Unsaturated Soil Mechanics
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Week - 08
Lecture – 24

Suction Controlled Direct Shear Test

Hello everyone, today we will discuss how the experimental data can be analysed, the experiment data of time from modified shear test we discuss and we also discuss how to analyse this data? Today, let us discuss what type of a data be obtained from Suction Controlled Shear Test.

And, also how to analyse this data to interpret the effective stress concept for Unsaturated Soils will look into. So, as I explained in the previous lectures, the unsaturated strength parameters can be analysed by considering two independent trusted variables, such as net normal stress and matrix suction. And, bishop is a person who introduced these two independent trusted parameters and lumped into one single equation for defining the effective stress equation.

So, using the modified more column concept by introducing this effective stress principle into the equation one can obtain the effective stress parameter xi can be estimated and xi is a function of weather volumetric water content or matric suction. So, this functional form can be obtained from the experimental data. So, let us understand what kind of experimental data we obtained from suction controlled shear test such as suction control direct shear and suction controlled triaxial test. And, from the data how to interpret this effective stress parameter we will understand.

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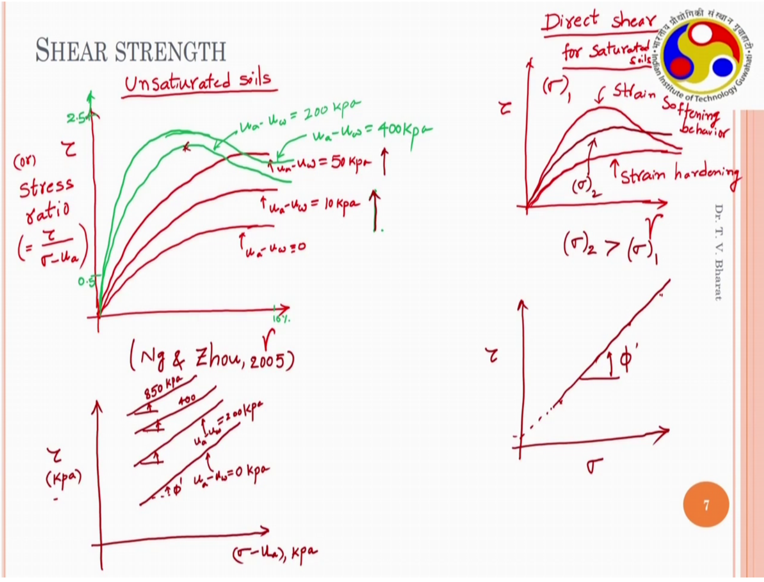

It is seen that many researchers when they have conducted tests on the suction controlled shear test. Especially suction controlled direct shear test setup, they observed that the strengthen soil varied in this particular manner. So, when they plotted so, generally in our direct shear test, we obtain shear stress versus shear strain we written in terms of written has gamma. And, the stress versus strain relationships for NC soils look somewhat like this and, for the OC soils it appear somewhat like this. And, this is called strain hardening behaviour and this is strain softening behaviour, because after this the shear stress decreases so, it is called as strain softening behaviour.

So, now what kind of results you get this is a normal direction for saturated soils and this is from unsaturated soils. So, here you can plot either tau here are the test is for one particular sigma normal stress. So, here when you plot tau versus gamma are often this is plotted as stress ratio also. The stress ratio is defined as tau by the normal stress. Here this is the net normal stress sigma minus ua because this test is conducted under one particular net normal stress.

So, when you control the particular one net normal stress you get tau versus gamma, where is shear stress versus shear strain, you can also keep changing these values. So, that you will get a stress ratio versus this one it is observed that for nearly saturated soils this is the behaviour of our NC soil. So, this is for suction ua minus uw is equals to 0 so, this is for saturated soils.

So, as you increase the suction it is observed that it increases in this particular manner. So, this is another particular suction ua minus uw is equals to 10 kilo Pascal. And, similarly when you increase 50 kilo Pascal, interestingly if you increase the suction value beyond this, it is observed that it behaves in this particular manner.

So, let me redraw this with different colour with different marker colour. So, this is the behaviour at ua minus uw is equals to say 200 kilo Pascal. And, this is increase further this is how it changes? And, the peak stress the ultimate stress increases. So, this is interesting trend you get when the suction control shear tests are conducted on unsaturated soils, when the stress ratio kept on increasing. So, this could vary in the range of say 0.5 this one and this can go up to say 2.5 also stress ratio value and this can be around say 10 percent strain.

So, interesting trend is that as the suction increases the shear stress and ultimate shear stress increases. And, this exactly behaves like strain hardening behaviour, but beyond certain suction value say more than 50 kilo Pascal. It exhibited strain softening behaviour it has a peak which has a peak behaviour peak stress and after that it reached to the ultimate.

So, this ultimate stress now again keeps increasing with increase in the matric suction. This is a trend this is shown by researcher’s N g and Zhou into 2005 using modified direct shear test. And, further if you generally you know these tests are conducted between tau and gamma, that is shear stress and shear strain and different normal stresses. So, this is at one particular normal stress and when you conduct with different normal stress. So, this is with sigma 2 where sigma 2 this is not principal stress by the way this is one particular stress one particular normal stress and this value is more than sigma 1.

So, then as the normal stress increases the ultimate shear stress increases. So, in this particular case under the given normal stress as the matric suction increases the shear stress increases ultimate shear stress increases. Then, generally what will do is we in direct shear stress for saturated soils we plot tau versus sigma. So, under different normal stresses when you conduct the test you get different ultimate shear stress values, then when you plot. So, you get trend like this.

So, this is angle of internal suction phi, if you have intercept then you get a cohesion term. But, if it is a pure sand then you will not have cohesion intercept and you will have only angle of internal suction value. So, what kind of a trend we get in this particular case.

So, here when you plot tau on y axis and you plot net normal stress that is sigma minus ua on x axis, then for s equal to 0 you get the same trend. So, the angle is phi dash so, this is for s equals to 0 kilo Pascal. As s increases you see that the critical shear plain critical straight line also increases. So, this is s equal to say 200 kilo Pascal and this is for 400 and this is for 850 kilo Pascal this s is nothing, but ua minus uw sorry, this is this is matric suction ua minus uw.

So, this is the trend you get and the angle nearly remind same, angle does not significantly change, the angle of internal suction value appear to be nearly constant. Does not significantly change for different matric suction values that relationship between tau versus sigma minus ua. So, the relationship between shear stress versus net normal stress for different matric suction values the angle of internal suction value is nearly same. So, this is another observation and often we plot the dilatancy effect.

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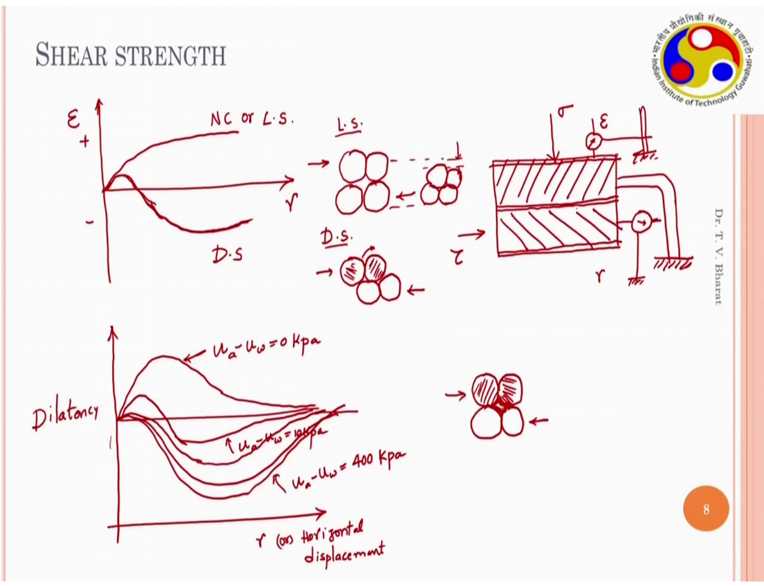

So, in our shear stress test direct shear test we have 2 halves. So, this is soil and this is soil again and you have say porous plate etcetera the top and bottom. And this is connected to rigid base then when you apply load. So, this will be reaction and this starts moving and you connect to a dial gauge. And, you can note down what is the strain this is the shear stress that is applied and shear strain can be determined from this gauge. And, also apart from this there is a one normal stress applied, that is sigma applied and there is one another dial gauge is kept for recording the strain in vertical direction.

So, here you get shear strain and here you get vertical strains. So, when you have this kind of a setup often we measure the dilatancy effect by plotting with shear strain, what is the normal strain we get or the vertical displacement you get, that can be observed and of positive is compression and negative is dilation are swell or increase in the volume. So, when the volume decreases that is positive and when volume increases that is dilatancy negative. And, we often observe that the NC soils behaves in this manner and OC soils are densely compacted soil exhibit this kind of behaviour.

So, this is for N C or normally consolidated clay or the loosely compacted sand and this is a densely compacted sand so, this soils exhibit dilation behaviour. We have also seen this is because when the particles are in loosest possible state then assume this particular configuration and when you shear.

So, during shearing operation they eventually rolled down to denser packing. So, because of which the volume decreases. So, because of this denser packing, they exhibit strain hardening behaviour. And, as well as there is a volume decrease, that takes place during measuring, this is with loosely compacted sands. In case of densely compacted sands initially soil itself in a denser packing.

So, this will be configuration and then when you shear the soil particles have to roll up all the way up on this particles. So, this is one particle and this is another particle so, this particle has to roll up and to the other particle. And, because of which the stress increases and it reaches peak value and after that the stress drops. And, strain softening is exhibited because of this particular behaviour. And, because of this the volume of the sample increases initially you know initially small settlement that takes place after that the dilation are increase in the volume that takes place when the soil (Refer Time: 17:08). So, this is observed in saturated soils.

Now, if a test similar test conducted in unsaturated soils in the suction control test, then the behaviour is shown here. So, the dilatancy is plotted on y axis and on x axis either normal strain or sorry shear strain gamma or horizontal displacement is plotted is plotted on x axis. So, the dilatancy is represented so, here there is an interesting behaviour for s equals to 0 the suction is 0 ua minus uw is equals to 0, it exhibited this behaviour.

And, when suction is slightly increase this is ua minus uw is equals to 0 kilo Pascal. And, the suction is slightly increased, this is the trend that exhibited this is 10 kilo Pascal. And, interestingly if you keep on increasing the dilation increases so, this is the behaviour it show.

So, this is may be at suction value ua minus uw is equals to say 400 kilo Pascal. So, as I mentioned in the previous slide also that as suction increases the soil exhibits strain softening behaviour. So, which is similar to because of that the volume of the sample increases as shear strain increases so, as horizontal displacement increases the vertical displacement observed on the thing is dilatancy dilation is observed in the soils.

So, here also even though sample whatever the condition initial it is initially, when the soil is in a looser state or something it exhibited similar behaviour, but when it has some suction that some water is presented in the soil something like this. And here when you when we are shearing so, the particles have to overcome the tensile stresses are tension within the force. And, it has to overcome that because of which initially it shows increase in the shear stresses.

So, it reaches a peak value and once this surface tension bonds are broken, then it exhibits a strain softening behaviour therefore, overcome the surface tension forces in the soil force. So, it exhibits dilation behaviour similar to a densely packed soils so, this is a very interesting behaviour that we understand from such stress.So, now, the question is how to analyse such data, to interpret the results in the field.

So, the laboratory test help us in establishing constitutive relationships such as stress versus strain behaviour. And, once this behaviour is very well known, then we can utilise these relationships directly to understand how the failure takes place within the soil in the field directly.

So, here we need to establish the unknown parameters, apart from cohesion. And, angle of internal friction these two are material constants and another parameter that is available that is known as effective stress parameter. If, these parameters are determined in the laboratory for a given soil under different stress state conditions, then the behaviour of the soil in the field can be predicted very well.

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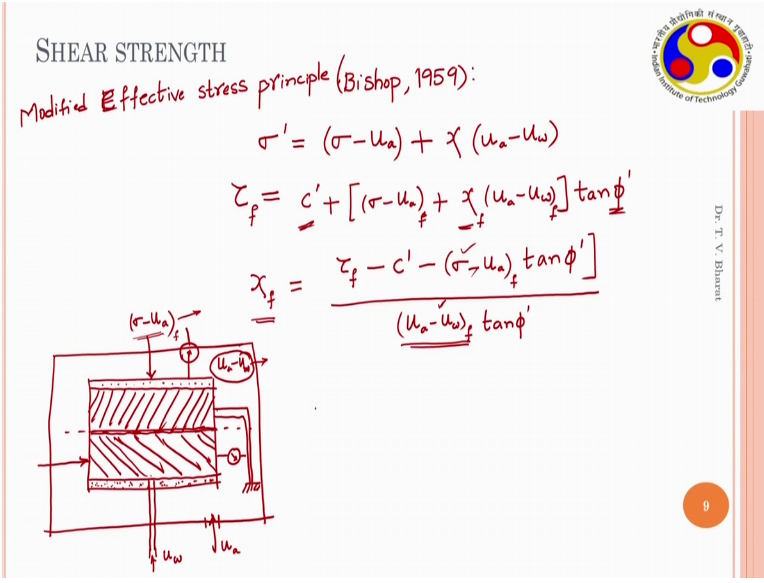

So, earlier have shown that the Bishop has given effective stress principal;, modified effective stress principle for soils, unsaturated soils, which can be written as the effective stress principle given by Bishop. So, this is modified for unsaturated soils given by Bishop in 1959, which is sigma dash is equal to sigma minus ua plus xi ua minus uw.

And, when you substitute in the more column equation are simply the column principle, the modified theory is tau f at failure is equal to tau equals to C dash plus sigma minus ua plus xi ua minus uw into tan phi. Here the interesting thing is that the determination of xi is very complex, but at failure the xi can be determined for non-value of stress state.

So, at failure, if we know these trusted variables, we can determine the C dash phi dash and xi f. So, therefore, that is the possible then xi f can be written as tau f minus C dash minus sigma minus ua phi tan phi dash divided by ua minus uw f tan phi dash sSo, by knowing the strength shear at failure. So, the xi f can be obtained and for different values of matrix suction can be obtained, because xi f depends on either volumetric water content or matrix section. So, xi f function in terms of matrix action or theta can be determined from experimental measurements.

So, let us see how the experiments are conducted. So, from this particular data it is evident that, when we control the sigma minus ua independently and ua minus uw see when we control the sigma minus ua and ua minus uw independently. And, when the soil fails at that particular state if these two parameters are known these two stress state variables are known. So, then by conducting series of tests by varying these trusted variables we can obtain xi f value.

So, let us see how we do it? So, the modified direct shear or suction controlled sheared box text, which is similar to the normal shear direct shear operators, where you have two halves, where the soil is available and you have a porous (Refer Time: 26:10) at the top and bottom. Here soil is available and here also soil will be available.

So, this is a shear plane along which the shearing takes place when load is applied and, this is a course for a stone and this is higher inter disk. And, here this whole thing kept in a airtight chamber and shear stress are applied and this one box is confined. So, therefore, the other box can be sheared and similarly you have dial gauges kept on bottom and top and there is a provision to apply sigma minus ua net normal stress.

And, here the air can be control inside so, air pressure can be controlled and this is connected to water chamber. So, u w can be controlled through this and u a can be controlled through this. So, uw can be kept at atmospheric pressure ua can be controlled to any values so, that ua minus uw inside the soil can be controlled.

And under this suction control environment the shear test are conducted by varying the normal stress are the net normal stress and ua minus uw within the soil mass. Set failure when the soil fails this ua minus u w at failure is know and sigma minus u at failure is also known. By knowing these two things we can obtain the xi f parameter let us see how I estimate.

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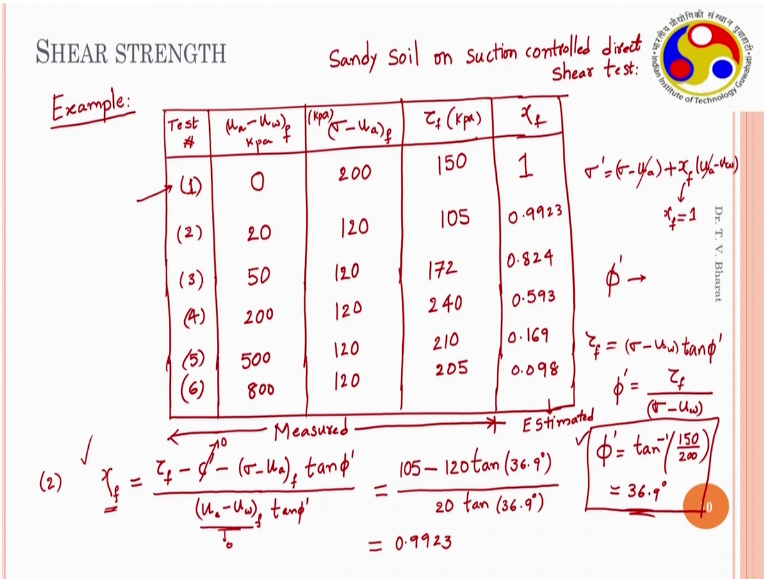

Let us solve simple example so, here the data of some synthetic data is generated for understanding how we estimate the xi f parameter these are at failure and this is also in kilo Pascal. So, 1st set of test is a test number so, 1st test is conducted by maintaining a suction value of 0. So, this is a data of sandy soil on suction control direct shear. So, when u a minus u w is controlled to 0; that means, fully saturated soil, this is typically your normal direct shear test, but here you have a dryness control.

So, therefore, so pore water pressure can be better control. So, the sigma minus ua is kept 200 kilo Pascal so, then when the sigma minus ua is kept 200 kilo Pascal, then the tau f the shear stress at failure is observed to be 150 kilo Pascal so, this the 1st test. And, when you conduct 2nd test by maintaining a suction value of 20 kilo Pascal and sigma minus ua is maintained to be 120 kilo Pascal and tau f is observed to be 105. So, the 1st test is saturated test, because in our Bishops expression and ua minus uw is equal to 0, it boils down to (Refer Time: 31:01) expression, then again this is a sandy soil.

So, dash is not present. So, only phi dash is present and phi dash can be now determined using the 1st test. And, subsequent tests would help in understanding how xi f changes with change in the suction value, knowing the phi dash which is nearly constant that is observation I had shown in the beginning that the phi dash nearly is constant.

So, the increase in tau dash with increase in ua minus uw and the changes in tau verses sigma minus ua for different suction values is similar and in fact, their the critical state lines are parallel to each other. So, therefore, phi dash could be nearly same so, therefore, we are issuing that phi dash remain same and then therefore, when suction is increased how xi f changes can be obtained.

So, therefore, the tester also controlled tester also conducted in the same manner. One test is conducted saturated and other tester conducted at unsaturated conditions. And, 50 kilo Pascal and similarly 200 500 and 800, nearly 6 test are conducted; 6 test are conducted under 50 kilo this is kept constant after first test.

So, because suction values varied the tau f started increasing, 172 240 and slightly decrease here onwards 210 205. So, now, this is a measure data from suction control tests and this is this need to be estimated this one. The xi f value for the first test, because it is the saturated soil the sigma dash equals to Bishop's effective suspenseful sigma minus ua plus xi f ua minus uw in this if xi f becomes 0, this is completely dry test dry soil and xi f equals to 1; that means, these to get cancelled and this is sigma minus uw this is effective suspenseful for completely saturated soils.

So, therefore, xi f needs to be 1 and this particular condition ua minus uw is equal to 0 should not be substituted in the previous equation. Previous equation is xi f is equals to tau f minus C dash minus sigma minus ua f tan phi dash by ua minus uw failure tan phi dash. So, here if you substitute ua minus uw is equal to 0, then xi f becomes infinity it does not have any meaning. So, here we know that this effective suspenseful itself is that sigma minus uw so, if you substitute directly and anyways xi f should be 1.

So, we do not need to substitute here there is no ua minus uw that is it. So, xi f maximum value that can take is 1 so, maximum value is 1 xi f infinity means in fact, the maximum value maximum value is 1, that also can be (Refer Time: 35:25), but the xi f value should not be obtained from this equation by substituting ua minus uw is equals to 0.

Otherwise, if you interpret that the maximum value of xi f is 1. Therefore, xi f is equal to infinity means xi f is equals to 1. So, other values can be obtained by first by obtaining the phi dash value, this is the material constant see if the phi dash is obtained then other values of xi f with ua minus uw can be obtain.

So, from the first equation itself, you can estimate that, tau f is equals to sigma minus uw. So, the effective stress this the applied stress is nothing, but effective stress at the particular point. So, therefore, phi dash is equals to tau f by sigma minus uw the applied stress sigma minus ua is nothing, but sigma minus uw know because of total stress, becomes a effective stress when the pore water pressure completely dispute. So, therefore, phi dash is equals to tan inverse of 150 by 200 so, this is equals to 36.9 degrees.

So, if this quantity is known this is the material constant, which this value is known, then other values can be obtained by varying the ua minus uw that is it. So, for one particular data that is a 2nd test. This is tau f is 105 minus C dash is not there. So, this is a sand and sigma minus ua is 120 tan 36.9 degrees divided by ua minus uw is 2 at failure tan 36.9 degrees so, this is equals to 0.9923.

So, this xi f value is 0.9923, when the ua minus uw is equal to 20. And, this value is 0.824 for ua minus uw is equal to 50 and 200, this value is 0.593 and at 500 this value is 0.169 at 800 this value is 0.098. So, this is how the xi f can be obtained from the modify direct shear test operate test data.

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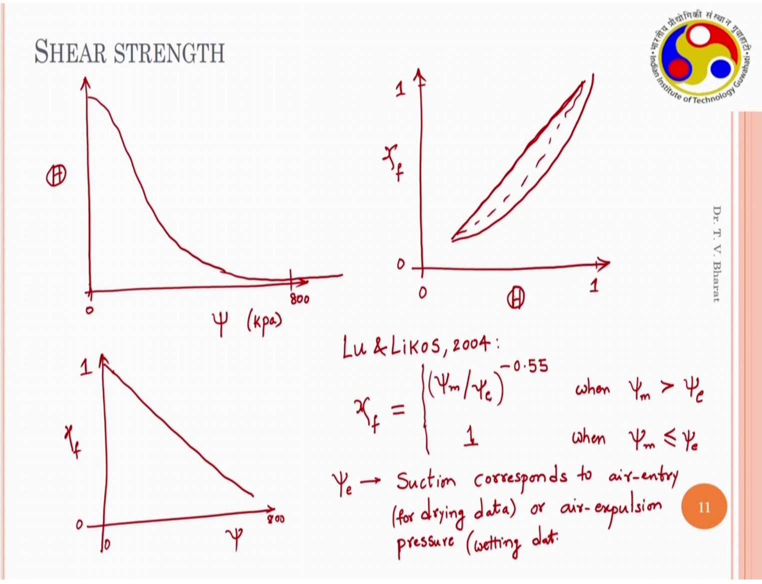

Let us see how this these values could vary? So, this is the variation of sw cc this is normalized volumetric water content verses suction in kilo Pascal tell the trend is like this so, if it is plotted on a normal scale. So, then a the variation of xi f is the normalised volumetric water content say varies from 0 to 1 and xi f varies from 0 to 1. So, variation is linear it could be linear like this. So, there is a problem with a pen so, this does not appeared to be linear, but this is linear right. So, so there is a this is how the xi f varies with volumetric water content. If, it is with suction as a suction increases xi f becomes smaller and smaller unit goes to 0 0 to so, say 800 kilo Pascal or something and this is 0 to 1.

When the suction is 0 this value is equals to 1 and when suction is very high this value goes to 0. And, the experimental observation shows that, this need not be linear also. On some cases it may be non-linear and it could be varying like this or it could be varying like this etcetera. So, there are several empirical equations proposed to estimate xi f value.

So, one such a empirical equation is which are given in Lu and Likos his implification are derived by several people like Khalili etcetera. One of such empirical relationship is xi f is equals to psi m by psi e power minus 0.55, when ua minus u w are psi m is the matric suction value is more than psi e. And this is equals to 1 when psi m is less than or equals to psi e so, what it psi e? Psi e is a suction corresponds to air entry for drawing data or air expression pressure, for pressure for wetting data so, what does it mean?

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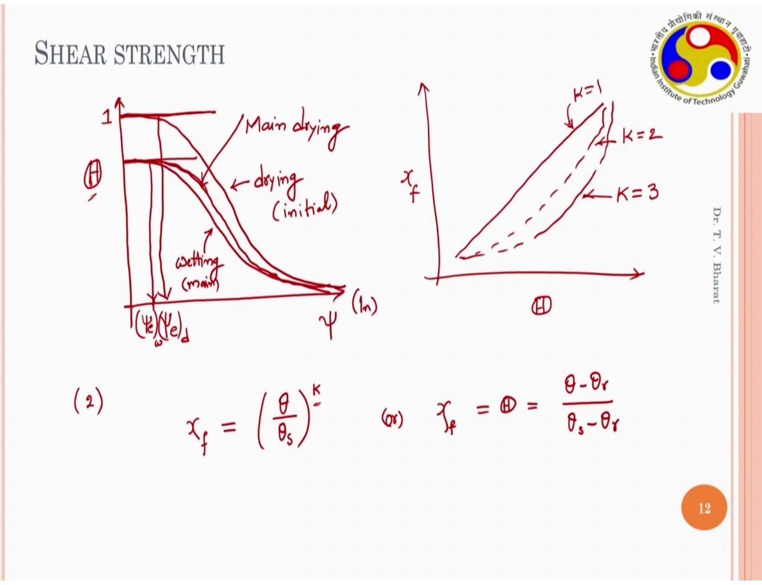

When, if you have a soil characteristic curve data, if you plot on semi log x axis log scale, then you will have a relationship somewhat like this. So, this is for drawing data so, this is for wetting.

So, this particular point, wherever this deviates from 1, that is a air entry value this is psi e air entry and here this particular point is psi e 2 so, this is for drawing this is for wetting. So, because we have seen that there is histories exist for soil water characteristic curve, the drawing data exhibits different trend compared to the wetting data. The generally this is initial drawing and this is main wetting, but if you do main drawing data, then it shows a very good histories data like this.

So, this point and this point again merges this is main drawing. So, essentially initially when normalised volumetric water content data is 1, then psi value is 1 and if the data the normalised volumetric water content theta value is less than 1, big theta is less than 1, then xi f value takes this particular form.

So, corresponding matric suction will be substituted and this is a bubbling pressure, in case of drying soil and this is air exposition pressure for the wetting soil, when you substitute power minus 0.55 should give u xi f. This is empirical relationship based on several observed measurements from the suction control test.

Similarly, you have another relationship that is available, that is very simple second empirical relationship that is a xi f is equals to theta by theta s power k, or simply xi f is equal to normalized volumetric water content, that is theta minus theta r, by theta s minus theta r. Here theta by theta s power k, when the k values change the nonlinearity between volumetric water content and xi f value change so, for example, I will plotted here.

So, this is xi f and this is theta big theta. For k equal to 1 this exhibits a linear relationship for other k values for example, k equals to 2 it exhibits this behaviour, for k equals to 3 non-linearity increases, this is how it varies? So, however, anyways we have very limited data from the suction control shear test, because there are several limitations associated with this test one major limitation is that the maximum suction range, would be in the range of 15 kilo 100 Pascal.

If you are using, if you are controlling the suction the shear test by utilising access translation technique or it would be around 2000 1000 to 2000 kilo Pascal. If we are controlling the suction by controlling the suction osmotically, in osmotic control test also the semipermeable membrane would start degrading after nearly 10 days this is research outcome by some researchers.

So, because of these limitations the equilibration time requires for the soil to establish for the soil to come to one particular suction value takes time. So, within this equilibration time if the semipermeable membrane degrades, then it allows the peg solution to go into the soil. So, because of the such situation the there is a limitation on the available data, especially for fine grain soils most of the data is available is for either sands or silt soils.

And, that to the measured shear test data in a small range of suction values. At very large range of metric suction values only recently this is attempted by controlling the suction within the shear test by (Refer Time: 48:13) vaporic equilibrium techniques. And, combining all these data's and considering the initial compaction etcetera, the test would be more complex and the analysis is very tough.

So, these are the major some of the major limitations we have with tests data. Apart from that as a matrix suction value increases within the soil mass the shear strength increases, but, this does not increase linearly or this cannot be direct proportional proportionality to suction value. There is because we have seen in our basic soil mechanics that the strength behaviour of sands in completely saturated state and completely dry state is same.

So, the factor of safety for infinite slope behaviour of sands, when the soil is completely saturated or when the soil is completely dry the factor of safety remain same, because the angle of internal friction is phi dash only. But however, due to the presence of small water film within the soil mass there is surface that is available which increases the strength of the soil. So, this increase in the strength that is with the increase in the matrix suction the increase in the strength of the soil is not proportional directly proportional for the entire range of metric suction values.

So, even though matrix as a matrix suction increases initially the shear strength of the soil increases, but beyond certain suction values the shear strength should drop and it comes to again back to the same value as it has initially at fully dry state. So, such concepts could be developed if more and more experimental data are available. So, based on the measurements we can build the effect we can develop models we can develop better constitutive models for understanding the behaviour of unsaturated soils.

Thank you.