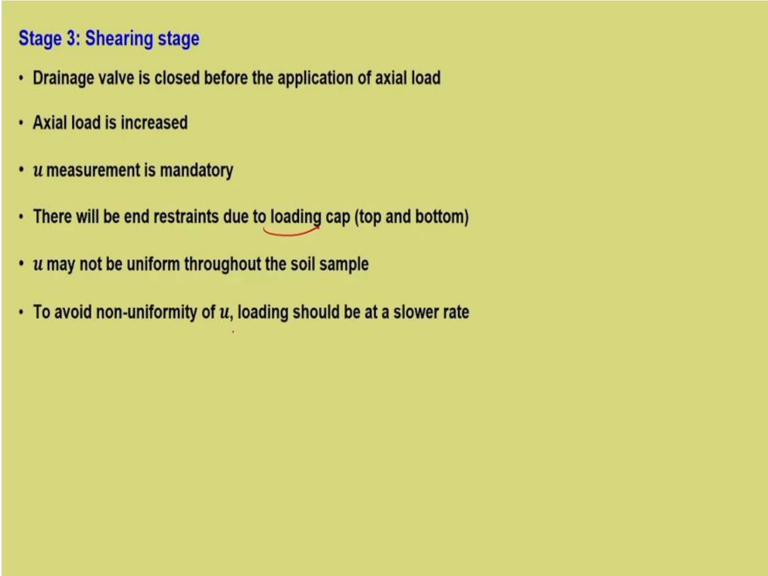

So, next is the shearing stage of CU test where drainage valve is close before the application of axial load and then axial load is increased which is the deviator load, u measurement is mandatory we have seen they will be end restraints due to loading cap whatever this particular aspect we have already discussed u may not be uniform throughout the soil sample to avoid the non uniformity of u loading should be at a slower rate.

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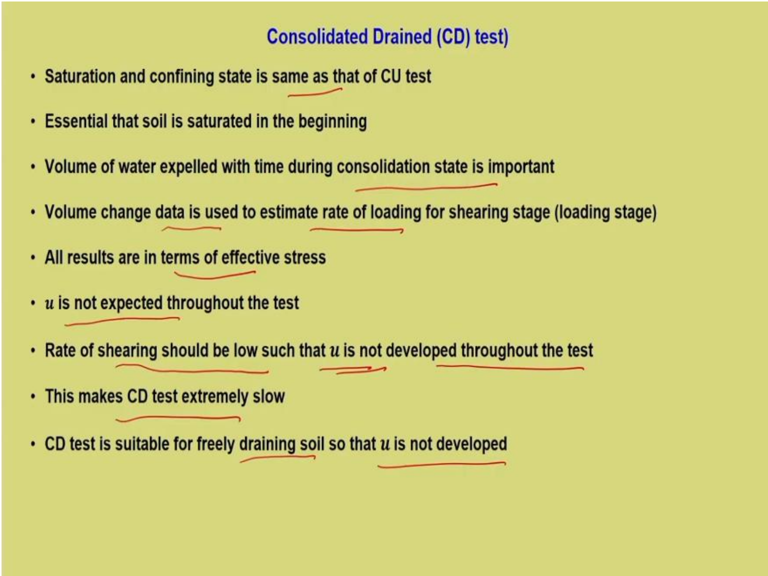

So that is about CU test and next is CD test. Now CD test is very much similar to that of CU test everything remains the same. Only thing is the drained loading happens saturation and confining stage. The same as that as CU test essential that soil is saturated this all same volume of water expelled with time during consolidation state is important that information is important volume change data is used to estimate the rate of loading for shearing stage that is the loading stage.

All the cells are in terms of effective stress because there is no development of pore water pressure during this test. Now this also induces the time required for conducting this test why because rate of shearing should be low such that pore water pressure is not developed throughout the test we have already seen in the previous lectures that if the rate of loading is higher then also there can be pore water pressure even though the permeability of the sample is more.

Here we need to ensure that there is no pore water pressure that gets generated during loading. Hence the shearing rate should be low. So that it does not allow any pore water pressure to develop. So, this makes the CD test extremely slow CD test is suitable for freely draining soil, so that u is not developed especially for Sandy type of soils where generally CD test is conducted. So that is all about the different types of tests that is conducted in triaxial those who understand these tests properly you can think of skipping this lecture.

But what are the different possibilities and during interpretation of triaxial testing we should know what are the different provisions of these tests. So that is why this lecture is important.

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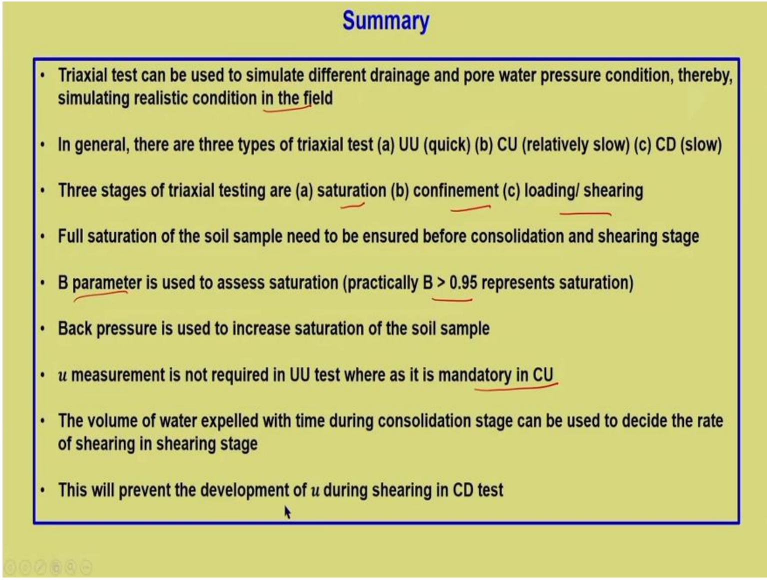

So, the triaxial test can be used to simulate different drainage and pore pressure condition thereby simulating realistic condition in the field. In general there are 3 types of triaxial test UU, CU and CD. There are 3 stages that is required in the triaxial testing which is the saturation, confinement and loading or shearing. Full saturation of the soil sample need to be ensured before consolidation and shearing stage.

B parameter is used to assess saturation and practically B greater than 0.95 represents saturation. Back pressure is used to increase saturation of the soil sample. In case it is found it is not fully saturated u measurement is not required in UU test whereas it is mandatory in CU test. The volume of water expelled with time during consolidation stage can be used to decide the rate of shearing in shearing stage.

This will prevent the development of u during shearing in CD test. So that is all about the discussion on different tests that we can conduct in triaxial testing. Next lecture onwards we will see the interpretation of different types of these tests which we have discussed today. And that interpretation is extremely important because from what test what shear strength you get is extremely important. And the results will be used further when we discuss module 3 and module 4. So that is all for now thank you.