Underground Space Technology
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Module No # 01
Lecture No # 03
Basics of Rock Engineering: Tensile Strength and Shear Strength of Intact Rock

Hello everyone, in the previous class, we discussed about some of the basics pertaining to rock engineering. And we discussed about unconfined compressive strength tests. I told you that how we can conduct the test, how we can find out the UCS, and how we can find out the modulus of the intact rock using the results of UCS. So today, we will continue this series of the discussion on basics of rock engineering, and we will discuss about the tensile strength and shear strength of intact rock.

So, to start with, we will first focus on the tensile strength of the rocks. Basically, this tensile strength of rocks can be obtained by 2 types of methods; one is the direct method, and the second is the indirect method. In direct methods, the specimens are made in such a manner that ends of the specimens they are held together, and then they are subjected to the tensile forces. The failure takes place in that mode only, and whatever is the strength that we obtained that directly gives us the tensile strength of rocks.

But the problem with direct methods is that you need to make special specimen of some special type of shapes which may not be that easy to make because of the reason that if you have to grip the specimen and subject it to the tensile force. Then when; you griping the specimen there, the shape of the specimen should be very typical. So that there are no stress concentration and the specimen will fail under tensile stresses only.

So, such things do not make direct methods very helpful as far as determinations of tensile strength of rocks are concerned. So, there come the indirect methods in which we apply the compressive force to the specimen, but then we obtain the tensile strength.

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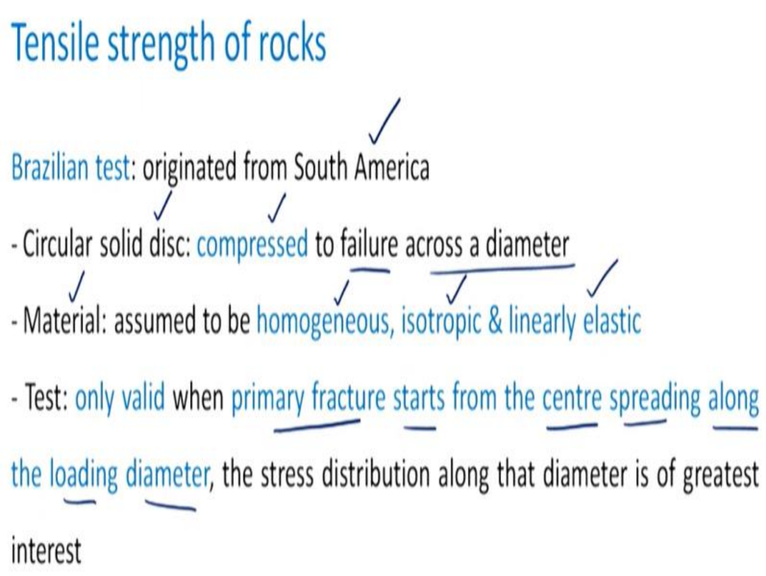

So, one such test is the Brazilian test which originated from South America, and this is the most commonly adopted test to obtain tensile strength of intact rocks. So that is what that we are going to discuss now. So, as I mentioned that this Brazilian test that it originated from South America. In this, you have a circular solid disk which is compressed to failure across the diameter.

So, that means that you have a circular solid disk which you will subject to the compressive loads rather than the tensile load. The material, in this case, is assumed to be homogenous, isotropic and linearly elastic there are some limitations with respect to this test which is mentioned here that this test is only valid when primary fracture starts from the center spreading along the loading diameter. So, that stress distribution along that diameter becomes of the greatest interest.

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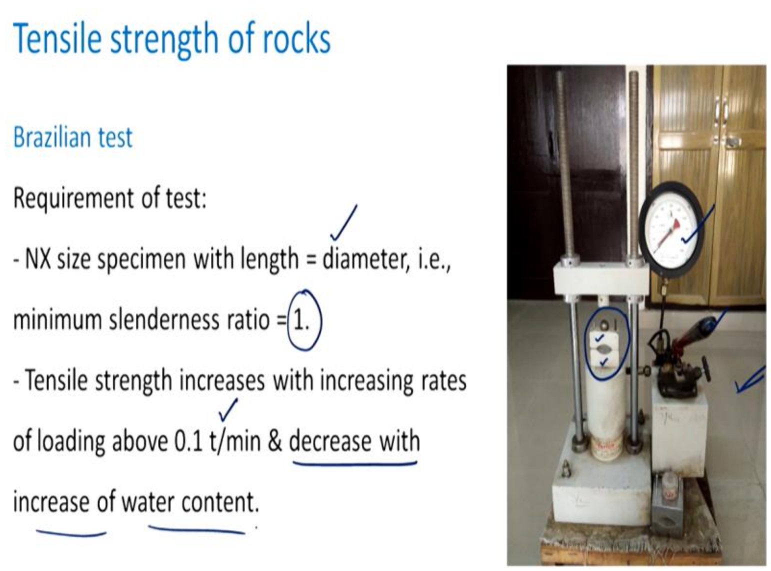

Take a look here; this is a picture which shows the apparatus for the conduct of Brazilian test. You can see that there is a grip here to blocks are there. So, the specimen is held between these 2 grips, and then with the help of this lever, you have a jack here; with the help of this, you apply the compressive load to this assembly. Which can be measured in this pressure gauge, and that directly gives you the tensile strength of the rock.

So, we have the expression, and there you just have to make some simple substitution, you will be able to obtain the tensile strength. Now before I take you to those expressions, first let us understand that what are the various requirement of the test. So preferably, we go for NX size specimen with length to diameter ratio to be equal to 1; that is, the minimum slenderness ratio that we take is 1.

Then the tensile strength of increases with the increasing rate of loading above 0.1 tonne per minute, and it reduces with the increase of the water content. So, in case it is sample is saturated. Obviously, it is tensile strength is going to be less as compared to the dry sample of the same rock.

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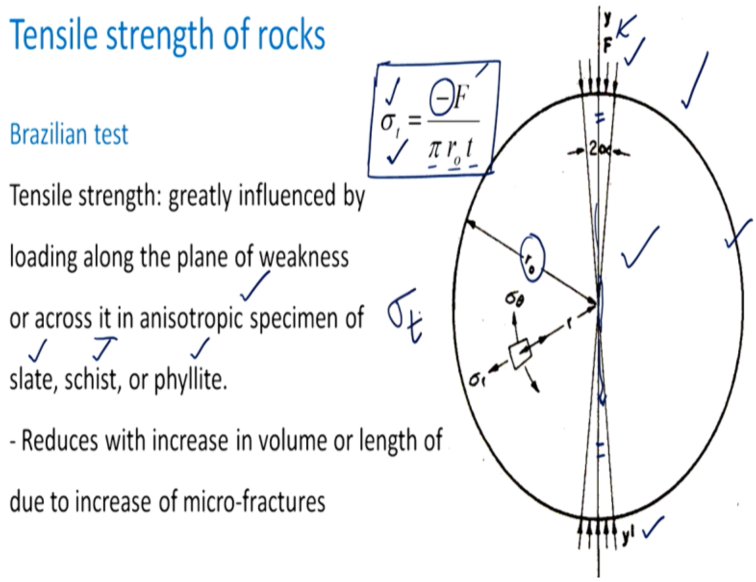

So, as I mentioned, this picture clearly shows how the loading will be applied, so along this diameter, the loading is applied, and see it is compressive in nature. And it is assumed that the crack will start from the center and it propagates towards the circumference or towards the end of this disc. So, tensile strength is found to be greatly influenced by the loading along the plane of weakness or across it in case you have the anisotropic specimen of rocks such as slate, schists, or phyllites.

Now, if you increase the volume or the length of the specimen, that tensile strength reduces; why so? Because when you have larger volume of the specimen, there are going to be more number of micro-fractures or micro-cracks present in that specimen, and that will result in the reduction of the tensile strength of the intact rock. So, I mentioned to you that we need to use an expression to determine the tensile strength of the rock.

So, this is the load F at which there is going to be the failure of this specimen, so that load divided by $\pi r_0 \times t$. That will directly give you the tensile strength of the intact rock where this r_0 be the radius of the solid disc and t be its thickness that is the dimension in the plane perpendicular to the plane of the screen. So why; there is this negative sign because we are representing compressive strength as positive and tensile strength as negative.

That is why we have kept a negative sign here while representing the expression for tensile strength. This tensile strength is represented by σ_t, so here is the picture where the sample is subjected to Brazilian test.

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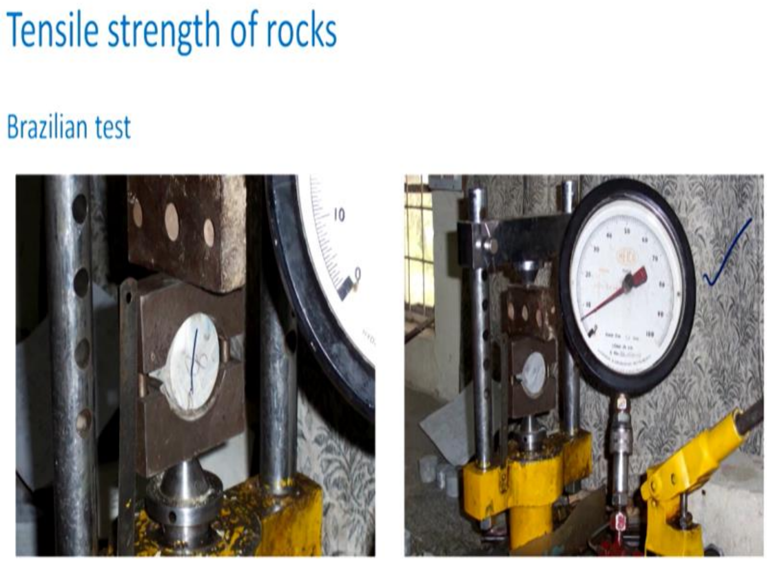

So, you can take a look that how the specimen is held between these 2 grips. This is the broader look, and this is the closer look of the specimen, and you can see that how the cracks are developed along this diameter. Now in the absence of any measurement that is let us say we are not able to conduct the Brazilian test or any test for that matter to determine the tensile strength of rocks.

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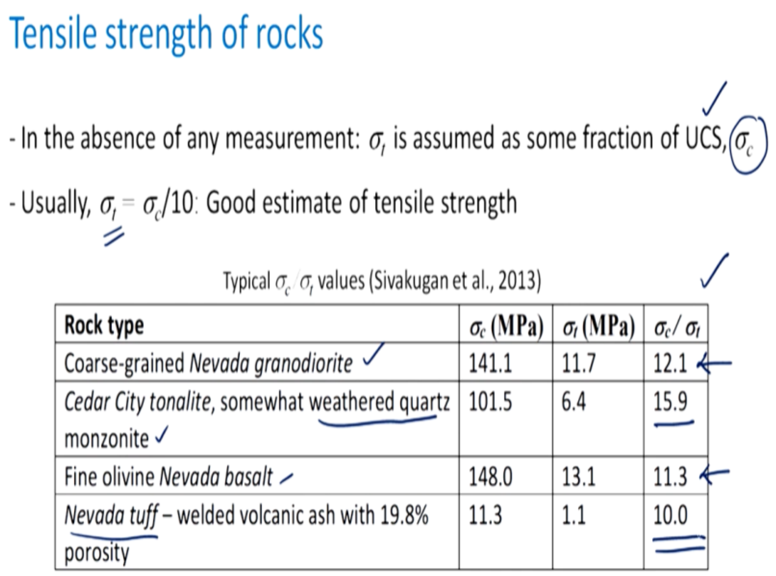

Rock type	σ_c (MPa)	σ_t (MPa)	σ_c/σ_t
Coarse-grained *Nevada granodiorite*	141.1	11.7	12.1
Cedar City tonalite, somewhat weathered quartz monzonite	101.5	6.4	15.9
Fine olivine *Nevada basalt*	148.0	13.1	11.3
Nevada tuff – welded volcanic ash with 19.8% porosity	11.3	1.1	10.0

Then this tensile strength is assumed as some fraction of UCS that is unconfined compressive strength which is represented by σ_c. So usually, this tensile strength is taking to be one-tenth of the UCS value. So, this more or less gives you the good estimate of the tensile strength, so some typical values of the ratio of compressive strength to tensile strength has been given in this particular table.

So here you have this coarse-grained Nevada granodiorite; for that, this σ_c/σ_t works out to be 12.1. In case of the somewhat weathered quartz monzonite, you have 15.9 and for a particular type of basalt worked to be 11.3, and for Nevada tuff, it is exactly 10. So basically, to the tune of 10 to 15, you will get a very good estimate of the ratio of UCS to the tensile strength of rock.

Now coming to the shear test, so there are basically 2 types of shear test, or I should say 2 categories of a shear test. In one type of test were the shear strength is determined without the specimen being subjected to the compression. So only the shear force is applied without the application of any compressive force on that shear plane. Second category belongs to the methods for determination of shear strength with compression.

Right now, we are going to discuss this second category because these are the most commonly adopted shear test to obtain the shear strength parameters of intact rocks.

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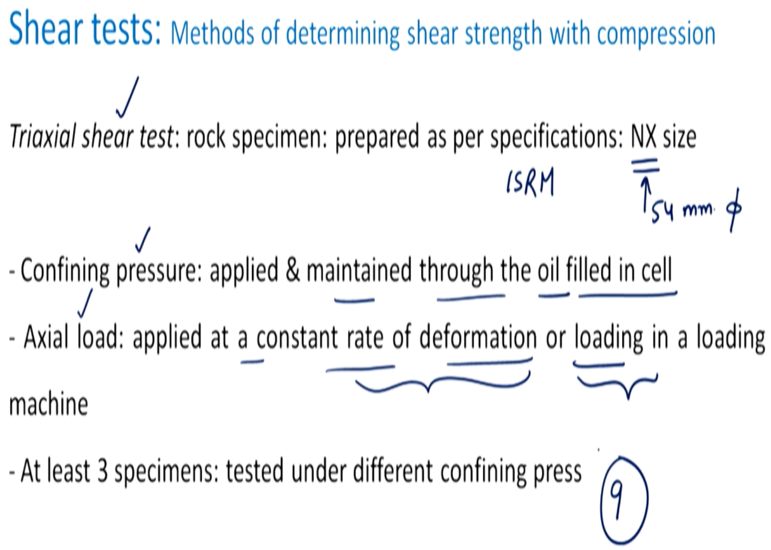

So, the first step test here is the tri-axial shear test in which we prepare the rocks specimen as per ISRM specifications. This we discussed in earlier class, and NX size is preferred, so when I say NX size, this means it is 54 mm diameter. Then the confining pressure is applied and is maintained through the oil, which is filled in the tri-axial cell. Now, if you compare this tri-axial shear test for rocks to that of the soil.

In case of the soil, this confining pressure is applied and maintained through the water. See, the shear strength of the rock is much larger as compare to that of the soil, and water will not be able to apply that much of the confining pressure, which is needed in case of the rock samples. That is the reason that we apply this confining pressure through the oil that is filled in the cell rather than water. Coming to the axial load, this is applied at a constant rate of deformation or loading in a loading machine.

So, when you have constant rate of deformation, you will have a particular, let us say, few mm per minute. And if you have the loading, then you have particular load per unit time. So, in this case, at least 3 specimens should be tested under different confining pressure. So, minimum of 3 specimens, but if you recall, we had the discussion in the previous call that when the rock is having more heterogeneity, then, in that case, we should have at least 3 specimens for each confining pressure, and minimum 3 confining pressures are needed.

So that ideally, one should have total of 9 tests to complete 1 tri-axial test. However, in case if you do not have that many sample, then at least 3 specimens, each at different confining pressure, should be tested to complete one tri-axial shear test and to obtain the shear strength parameters of the rock.

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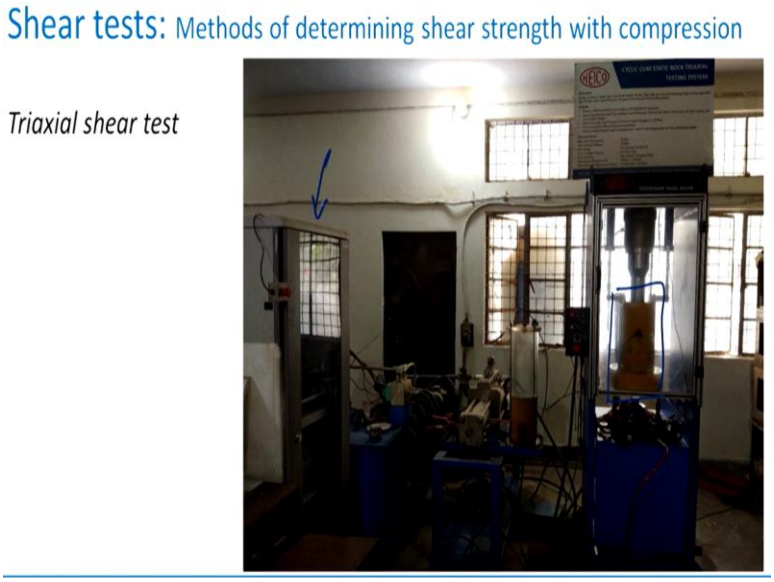

Now, this is the picture of the tri-axial shear test machine that we have in our lab. So, this portion you can see here the sample is mounted, and this is servo control machine, and the control is there it is, although it is not visible here. But then a system is kept in this enclosure where when you apply the load; it gives you the idea that corresponding to this load this is what is the deformation that is taking place or corresponding to this load.

This is what; is the deformation that is taking place or corresponding to this much of the deformation? This much is the stress that is being generated.

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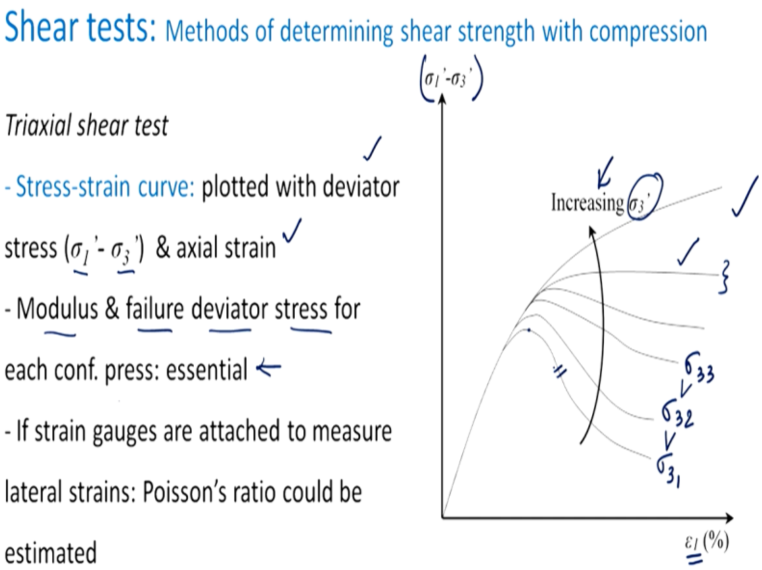

So ultimately, what we get after the conduct of axial shear test, we get stress-strain curve. So, these are plotted with deviated stress, that is, $\sigma_1' - \sigma_3'$ and the axial strain. So, you can see in this particular figure that on y-axis, we have this $\sigma_1' - \sigma_3'$, and on x-axis, we have this ε_1, which is representing the axial strain. Modulus and the failure deviator stress for each confining pressure is essential.

Now, if the strain gauges, they are attached to measure the lateral strains also, we can also estimate the Poisson's ratio from the tri-axial shear test. Now here, you will observe a very interesting phenomenon that is happening as we increase the value of σ_3; you see how the shape of stress-strain curve changes. When for the lower value of σ_3, so here in this direction, it is increasing, which is shown here in this figure.

So here, let us say this is σ_{31}, say this is σ_{32}, this is σ_{33}, and so on. So basically, this σ_{31} is smaller than σ_{32} that is smaller than σ_{33}, so what happens? When you conduct test at low confining pressure, you get the brittle kind of behavior as far as the stress-strain relationship is concerned. You see, it goes to the peak, and then the drop here in the stress is very sharp as compared to when you have increased the value of σ_3.

That is, you take a look here corresponding to this particular plot, and here it is, there is no drop. So practically, it has become like elastic-perfectly plastic kind of behavior. So basically, as we increase the value of σ_3, there is a transition in the material; that is, it is transitioning from the brittle to the ductile behavior. So, it is the same rock, but the value of confining pressure is making it behave as ductile or may be brittle at low confining pressures.

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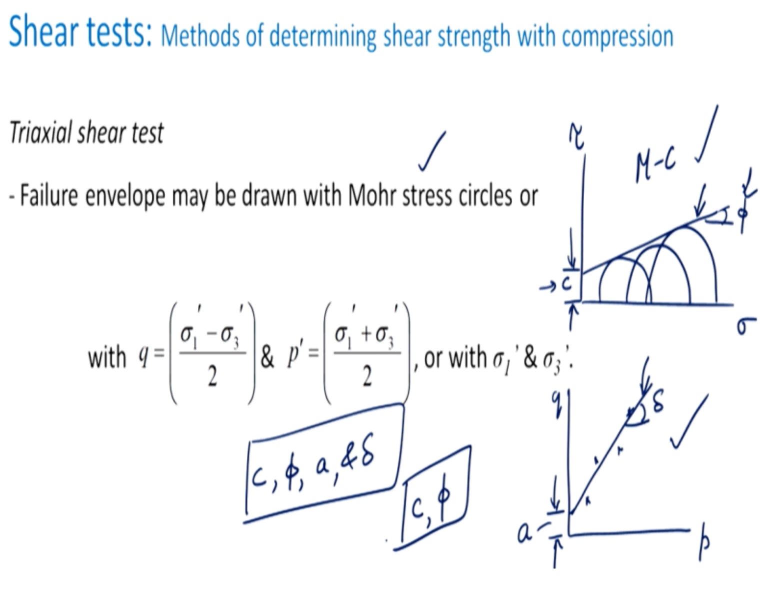

Now, as far as the stress-strain relationship was concerned that we saw but then how to determine the shear strength parameters. So, for that, you can develop the failure envelope using the Mohr stress circles because you know what is the shear strength and the principal stresses. So, you can have here that is this is τ and then σ. So, you can have this kind of you know Mohr circles, and then maybe you can draw the common envelope to it, and you can determine here it is this is going to be maybe c, and this is φ.

Now here we are making an assumption that this material is following the Mohr-Coulomb failure criterion, which may not be true. So, we will learn in brief that what all are the various failure criterion which are available for rocks and rock masses. But let us say I assume that it is following Mohr-Coulomb failure criterion, then using these Mohr stress circles, we can determine the value of c and φ.

Now similar thing can be determined using stress path method. How in case of the Mohr circle, the state of stress is represented by a circle. While in case of the stress path method, the state of stress is represented by a point. So here, what you need to do is you will plot p-q curve. So here, it is q, and here you have p; every state of stress will be represented by a point and then what you do is you try to fit a straight line to this, and there is the ordinate say here it is a and there is this slope δ.

Now, if you just try to compare the equation of Mohr-Coulomb failure envelope here and the equation here, you will establish a relationship between c, φ, a, and δ. So, either you can represent your test result in this form or, using the stress path method or p-q plot, you can determine this and find out the c and φ, which are the shear strength parameters for the rock.

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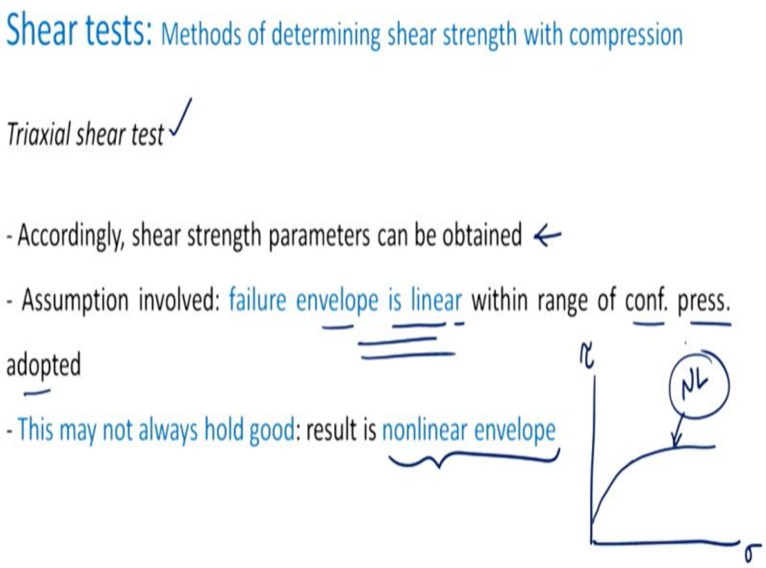

Now, as I mentioned that you can find out the shear strength parameters now; the assumption that is involved here is that the failure envelope is linear within the range of confining pressure that you adopt. But this may not always hold good, and the result, therefore, will be non-linear envelope. So, you see that as I mentioned that if you have here as τ and this as σ so in the beginning, you may have this kind of envelope which is not linear but non-linear.

So, assumption that we are involving in case of the triaxial shear test that is the failure envelope is linear in this case. So, you can go ahead with the non-linear one also, but then there are other failure criteria which are kind of modified more coulomb failure criteria which you must adopt to represent the failure criteria that the material is going to follow. So, we learnt about the determination of the tensile strength of the entire rock using an indirect method that is Brazilian test.

And then we also learnt about the determination of the shear strength parameters using tri-axial tests. So, we will continue this discussion in the next class. We will touch upon some of the other basics related to rock engineering. Thank you so much.