Traction Engineering
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Lecture 7
Measurement of Soil Strength, Cohesion and Angle of Internal Friction

Hello everyone. This is Professor H. Raheman from Agricultural and Food Engineering Department, IIT Kharagpur. I welcome you all to this lecture on Measurement of Soil Strength, Cohesion and Angle of Internal Friction.

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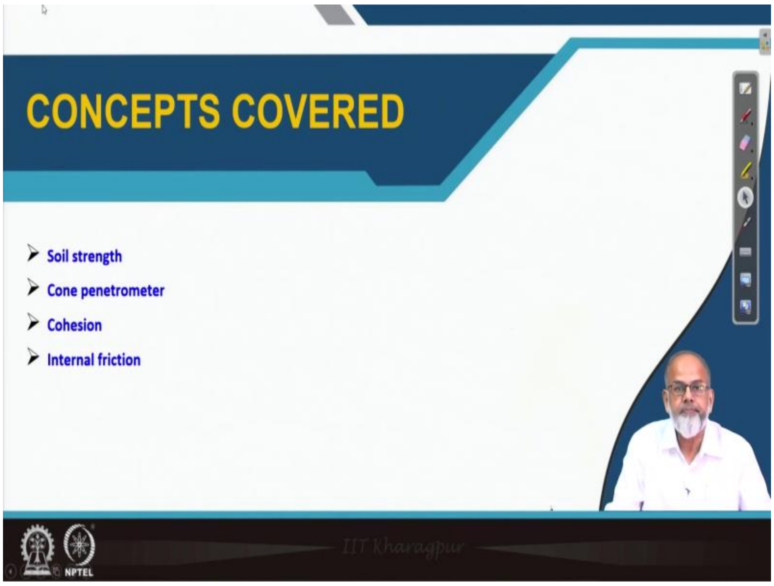

So, the concept which will be covered is what is soil strength, cone penetrometer, how it is related to soil strength and cohesion as well as angle of internal friction.

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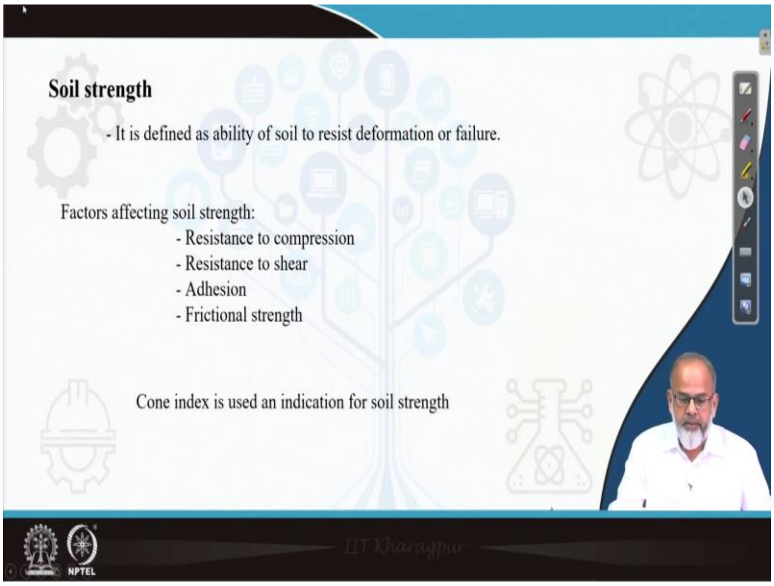

Now, we define soil strength as its ability to assist, to resist deformation or failure. How well it can withstand the external forces which are acting. It could be due to compression, due to shear, due to adhesion, due to frictional strength. So, cone index is used as an indication for measuring or indicating the soil strength.

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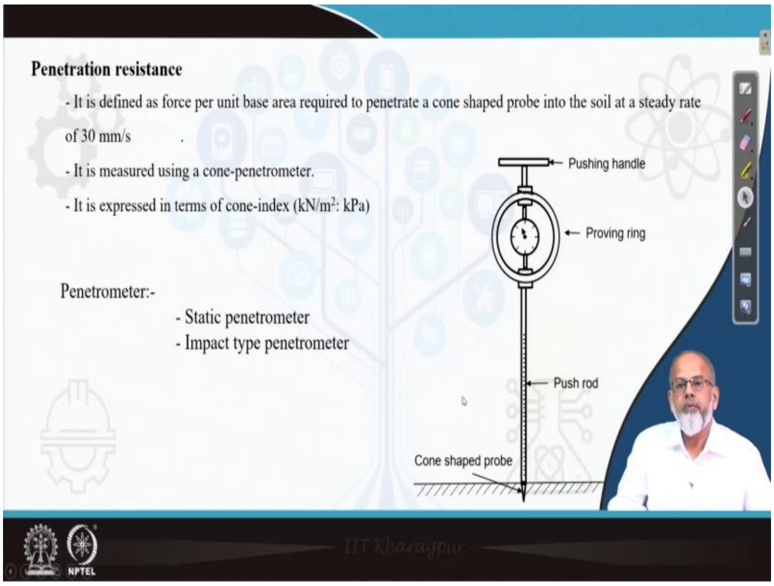

So, what is a cone-penetrometer? Basically, a cone shaped probe is forced into the soil and we define it as the force per unit base area, which is required to penetrate a cone shaped probe into the soil at a steady rate. The rate is around 30 millimeter per second. So, the strength that is the force per unit area that means, the force is expressed in kilo Newton and area is meter square that kilo Newton per meter square will be the unit of cone index.

Though it says cone index but it has a unit of pressure and this is measured with the help of a cone penetrometer. So, there are basically two types of cone penetrometer one is static cone penetrometer, the other one is impact type cone penetrometer. And whether it is static or impact type, the cone penetrometer will have a cone base at the bottom then there is a rod and there is a proving ring with a pushing handle or a stopcock.

So, in case of a static penetrometer, the one which is shown in this figure, this has to be forced into the soil either by human being or by handling pressure. So, that what is the resistance which is offered by the soil that will be recorded either manually with the help of this proving ring or it can directly put sensors that can record it for each unit of depth.

Maybe at an interval of one centimeter, even 0.5 centimeter is also possible. But usually a manual run static cone penetrometer, it has some graduations provided on the side and the rod. So, at an interval of one inches and the cone area is around, base area is around 3.23 square centimeter and the cone angle is 30 degree.

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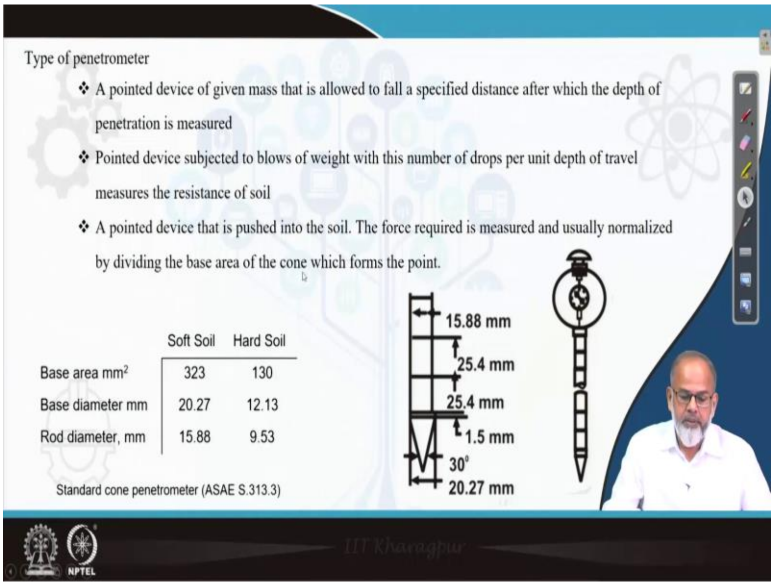

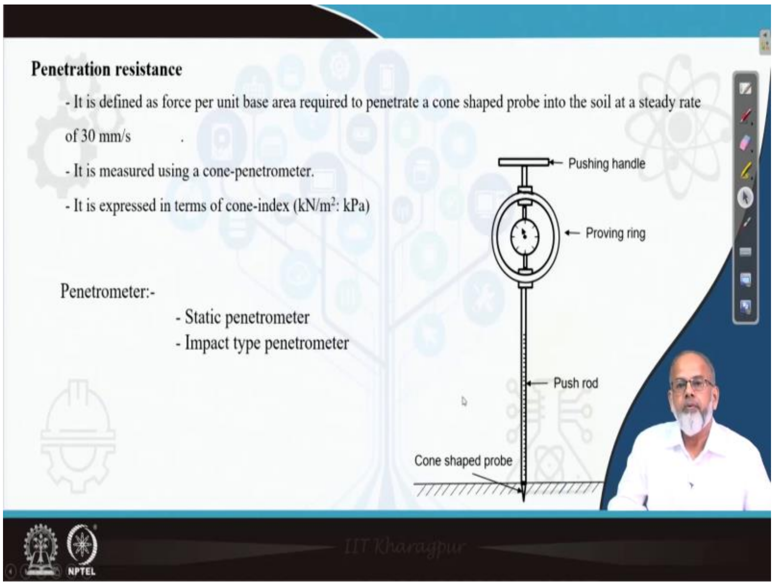

So, if it is a impact type penetrometer then a pointed device is with a certain mass that has to be dropped from a certain height and then you measure what is the corresponding depth of penetration. So, there are two types of impact type cone penetrometer, one is the pointed device is to be dropped from a certain height.

The other one is the pointed device is to be kept vertically in the soil then a mass of known weight which has to be dropped onto this and the number of drops required to cause an unit of penetration that is recorded. So, if it is a static penetrometer then there are certain standards which are given by American Society for Agriculture and Biological Engineers, what should be the best area, what should be the base diameter and the rod diameter.

So, if it is for soft soil, then the base area should be around 323 millimeter square and base diameter is around 20.27 millimeter and the rod diameter is 15.88 millimeter. If it is a hard soil, then the best area is 130 and millimeter square and best diameter is 12.13 millimeter and the rod diameter is 9.53 millimeter. These are the standards given by American Society of Agriculture and Biological Engineers.

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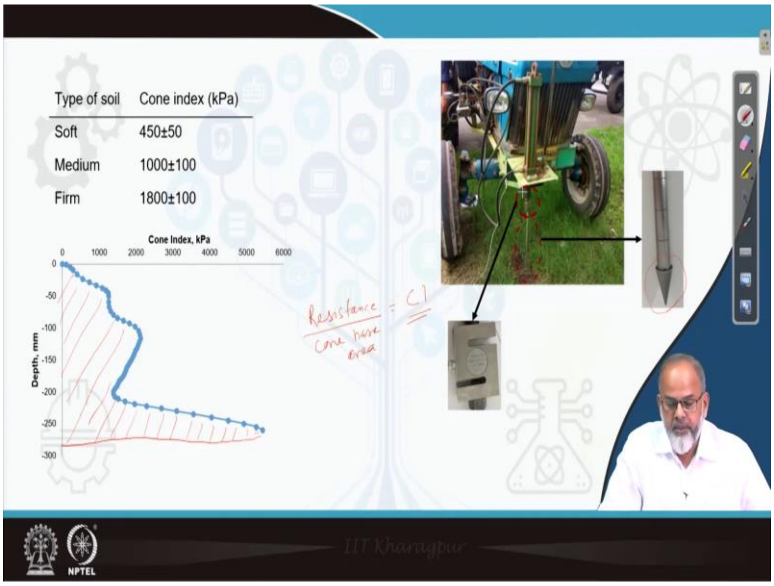

So, when it is pressed into the soil either manually or by a hydraulic power, which is shown in this figure on the right corner. So, we will get a plot like this that is the cone index, in fact, is the resistance which will be recorded then

$$CI = \frac{Resistance}{Cone\ base\ area\ (3.23\ cm^2)}$$

So, that is indicated as cone index. So, any plot cone index versus depth, so the nature of the curve and this is sample of the curve I have indicated. Then question arises, how to measure these resistance? We can put a load cell so, that you can directly take the output from the load cell then, once you calculate then the load cell has to be calibrated and after calibration, we can find out what is the corresponding cone index.

Now, this has to be pushed into the soil up to a depth of minimum 150 millimeter, nowadays it can go up to whatever depth we require up to that we can go So you will get a plot like this, if you get a plot like this, then how to find out the average cone index. So, average cone index will be the area bounded by this curve.

So, we draw a horizontal line, then what is the area, which is included. So, that can be calculated with the help of a graph sheet, then you can divide with depth. So, that will give you, what is the average cone index. So, based on cone index value, we classify soil into three types one is soft soil, medium soil and firm soil.

Soft soil is around 450 to plus or minus 50 kilo Pascal and medium soil is 1000 plus 100 kilo Pascal plus or minus then firm soil is 1800 kilo Pascal plus or minus 100 kilo Pascal. So, based on this cone index, we try to classify the soil when we use two types of penetrometer like static cone penetrometer or the impact type cone penetrometer, we use two different models for expressing the cone index.

One model is using the energy required to cause penetration which is nothing but the your impact type how much force mass is dropped to a certain height, so that will give you how much energy is required to cause penetration, but in case of a static cone penetrometer we measure force then we divide by area.

So, there are two basically two models which are used, one is using energy required to cause penetration or the other one is force required to cause penetration or force per unit area required to cause penetration. Cone penetrometer readings are affected by moisture content and it is affected by the bulk density.

So, you have to mention, what is the moisture content at which we carry out this test, then in addition if you want to find out the average cone index, in a plot, there you have to indicate, we have to measure the cone index value at different places, then you have to express the average with the standard deviation you have to mention and with the coefficient of variance.

So, on the right corner you can see how the cone shaped probe. This one, cone shaped probe, this is fixed onto a hydraulic cylinder, there is a double acting hydraulic cylinder and the hydraulic power is taken from the tractor.

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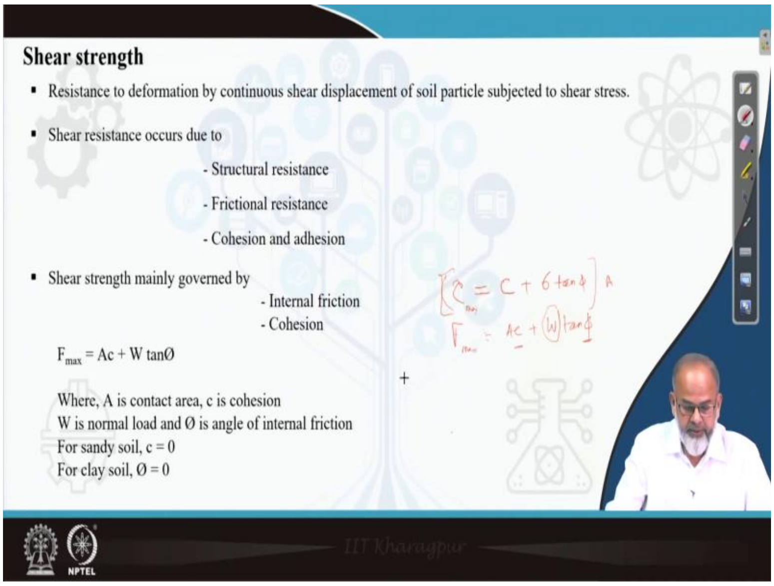

Now comes shear strength, resistance to deformation by continuous shear displacement of soil particles subjected to shear stress. Why you are interested in this because, they wheel, when it starts running that will create some shear displacement at the interface, interface of soil and wheel. So, that is why you are interested in measuring the shear strength.

So, shear resistance occurs due to structural resistance, due to frictional resistance, due to cohesion and adhesion and shear strength particularly is governed by two factors. One is your internal friction the other one is cohesion. So, usually, we follow the Coulomb's equation which says that

$$\tau_{max} = c + \sigma . tan\emptyset$$

So, if you multiply the contact area, then it becomes,

$$F_{max} = Ac + Wtan\emptyset$$

In this equation, the maximum thrust which is developed is a function of cohesion, is a function of angle of internal friction, is a function of the contract area, is a function of the weight which is coming on the wheel. Now, if it is a sandy soil, cohesion less sandy soil that means, c has no role. So, now, thrust maximum, which is developed is a function of cohesion is a function of angle of internal friction, is a function of contract area, is a function of weight coming in the contact area.

Now, if it is a cohesion less sandy soil that means, c is 0 and Ø has some value. So, there the maximum thrust will be dependent on W itself, where the area has no role. Now, if it is a clay soil that means, ∅ 0. So, obviously, the maximum thrust which is developed is dependent on the contact area. So, these are the two extreme conditions which I represented.

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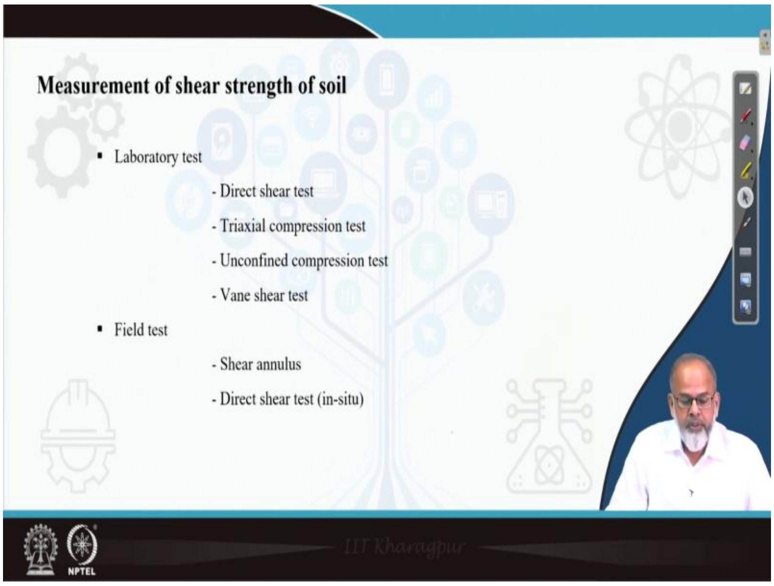

Now, how to measure the shear strength of soil. You can measure it directly in the laboratory or you can measure it in the field. In laboratory, what you have to do is you have to collect the soil sample, then you have to make cylindrical specimens by using direct shear test or triaxial compression shear test or unconfined compression test or vane shear test, we can measure the shear strength of soil.

But since all will be mostly in the field, so, that is why we will be concentrating on what are the apparatus available which can be utilized to measure shear strength in the field. So, there are two apparatus available one is shear annulus the other one is direct shear test. So, direct shear test is the equipment which is available for direct shear test and the equipment that is available for the direct shear tests in the laboratory they are different.

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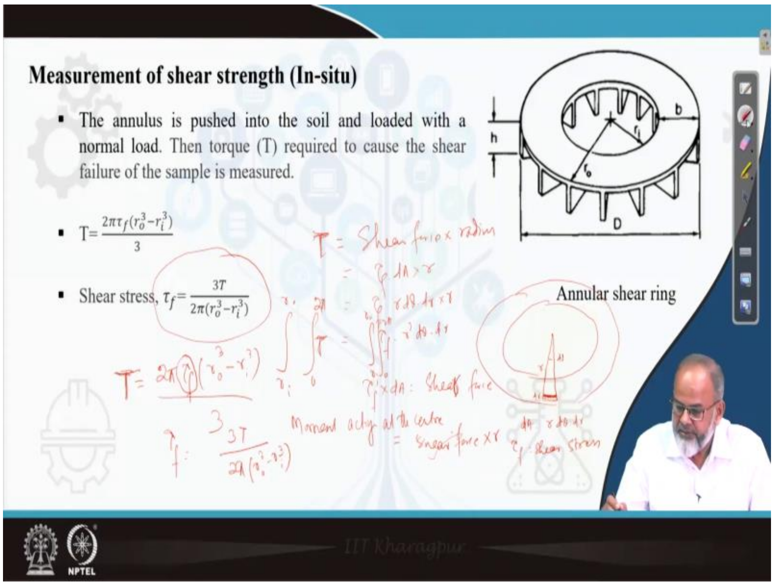

Now, this is the shear annulus, basically this annular ring with fins at the bottom. This has to be rotated. This has to pressed in the soil then it has to be rotated. So, that how much torque is required to cause failure of the soil that has to be measured? So, if the annular ring has an outer diameter r_0 and an inner diameter r_i, the fin has a width of b, and the height of fin is h.

So, the total diameter is indicated here as D, then you have to find that expression, how much torque is required to cause shear. Now, if I take the cross section where, the soil is going to be disturbed, so this is the cross section that the soil is going to be disturbed. Now, if I take a small angular radius is a correspond to dθ at radius r. So, r dθ will be this length and for an incremental length of dr, so, the area of this small element will be

$$dA = r d\theta . dr$$

Now, if τ_f is a shear stress which is applied. Then the shear stress into dA will give you the shear force. So, $\text{Shear force} = \tau_f \times dA$

This shear force is acting at a distance r, now the moment which is acting at the center will be,

$$Moment\ acting\ at\ the\ centre = shear\ force \times r$$

So, if T is the torque, so,

$$\text{T} = \text{Shear force} \times \text{radius}$$

$$T = \tau_f . r d\theta . dr \times r = \tau_f . r^2 . d\theta . dr$$

This is a torque which is acting in the smaller element now. If you want to find out the total torque, which is acting because of the rotation of the annulus ring. Then we have to integrate this expression

$$T = \int_{r_i}^{r_o} \int_{0}^{2\pi} \tau_f . r^2 . d\theta . dr$$

$$T = \frac{2\pi \tau_f ({r_o}^3 - {r_i}^3)}{3}$$

$$\tau_f = \frac{3T}{2\pi({r_o}^3 - {r_i}^3)}$$

So, this is how we arrived at this equation. So, this has to be rotated at a steady rate. It is not that once you rotate then leave for some time, so, that is not allowed.

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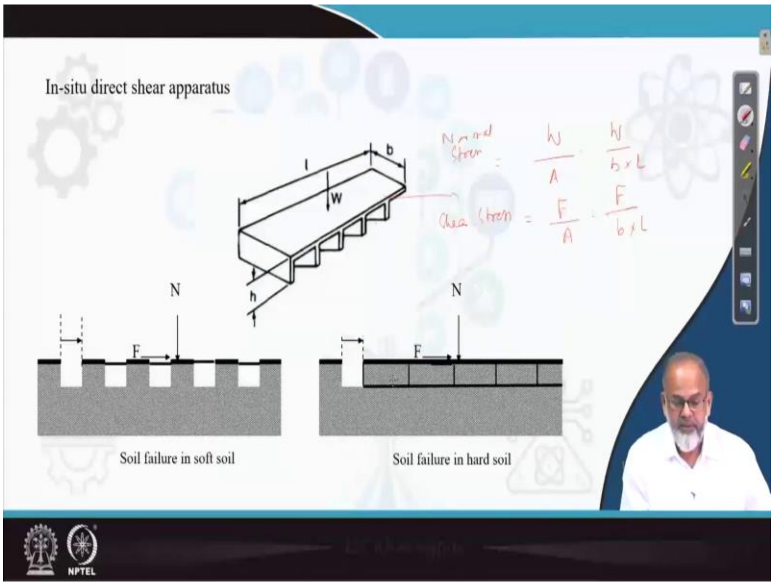

Next is in-situ direct shear apparatus. Now, it is a rectangular plate with having fins at the bottom this has to be pressed into the soil and then it has to be moved forward. So, what we measure here is what is the weight which we apply and what is the corresponding area on which this weight is applied. Then we measure the tangential force f and the corresponding shear stress which is caused, so that area if you measure then we can find out, we can correlate this shear stress with displacement or shear stress with normal stress.

So,

$$\text{Normal stress} = \frac{W}{Area} = \frac{W}{bl}$$

And shear stress

$$Shear\ stress = \frac{F}{Area} = \frac{F}{bl}$$

So, if you try to plot shear stress versus a normal stress, then you will get a kind of curve which will be shown in the next slide.

Now, if there are two conditions which are given, which are shown here, one is in the soft soil the other one is the hard soil. In the soft soil you can see the soil is not displaced, there will be pockets in between, whereas in case of a hard soil the entire soil mass is sheared, that is the difference.

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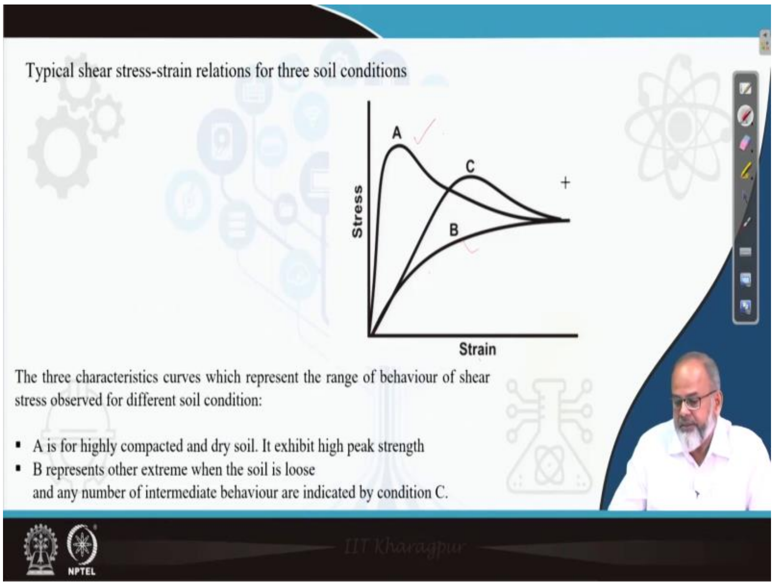

Now, when we try to apply the tangential force, then what we measure also is the strain.. So, if you plot stress versus strain that will be getting a nature of the curve either A type or B type, which is shown in this figure or C type. A type means, for a very hard soil, compacted soil, you will get a clear cut point, where we will get the peaks shear stress and after that the soil fails and it will start coming down. Now, this is the case for compacted dry soil.

Now for loose soil, we will get the stress versus strain curve would be like this. It will be initially rising at a faster rate, then slowly slowly it will slow down and it becomes, it will reach to a peak. So, these are the two extreme curves A and B, so in between when the soil is neither too compact or not too lose, then you may get an get a curve like this, where the nature of the stress and strain curve will be, it will first increase then reach to a peak. But that peak is not as prominent as you get in case of a hard soil or the dry soil. But you will definitely get a peak, then after that the failure starts and it goes down, the shear stress goes down. So, these are the three typical curves which are experienced in the field.

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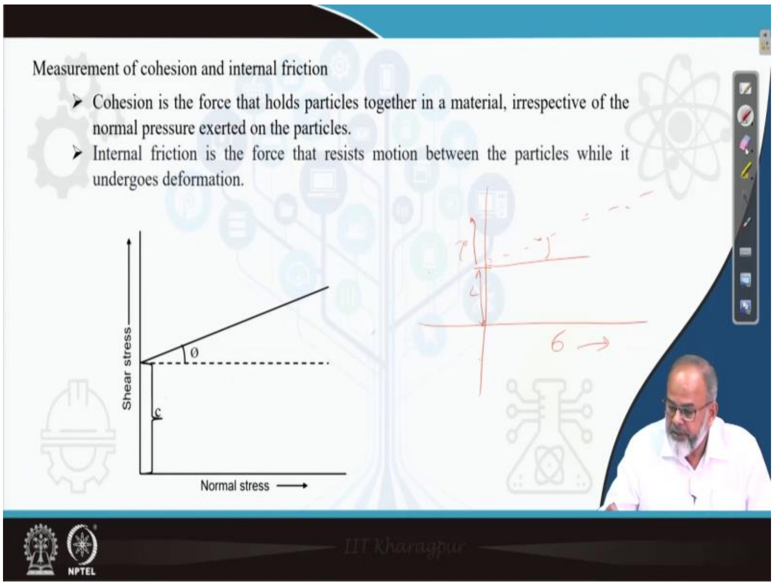

Now, when you try to plot to the shear stress versus normal stress, then what we observed is that we will get a straight line. So, if you best fit the line, then shear stress versus, this side is shear stress, this side is normal tress. So, you will get point like this, if you best fit this line and extend it to touch the y axis, the intercept will give you the value of c and the slope will be the value of Ø. So, c is nothing but your cohesion and Ø is the angle of internal friction.

Now c as the name indicates, is a cohesion. It has the unit, which is same as that of stress. So, basically c can be divided, can be defined as the shear stress when the normal stress is 0. That means cohesion is the force that holds the particles together in the material irrespective of the normal pressure exerted and the particles. Ø which is called the internal friction angle, the force that resists motion between the particle while it undergoes deformation.

So, these are some of the ways by which you can measure shear strength of soil and from the shear strength, you can find out what is the value of c, and then we find out what is the value of Ø in the field.

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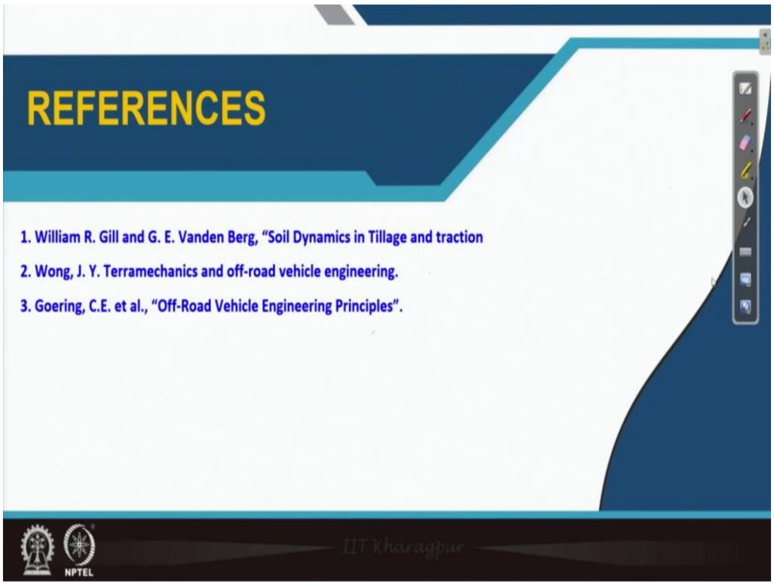

So, the reference books we can take as 'Soil Dynamics in Tillage and traction' and then 'Terramechanics and off-road vehicle engineering', then 'Off-road Vehicles Engineering Principles,' these are some of the books which can be looked into to further enhance your understanding.

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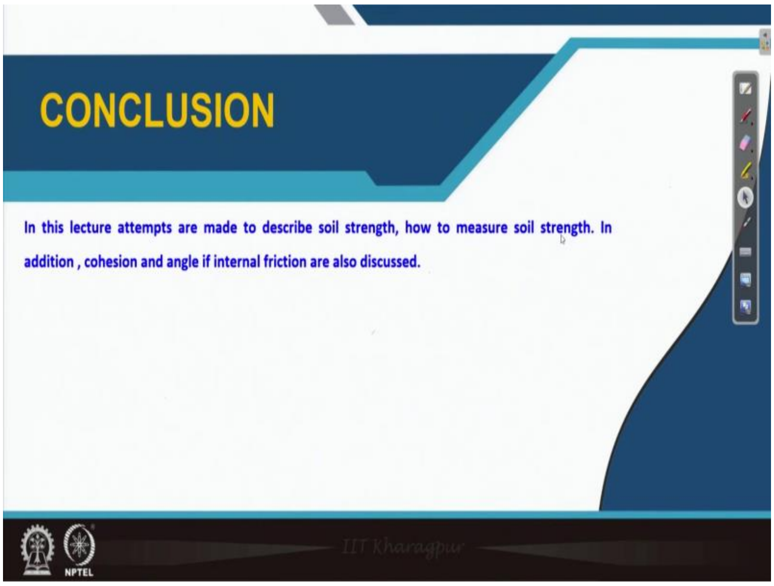

So, in brief, what we have done is, we tried to explain what is the strength of soil, how do we measure the strength of soil, then we tried to find out shear strength of soil and what are how to find out cohesion and an angle of internal friction from this shear strength. That is all thank you.