Expansive Soil
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Lecture 4
Engineering Properties of Soil – II

(Refer Slide Time: 00:30)

Hello everyone, welcome to the course expansive soil. This will be the third lecture of this Module 1. In the previous class we discussed about the two engineering properties which were the compaction and the permeability of the soil. Continuation with this two engineering properties today we will be learning about the other two engineering properties which are the shear strength and the consolidation behavior of the soil. In the previous class, we have discussed about the compaction characteristics and permeability of the soil. In today's class we will be learning about the compressibility and the consolidation characteristics, and the shear strength of the soil sample.

(Refer Slide Time: 01:11)

Next, I will discuss about the compressibility and consolidation characteristics of soil. In order to know the stability of a soil we need to determine its settlement under a load. When we apply a load to a soil, the soil will undergo compression. And if we assume that the soil is fully saturated and the solid particles are not compressible, as well as the water is not compressible, then the volume decrease of the soil will take place only because of the expulsion of the water. So, the process in which the volume decrease of a soil takes place due to the expulsion of the water is known as consolidation.

Here we can see in the example, a soil sample has been taken, which is fully saturated and it is consisting of water and the solid particles. So, when we apply a load to the soil and if we assume that water is incompressible as well as the solid particles are incompressible, due to this load the soil will undergo compression. And this compression will be only due to because of the expulsion of the water. And this process in which the water is expelled out from the soil and the volume reduction takes place is known as consolidation.

What happens is that soon after applying the pressure, the pore water pressure starts to increase and it will dissipate it slowly. Depending on the permeability of the soil, the rate of dissipation will also be different. For a highly permeable soil the pore water pressure will dissipate very fast, whereas, for a low hydraulic conductivity soil the pore water pressure will dissipate very slowly, and so the rate of consolidation.

Therefore, the rate of consolidation or the rate at which the soil will be consolidate is a time-dependent process, which depends on the permeability of the soil. So, when we talk about consolidation, we need to calculate the magnitude of the settlement that means how much a soil is being getting settled or how much the soil is being consolidated due to the application of the load, as well as how much time it's taking to complete the consolidation process.

First going with the settlement, when we apply a load, the soil will settle. And if we look into the total settlement, so the total settlement of a soil is made of three components. The total settlement will be made of the initial settlement, the primary settlement and the secondary settlement. Immediately when we apply a load, there will be a marginal decrease in the volume of the soil takes place.

This decrease in the volume will be due to the expulsion and compression of some air present in the air pockets, as well as the compression of the solid particles. And also this takes place due to the distortion of the solid particles within the soil mass. However, the amount of settlement in this stage or in this process will be very less and it can be derived using the elastic theory. Once the initial settlement is over, next comes the primary settlement of the soil.

During the primary settlement a large volume decrease will take place and this volume decrease will take place only because of the expulsion of the water. In this process it is associated with a large volume reduction, and depends on the process and is a function of permeability. As soon as we apply the pressure to the soil, the pore water pressure will increase and it with time it will start to dissipate. As the pore water gets expelled out from the soil, the volume reduction takes place. And this volume reduction or the settlement is known as the primary settlement.

Once the primary settlement is over next comes the secondary settlement. In this process, some plastic readjustment of the solid particles takes place and because of this plastic readjustment of the solid particles a minimal or a slight decrease in the volume of the soil will take place. And this settlement can be can be derived using the plastic theory. So, these are the three settlements, which we can generally find when we apply a load to the soil sample.

(Refer Slide Time: 05:49)

In order to determine the consolidation characteristics of soil, the Terzaghi theory of consolidation is generally used. So, here we can see a soil profile, say for example, a soil has been taken over here with a height H. Now, when we apply a load Δσ over here, initially, when the all this load will be taken up by the water present over here. So, therefore, there will be rise in the pore water pressure here.

Here we can see, at t equals t_0 that means, at the initial stage, the pore water pressure at all the different depths of the soil sample will be equal, and this will be equals to $\Delta\sigma/\gamma_w$. With increase in the time the pore water will start to dissipated. Initially the water present next to the boundary layer between the drainage and the soil sample will escape out first, as a result of which the pore water pressure at this boundary layer will become equals to 0.

We can see here. And the points very close to the boundary layer will have a lower value of pore water pressure. So, if we draw the isochrones, we can see the distribution of pore water pressure at different location. So, this is for different time say t_1, this is the isochrones for time t_2, this is for time t_3. The consolidation is over at t_t equals to t_f all the pore water pressure will escape, and the pore water pressure at all the points will be equals to 0 over here.

So, therefore, we can say that the rate of settlement of a soil sample is directly proportional to the dissipation of the pore water pressure. The Terzaghi's partial differential equation of consolidation describes the distribution of the hydrostatic pressure with time and depth. So, this equation was given by Terzaghi and known as Terzaghi's theory of consolidation.

According to Terzaghi's theory of consolidation;

$$\frac{\partial u}{\partial t} = c_v \frac{\partial^2 u}{\partial z^2}$$

Where, c_v is the coefficient of consolidation and can be defined or can be calculated using this equation. And c_v generally describes the rate of consolidation of a soil sample. Higher is the c_v, higher value of the rate of consolidation or the soil gets consolidated faster.

Terzaghi has assumed certain assumptions while deriving this theory of consolidation. Those assumptions are the soil is homogeneous and isotropic, soil is fully saturated, the solid particles and water are incompressible, k is constant throughout the soil and Darcy's law is valid. So these are the few assumptions Terzaghi's had made to derive the theory of consolidation.

Depending on how much pore water pressure has been escaped from the soil a term called degree of consolidation can be derived using this formula,

Degree of consolidation =U= $\frac{u_i - u_t}{u_i}$

Where, u_i is the initial pore water pressure, u_t is the pore water pressure at any time t. When the degree of consolidation is 100 percent that means, u_t will be equals to 0, that means, the consolidation has taken place completely. So, that this part will be 100 percent.

When u_t is equals to u_i, that is at the application of the load, U will be equals to 0. That means, the 0 percent degree of consolidation has taken place. So, this is U will be 0 when t equals to 0 and U will be 100 when t will be equals to the end of the consolidation maybe that is t_f which is over here.

At this point the U will be equals to 0 and at here you will be equals to 100 percent. Now, this there is another factor called Tv which is related with the degree of consolidation.

$$T_v = \frac{c_v t}{\left(\frac{H}{n}\right)^2}$$

Where, H is the thickness of the soil and n is the number of drainage paths available for the soil.

For example, in this case, the water can escape through both the ends because both the ends the drainage are permitted. Hence, the n value will be equals to 2 over here. Say for example, in this case if a rock strata is present, over here, then the water will not be able to escape. In that case the water can escape only through this end of the soil and hence the n value will be equals to 1. Therefore, the depending on the number of drainage path, the n value can be 1 or 2 in this equation, and H is the thickness of the soil strata.

(Refer Slide Time: 12:38)

Next how to determine the consolidation in our laboratory. Generally, the consolidation can be determined using an odometer in the laboratory. You can see one odometer test apparatus here. So, this is a soil sample mounted on a mold here. This is a ring known as odometer ring, this is a loading frame, the load is applied here, and water is applied through this chamber to this sample, so that the soil will be saturated all the time.

There will be dial gauge to take the readings of the settlement. So, here you can see, this is a soil sample, which is present in odometer ring. This odometer ring is 60 mm in diameter and 20 mm in thickness and porous stones will be provided at the both the ends of the soil samples. Then with the help of a loading frame load will be applied, and a dial gauge will be here to measure the settlement of the soil sample because of this load. And the soil will be submerged all the time, so that the degree of saturation becomes 100 percent, during entire period of the test.

And IS 2720 part 15 explains the method to determine the consolidation in the laboratory. We need to take the soil sample, the soil maybe compacted at MDD OMC or maybe compacted to its in-situ density. Then the soil will be kept inside this odometer ring, and the porous stones will be provided at the both the ends, and the filter paper will be provided at the both the interface between the porous stone and the soil sample.

Then the soil will be submerged, and load will be applied. As the load will be applied in the sequence of 0.05 kg/cm^2, 0.1 0.2 0.5. So, in this sequence the load will be applied, and the load will be applied in an increment ratio of 1. That means, the load, whatever the load is present the same equal amount of load will be applied as an increment in the next load.

So, when we see a soil sample say for example, this is a soil sample under a load of P. Now, we will apply an additional load of ΔP here. Due to this additional load the sample will settle, if H is the initial height of the sample and due to the application of this load ΔH will be the change in the thickness of the sample.

Since the soil is laterally confined, there will be no change in the diameter of the soil sample. So, we need to measure the change in the height of the soil sample for each, every load increment of this test. And from this change in the height, we can calculate the change in the void ratio of the soil sample corresponding to every load increment.

(Refer Slide Time: 16:11)

So, here we will be knowing H_i which is the initial height of the soil sample, initial void ratio we will be knowing. So, from all this we can calculate Δe, then we can calculate e corresponding to different pressures. After completion of the load, we can plot the void ratio and pressure plot where the void ratio corresponding to different pressure will be plotted like this and this is known as the e-log P curve of the soil sample. This e-log P curve will give us many consolidation characteristics of the soil. Say, for example, compression index. This compression index is the slope of this virgin portion or the straight line portion of this curve. So, compression index is defined as the slope of the linear virgin portion of the void ratio pressure plot.

If we calculate the slope of this line, so that will be the compression index. So, compression index can be calculated using this formula. If we know the void ratio corresponding to this pressure say, for example, this is e_2 and pressure P_2 and this is e_1 at pressure P_1 then knowing this P_1, P_2 and e_1, e_2, we can calculate the slope of this line. So, this is known as compression index.

Compression index generally tell us about how much the soil can be compressed or the compressibility of the soil. Higher is the compression index, higher the soil can be compressed. Compression index can also be related with the liquid limit for a for an undisturbed soil sample,

$C_c = 0.009\ (W_L - 10\%)$

For a remoulded soil, $C_c = 0.007\ (W_L - 10\%)$

The other parameters which we can determine is coefficient of volume change m_v, which is defined as the ratio between the volumetric strain due to the change in the stress on the soil. So,

$$m_v = -\frac{\Delta V / V}{\Delta \sigma'}$$

For each load increment we can calculate the value of m_v.

Similarly, the coefficient of compressibility, a_v, which is defined as a decrease in the void ratio per unit increase in the effective stress. Since, due to the application of the load, the void ratio decreases that there is a term negative over here and also for each load increment, we can calculate the a_v value for a soil.

(Refer Slide Time: 19:00)

Next comes the normally consolidated and over consolidated soil. Depending on the stress history and the present stress or present load of a soil, the soil can be named as normally consolidated and over consolidated soil. Say, for example, if we take a soil sample if we take a soil sample which has been subjected to a load due to its overburden pressure, say this load is P_1.

Now, this load has been removed from the soil, and then, a construction of a structure was carried out. Depending on the load of this structure the soil can be termed as normally consolidated or over consolidated. Let the structure load is P_2. If the value P_2 is greater than P_1, then the soil can be termed as normally consolidated.

If the P_2 is smaller than P_1 that means P_1 is larger than the soil will be known as over consolidated soil. So, depending on the soil, the soil is over consolidated or normally consolidated its behavior will be different. So, going by the definition, a normally consolidated soil is a soil, which has not been subjected to a pressure greater than the present existing pressure. Say in this case, as I told you, since the P_2 value is larger than P_1 the soil had not been subjected to a load P_2 which was higher in comparison to its previous stress history.

Similarly, over consolidations, over consolidated soil can be defined as a soil which has been subjected to a pressure greater than the present existing pressure then it is known as over consolidated soil. We can see from this diagram this void ratio pressure diagram, take a soil sample and apply gradual loads to the soil.

So, soil has been compressed from A to B, once we reached the point B, then we will start to remove the load. The volume of the soil will increase, this is known as expansion curve. Since the volume of the soil will increase, this will be known as expansion curve. Then after reaching the point C. Again, we will reload the soil, as we reload the soil again the volume of the soil will decrease.

So, this part of the soil is known as re-compression. The portion CD is known as a recompression curve. Once we reach to D, we can see that the curve is not following the initial path, it is deviating from the path from which where we had stopped loading. Then we will continue the load up to E point.

Now, if we compare with this normally and over consolidate soil, then we can see here the soil in the zone AB has not been subjected to this load previously. So, this is a part of normally consolidated soil. Now, again when we remove the soil there is an expansion taking place. And again, when we load the soil sample at any point in the path CD the load has, the soil has been loaded to a load which has been subjected in the past.

Say for example, if we take a point here, this amount of load has already been subjected in the past. That is why the portion CD will be known as over consolidated soil or over consolidated zone. And if we compare the past history, the maximum load the soil was subjected at B. The pressure at point B is known as the pre-consolidation pressure. That means, the maximum pressure to which an over consolidated soil has been subjected in the past.

So, this pressure is known as the Pc or pre-consolidation pressure. And when we compare the Pc with the existing pressure, then we will get the over consolidation ratio. This over consolidation ratio is the ratio between the pre-consolidation pressure to the present pressure. So, if we take a pressure say P_1 the ratio between P_c and P_1 is known as the over consolidation ratio.

(Refer Slide Time: 23:56)

Next is the shear strength of the soil. Again, to analyze the stability of a soil, we need to know the shear strength. When we do the analysis, stability analysis of the soil we need to check two things that the soil is safe in settlement that means the settlement is not exceeding beyond the permissible limit, and also the soil is safe against shear.

So, therefore we need to understand the shear strength of the soil in order to know its stability or the bearing capacity of a soil. Generally, all the structures such as foundation or earth retaining structure, soil mass has to withstand the shearing stresses. The shearing stresses tends to displace a part of soil mass relative to the rest of the soil mass.

The shear strength of a soil is a capacity of soil to resist this shearing resistance. The maximum shearing resistance which the material is capable of developing is known as the shear strength of the soil. And the shear strength is the most important engineering properties of the soil, which governs the bearing capacity, the stability of the slope and the earth pressure against the or earth retaining structures.

When the shearing stresses induced on a soil mass exceed the shearing strength of the soil, then the soil will fail in shear. Therefore, in order to have a higher stability or in order to have a more stability of the soil, the shear strength of the soil should be more than the shearing resistance generated by it. And once the shearing resistance is exceeding the shear strength, the soil will fail due to the relative movement of the soil particles with each other.

Now, this shear strength is generally composed of two things. One is the frictional resistance, and the second one is cohesion between the particles. So, if we take a block and apply a load N and if we start to push the soil, push the block in forward direction, then this block will try to resist this movement. And this resistance to the movement will comes from the two components.

The first one is because of the frictional component. The frictional component comes between the friction between the block and the table over here. Now, if we provide some additional glue between the solid particles between this block and this table, this glue will provide some additional resistance against this force P.

So, if we talk this one in terms of soil mechanics, this frictional component will be coming from the frictional resistance between the soil particles and this glue which will provide some additional shear strength to the soil will come from the cohesion. So, therefore, the shear strength of a soil comes from the two components, one is the frictional resistance and other is cohesion.

This frictional resistance develops due to the friction between the soil grains and the frictional resistance increases with the compressive stress produced in the soil mass and this is proportional to σ' tan ϕ, where the σ' is the normal intergranular stress and the ϕ is called as angle of internal friction.

This frictional resistance generally comes from the three components. One is the sliding friction, rolling friction or interlocking friction. Then comes the cohesion, cohesion is the force of attraction between the similar particles, and this force binds the clay particles or soil particles together. And this is generally denoted by c. And this is c is due to the intermolecular attraction between the particles or maybe the surface tension and adhesion of the, and the adhesion of absorbed water layer present around the soil particles.

So, these three components can provide the cohesion to the soil. And this c and ϕ are known as shear strength parameters. We need to know that this c and ϕ are not unique to a soil. This c and ϕ depends on the testing condition by which we are determining these two parameters,

(Refer Slide Time: 28:35)

Then how to determine this shear strength of a soil. Generally, there are tests available in the laboratory to determine the shear strength. I will explain the test briefly how to determine the shear strength in the laboratory. Before that, we need to understand the different stages of this test.

The determination of shear strength can be carried out under different drainage conditions to simulate the real field problems. During the test there are two stages involved, one is consolidation stage, second one is the shearing stage. During the consolidations stage, first a soil sample will be prepared of required density and water content, then the soil will be saturated using a back pressure then during the consolidation stage a confining pressure σ_3 will be applied to the soil sample.

So, this is known as consolidation stage. In the second stage, once the consolidation of the soil sample is over, then a shearing stage will come. In shearing stage, apart from this confining pressure σ_3 an additional axial load σ_d will be applied which would be equals to P/A. This σ_d will be applied by applying a load P to the soil sample, and that σ_d which is known as deviatoric stress will shear the soil sample.

And once in when we apply this load here the σ_3 will be there, which will be, which will becomes the minor principal stress and then the σ_1 will be the major principle stress;

$$\sigma_1 = \sigma_3 + \sigma_d = \sigma_3 + P/A$$

And during this consolidation stage or shearing stage, depending on the testing condition the drainage can be kept open or can be kept closed. So, we will discuss about those things later on. Therefore, there are two stages of any shear strength test in the laboratory that is consolidation stage and the shearing stage.

(Refer Slide Time: 30:56)

So, depending on the drainage condition there are three types of tests available. One is Unconsolidated Undrained test which is known as UU test. In Unconsolidated Undrained test, the drainage is not permitted both during the consolidation as well as the shearing stage. Since the pore water pressure is not allowed to escape, this test takes place very quickly, so this is also known as a quick test or a Q test.

The next comes the Consolidated Undrained test or this is known as CU test. In this test, the drainage is permitted during the consolidation stage, however, the drainage will not be permitted during the shearing stage. So, therefore, this will be consolidated undrained test. Next comes the consolidated drained test.

In this test, the drainage will be permitted both during consolidation stage, as well as during the shearing stage. Since the sample is drained in the shearing stage, the sample will be sheared at a low rate to permit the drainage condition, and therefore, this test takes a lot of time to complete and hence it will be a slow test or S test. So, based on the drainage condition during the shearing and consolidation stage the test can be either UU test or CU test or a CD test.

And also, during the shearing process we can apply the shear force in two ways that one is called strain-controlled test and the other is called stress-controlled test. In the strain-controlled test, the shearing strain will be increased at a constant rate. And this rate of increase in the shearing strain will be kept constant throughout the experiment.

Now, strain control test has certain advantages, because in this test, the relationship between the stress-strain can be easily obtained, as the shape of the stress-strain curve can be observed beyond the peak value and also it is easier to perform. In the stress-control test the shear force will be increased at a constant rate and this rate of increase in the shear force will be kept constant throughout the test. These are preferred for conducting shear test at a lower rate. And also this is quite resembles to the field condition. So, the test which we can do in the laboratory can either be a strain-controlled test or can be stress-controlled test.

(Refer Slide Time: 33:44)

Now, based on the test, we can determine the shear test by using a direct shear test. This is a most one of the simplest test in which there will be a shear box, which will be divided into two portions here we can see. First one half and two half, it can be divided into two halves, and the soil sample will be kept here. Generally, soil sample of dimension 60 mm by 60 mm by 20 mm is used and the details about the test can be is given by IS 2720 Part 13.

Here the soil sample will be kept, and a vertical load P_z will be applied. Then the apparatus will be kept over rollers and a load will be applied here, a P_x load will be applied here. And the test can be conducted by either strain-controlled or by stress-controlled test. The specimen will be gradually sheared by applying a horizontal force, which will cause these two halves to move relative to each other.

Then the sample is sheared at a constant rate of strain, and the magnitude of shear force, the shear and vertical deformations are measured using the dial gauges fixed over here. And that will also give us the change in the volume of the soil sample during the testing. This is a quick test and inexpensive test. So, here we can see some of the plot which we can get for different kinds of sand.

If we take dense sand and if we plot the stress versus strain graph, we can see over here with increase in the strain the shear strength of the soil will increase, and it will reach to a peak value then it will start to decrease. So, this is the peak strength of the soil sample, and then, it will be decreased and becomes constant, so this is known as ultimate shear strength of the soil sample.

But if we take a loose soil, loose sand, then we can see with increase in the strain, the shear stress of the soil will increase and it will reach a value then it becomes constant over here. So, this is for the loose soil. Similarly, if we check the change in the volume to the strain relationship, we can see for the dense sand initially there will be a decrease in the volume of the sample, then with a further increase in the strain, the volume of the soil sand will increase.

However, for the loose sand, the volume of the sand will decrease continuously due to increase in the strain of the sample. Then this test will be conducted at with the four, five samples at different loads and then the plot will be plotted between the shear strength and effective normal stress, and then we can determine the phi value of the soil.

Here we can see, we plot the void ratio and strain plot. For a dense and the void ratio will keep on increasing with increase in the strain, however, for the loose sand the void ratio will keep on decreasing. And finally, they reach to a constant value or that is known as the critical void ratio. CVR this is known as the critical void ratio.

However, there are some demerits of this test. The one of these demerits is the failure plane of this test is fixed. Therefore, irrespective of whether this is a weakest plane or not, the soil has to fail in this plane. Another problem is related to the drainage. The drainage cannot be controlled over here and pore water cannot be measured, so therefore, the effective stress cannot be calculated over here. So, this is the direct shear test.

(Refer Slide Time: 37:54)

The next comes the Triaxial test. In the triaxial test, as the name suggests, the specimen will be subjected to all around pressure, and then it will be sheared. Generally, a cylindrical soil sample of diameter 38 mm to a height of 76 mm or 100 mm to 50 mm is used. And you can see here, the soil will be first subjected to a confining stress σ_3 and then it will be subjected to a deviatoric stress σ_d and it will be sheared.

So, this is a set of the soil samples is here, and it will be confined to a confining pressure, and then it will be subjected to a deviatoric stress over here. This is the typical setup for the triaxial test. Depending on the different testing condition, the triaxial test can be of different types.

(Refer Slide Time: 39:01)

The first one is unconfined compression test. This is a type of triaxial test, but in this case no confinement is provided. So, σ_3 is 0 here. Since no confinement is provided here, this type of tests are generally carried out on the soil sample which can sustain themselves without any support. So, mostly clayey soil sample can be used for this kind of test.

This test determines the undrained shear strength of a saturated clay very quickly, and no confining pressure is applied. The loading is applied quickly so that pore water cannot drain out from the soil sample. And since the pore water cannot escape out, the sample will be sheared at a constant volume.

And when we plot the shear stress versus normal stress plot, we will get a Mohr circle passing through the starting from the origin and a single Mohr circle can be obtained. And ϕ_u, undrained frictional angle, will be equals to 0 and,

Undrained shear strength, $c_u = q_u/2$

This is σ_1 and this is σ_3, which is equals to 0. For this test, we will get only one Mohr circle. So, this is unconfined compression test. So, this is a very quick test.

(Refer Slide Time: 40:35)

Next comes the unconsolidated undrained test. So as I told you earlier, in unconsolidated undrained test the drainage is not permitted during the consolidation stage and also during the shearing stage. So, this is a soil sample. First, the soil sample will be subjected to a confining pressure σ_3 and the drainage valve will be closed or drainage will not be permitted therefore, the pore water pressure will start to increase and Δu which is a pore water pressure, which will not be equals to 0. Then the sample will be subjected to a deviatoric stress σ_d which will be equals to P/A and then the soil will be sheared.

And this test will be repeated with more than one sample at different values of σ_1 and σ_3, and we will get the different values of Mohr circles corresponding to different values of σ_1 and σ_3. So, based on this Mohr circle, we could see this we can get the c_u undrained cohesion value. This is for a normally consolidated soil sample.

So, this plot shows the relationship between the normal stress to the shear stress for a normally consolidated soil sample. The advantage of the UU test over the UC test is that the soil sample is stressed in lateral direction to simulate the field condition. In UC test the σ_3 was equals to 0, so that is why the sample was subjected to stress in only one direction.

Whereas in UU test, the σ_3 is not equals to 0, therefore, the sample has been subjected to stress in both horizontal as well as in the vertical direction. And also, this UU test and UC test can be carried out in the to determine the to do the preliminary analysis for the design of slopes foundation and retaining walls and other earthworks. In UU test the Mohr circles whatever we will get will have similar magnitude in the diameter that is why the ϕ_u will be equals to 0 over here.

(Refer Slide Time: 43:07)

Next comes the consolidated undrained test. As the name suggests, in consolidated undrained test the sample will be consolidated in the first stage by opening the drainage valve, and it will not be allowed to consolidate during the shearing stage by closing the drained valve. So, this therefore, this is undrained test.

So, here we can see a soil sample is taken and then in the consolidation stage a confining pressure sigma 3 will be applied. Since the soil sample is allowed to dissipate its pore water pressure or the drainage valve is kept open the pore water pressure will not be generated and *u* will be equals to 0. Therefore, the σ_3 will be equals to σ_3'. And similarly,

$$\sigma_1 = \sigma_1' = \sigma_3 = \sigma_3'$$

Next, during the shearing phase a deviatoric stress will be applied, which will be equals to σ_d, which will then,

$$\sigma_1 = \sigma_3 + \sigma_d = \sigma_3 + P/A$$

And during this stage as the drainage will be kept closed, the pore water pressure will not be equals to 0. The pore water pressure will be generated and,

Effective stress $= \sigma_1' = \sigma_1 - u$

And here we need to understand that for normally-consolidated soil, the pore water pressure will be positive and for an over-consolidated soil the pore water pressure will be negative. Then we can determine the total as well as effective stress and then we can calculate the relationship between normal stress and the shear stress, both in terms of total stress and the effective stress. So, this test will be repeated for different values of σ_3 and σ_1, then the Mohr circles will be plotted. And depending on the total stress or the effective stress we can calculate phi dash or phi. Generally, the ϕ' is higher than ϕ or the effective angle of internal friction will be more in comparison to the total angle of internal friction.

(Refer Slide Time: 45:45)

Next comes the consolidated drain test. In this test, during the consolidation part, and as well as for the shearing part the drainage will be kept open. So, therefore, this is a consolidated drained test. Generally, this test is performed to determine the shear strength parameters and to analyze the long-term effect of loading on a soil mass. The displacement rate or the strain rate using the shearing stage must be slow enough to allow the excess pore water pressure to dissipated, so, that the drained condition can be maintained during the test.

And for a fine grained soil, since the hydraulic conductivity is very less, the rate at which the water will escape will be very low, therefore, it takes a lot of time in comparison to a coarse-grained soil. And this test will also be carried out in two stages, consolidation phase and shearing phase.

In the consolidation phase a confining pressure of σ_3 will be applied all around here. Since the soil is allowed to dissipate its pore water pressure, so *u* will not be generated. *u* will be equals to 0, therefore,

$\sigma_3 = \sigma_3'$ and $\sigma_1 = \sigma_3 = \sigma_1' = \sigma_3'$

During the shearing phase, over here, the deviatoric stress will be applied and *u* will be equals to 0 as the drainage is permitted here, therefore,

$\sigma_3 = \sigma_3'$ and $\sigma_1' = \sigma_3' + \sigma_d$.

Again, this test will be repeated for different values of σ_3 and σ_1 and the Mohr circles corresponding to each test will be plotted over here. Then again, we will get the angle of internal friction corresponding to the drained condition we can get it over here. So, this is for a again a normally consolidated soil. We can see here, the line is passing through the origin over here. So, this is how we can conduct the consolidated drained test.

(Refer Slide Time: 48:09)

Now, the question is which type of test we need to do in the laboratory. So, that depends on the soil type and the purpose. For a coarse-grained soil, the drainage takes place very quickly, and the consolidated-drained test is preferred. Similarly, when a large mass of saturated soil sample is subjected to quick loading, such as the earthquake loading, the pore water pressure will not be able to dissipated that quickly, therefore, the undrained testing condition will be preferred.

If we want to analyze the long-term stability of a soil sample under a load, then we need to go for a consolidated-drained test. Again, as I told you, the for fine grained soil, since the drainage is very slow undrained test can be performed or can be preferred. So, this is all about the different engineering behavior of the soil sample. These are the few of the references which has been used to make this class. And thank you very much for your attention.