Soil Mechanics
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Lecture – 36
Consolidation and Settlement
Lecture No: 3

Students so we meet again. Today we have the third lecture in the series of lectures on consolidation and settlement. As always we shall first review a little bit of what we have discussed in the earlier lectures and then go forward with new material. Let us take a look at the next slide. So as the slide shows in the last lecture I introduced the phenomenon of consolidation shown of all mathematics, just the basic physical phenomenon that takes place which is responsible for time dependant settlement or compression. And that's what is known as consolidation.

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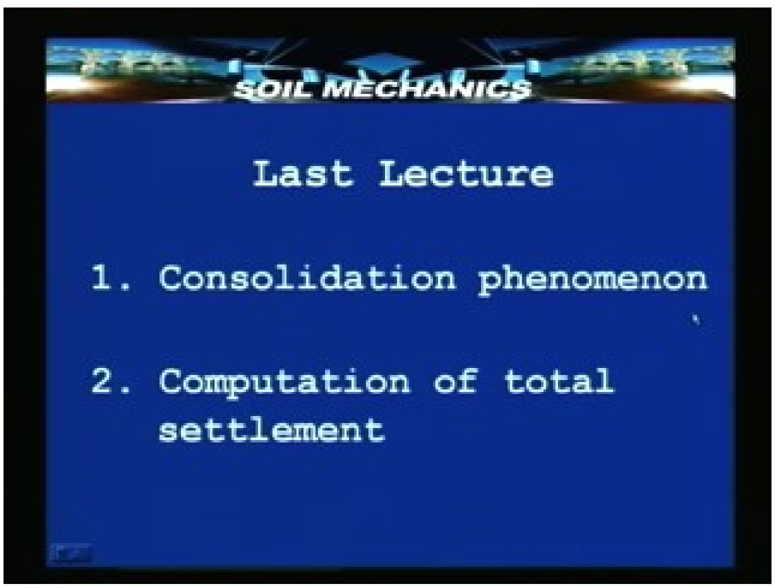

Briefly speaking we saw that consolidation is a gradual phenomenon of compression which takes place due to gradual expulsion of water from the voids of a saturated soil. The soil usually is clay as we discussed last time, its clayey soils when saturated which exhibit predominantly time dependant compression. In view of the low permeability or the low coefficient of permeability of these soils which are in the range of say 10 raised to minus 6 to 10 raised to minus 7 or minus 8. Now in view of this kind of compression taking place with time, we have 2 questions to be answered. One is what is the likely compression, when a building is constructed on such clay or for that matter in general when a load is applied on the surface of such a clay layer.

What's the likely maximum compression, the total compression or the ultimate compression that is likely to take place. And not only that which is probably of greater importance is the rate at which this settlement takes place. So we got into discussion of the first part of this problem, that is the computation of the total settlement. The computation of the total settlement is important because we cannot afford to design the building and take a chance and see how the compression takes place because during the process of consolidation or compression if the building is unable to adjust to the degree of compression that takes place, it is not possible to do any mid course correction. A building is not an object where you can do any changes or alteration or rectification, while the settlement or consolidation is taking place during its life time.

In view of these it is important that we have a method to compute this possible compression or consolidation before an activity takes place, that is before a construction or before application of load takes place, we should have a method to compute the likely compression or the total consolidation settlement that is going to take place. And unless we know this we cannot possibly adjust the stress that is transferred to the soil due to the building, there by save the building from possible excessive settlement and possible distress. Then in short therefore we need to know how to compute the total settlement that is likely to arise due to a construction or in general due to a change in stress.

So if there is an increment in stress that is existing on the soil in the normal conditions then a compression is going to be induced and we need to know how much this compression is going to be. It's also therefore of importance to know in what time this will take place. Theoretically ideally speaking it will take infinite time, this compression is a time dependant phenomenon which will go on but from a practical point of view most of these compression, almost entire compression or about 95% of the compression takes place within a certain time duration. So within the life time of this building, how much is the compression that is going to take place and at what rate it is going to take place is of great importance.

We will be in a position to see the computation of the time rate as well but to begin with let us spend a little time on the computation of the total settlement. Last time we saw in some detail about the computation of the total settlement, we even saw a numerical example. To put it briefly we said that the total compression that is going to take place is dependant upon the change of void ratio which let us say is e_0 to begin with and changes to e_f. During the application of a load which in terms of stress may be considered as sigma_0 dash initially, if we consider the effective stress and which increases to sigma_f effective.

Why we are considering effective stress? Also we discussed in the last lecture, the explanation for this is that, is the effective stress which is transmitted ultimately to the grains of the soils solids and that's what is responsible for the actual compression or the change in volume that takes place. As we discussed last time initially when the load is applied, since the solids are incompressible they do not take any of these loads. The loads are first getting transmitted to the water but water also being incompressible does not take the load how ever it's able to move out from the voids of the soils.
And therefore the load which comes on the water gets transmitted immediately to the

solid grains as the water moves out. And this causes the solid grains to readjust themselves, reorient themselves, move and then make up a more compact or more compressed volume of soil. And this compression is what we are planning to compute and since this is essentially due to the stress that is transmitted to the solids or the grains, we shall be computing the effective stresses and their relationship to the void ratio. Let us proceed further.

So we saw in the last class that if we apply this principle, we can compute the total settlement that will take place in terms of the total void ratio change that is going to take place. Since this settlement depends upon the thickness of the soil layer, we need to compute the change in volume or change in void ratio per unit volume which is the same as saying per unit thickness, since the area remains constant during compression. And this when multiplied by the actual thickness of the layer will give us the total settlement. So if you look at this formula, we have a term here which is change in volume or change in void ratio that is change in volume is expressed in terms of change in void ratio, since the volume of the solids has meant shown here remains constant.

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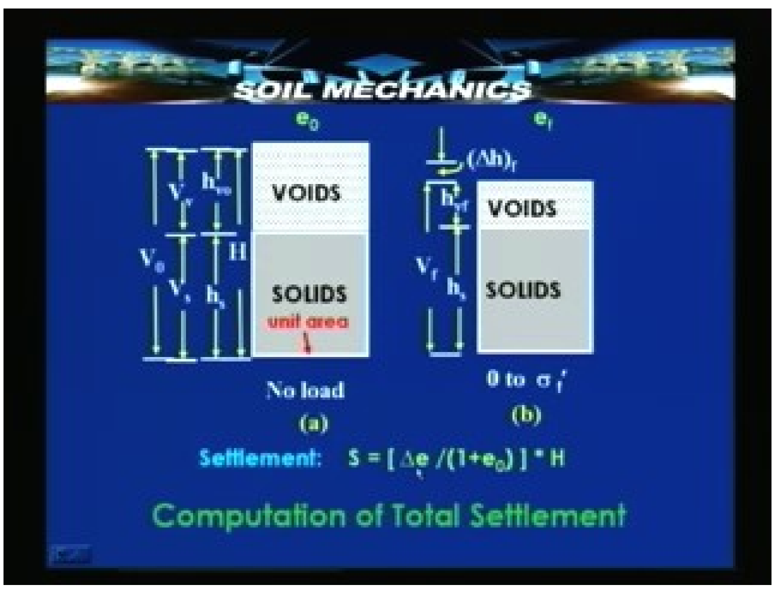

And per unit original volume will tell you how much is the settlement that takes place in the unit thickness of a soil, this multiplied by h the actual thickness of the soil, total thickness will tell you the settlement that is likely to take place in the total thickness over the total thickness of the clay layer. So this is the settlement and this requires the computation of initial and final void ratios as we just now saw. How do we get these void ratios? We can get these void ratios by conducting a test, we also saw the name of the test and some details of this test that was the oedometer test. Now once we know the fact that the settlement depends upon initial and final void ratios, since the initial and final void ratios are effectively caused due to the stress changes in the soil due to the application of external loads.

We must relate these void ratios to the stress changes thus if we want to know e_0 and the final void ratio e_f due to an application of certain external load, we must know the linkage between e_0 and e_f and the initial stress sigma$_0$ and the final stress sigma$_f$ that is going to arise due to the application of the load. This expression which I have written here is in general terms, in particular how ever while calculating the settlements we will be dealing with not just sigma$_0$ and sigma$_f$ but the effective stresses sigma$_0$ dash and sigma$_f$ dash. So this means that we need to establish a relationship which can be called as sigma e relationship, the stress versus void ratio relationship. In general it will be a stress change versus void ratio change relationship but then we can always express in terms of the applied load and the resulting stress change.

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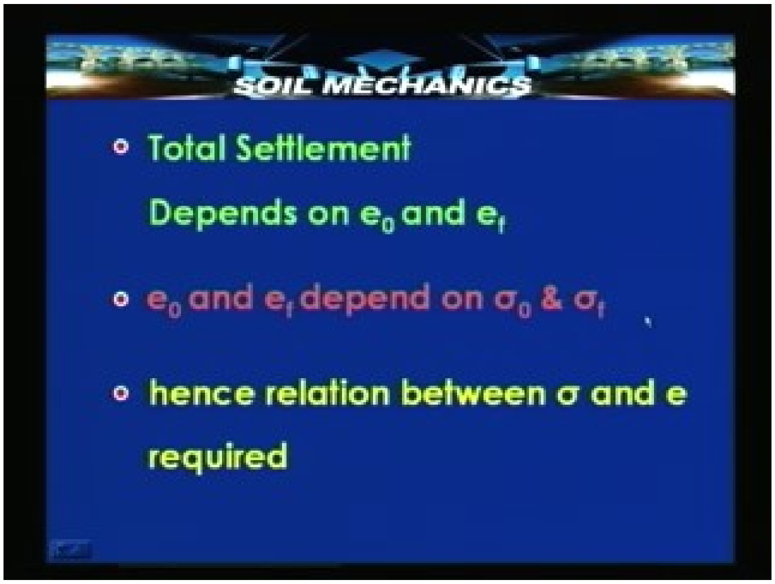

Let us take a look at the next slide. So now over and above what we had discussed in the previous lectures, in today's lecture we shall be dealing with how to relate the stress with the void ratio or the void ratios with the applied corresponding stresses. Then we shall see in general how compression of clays takes place? What's the type of e and p relationship? And how we can describe this in terms of certain compressibility parameters? And then of course we shall see what we have been talking about, that is the theory of one dimensional consolidation.

Let us go back briefly to the consolidometer or the oedometer. We know that in this we will have a soil specimen bounded between or sandwiched between 2 porous sand stones inside a container filled with water. When we apply a load drainage takes place, the water in the soil specimen oozes out is expelled through the porous stones and the soil specimen compressors. And a typical oedometer test consists of measuring this compression. What we do therefore is we have this dial gauge, we can measure the compression that takes place in the soil specimen in terms of thickness change. Suppose this is the original thickness of the soil specimen, the thickness let us say is H.
The change in thickness say delta H that takes place with every application of load increment can be calculated, can be in fact measured. So there is this dial gauge which

keeps on measuring the change in thickness. So we can take readings of this dial gauge, readings of this compression at different time values. So effectively in a oedometer or a consolidometer test the output that we get will be in the form of a table in which we will have time starting from zero to various different values and the corresponding change in thickness or in other words the initial and the final dial gauge readings which in turn will help us in terms of their difference to compute the change in thickness, which we are interested in. So if the initial thickness is H, the initial dial gauge reading is let us say d_0 and the first dial gauge reading is d_f due to a particular load increment, then the difference between these two will give you delta H.

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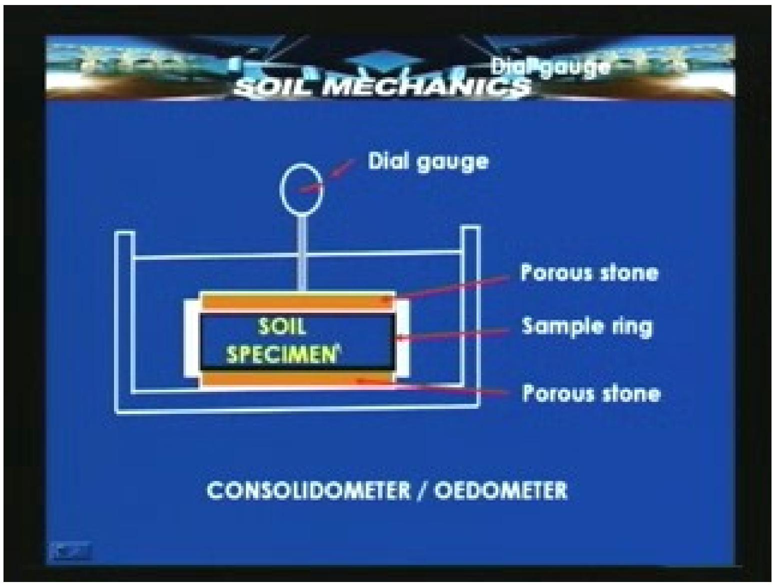

Now how and when do we know that we have to take the final dial gauge reading? Normally what happens is when you apply a stress, the compression phenomenon starts taking place. This compression phenomenon as we have seen is time dependant and that's the reason why we are looking into this phenomenon so critically. Theoretically speaking it goes on taking place indefinitely. But then from a practical point of view, the dial gauge reading which in fact depicts the compression becomes steady after a certain period of time.

Suppose we apply a load of, to begin with let us say 0.5 kg per centimeter square on the soil specimen. There will be some initial dial gauge reading which will correspond to the initial thickness of the soil specimen. Now when you increase the stress the specimen thickness decreases and therefore a new reading arises and this reading will go on changing with time. At some point of time, usually after 24 or 48 hours this change in reading is so small that the dial gauge cannot possibly measure this change in reading.

The dial gauge starts showing a stable, some what stabilized value of reading and its therefore important that in situations where the dial gauge readings is very small, we must be able to measure it very accurately which means that we need a dial gauge of very high accuracy. The least count to the dial gauge must be such as to capture even small changes in thickness of the clay specimen. Usually we use a dial gauge with a least count of 0.001 inch or millimeter. This is sufficient enough to capture the change in thickness that takes place with time and when the thickness change and correspondingly the dial gauge reading reaches a level which is below the least count of dial gauge, then the thickness will appear to be steady or unchanging and that is the time to apply the next increment of load.

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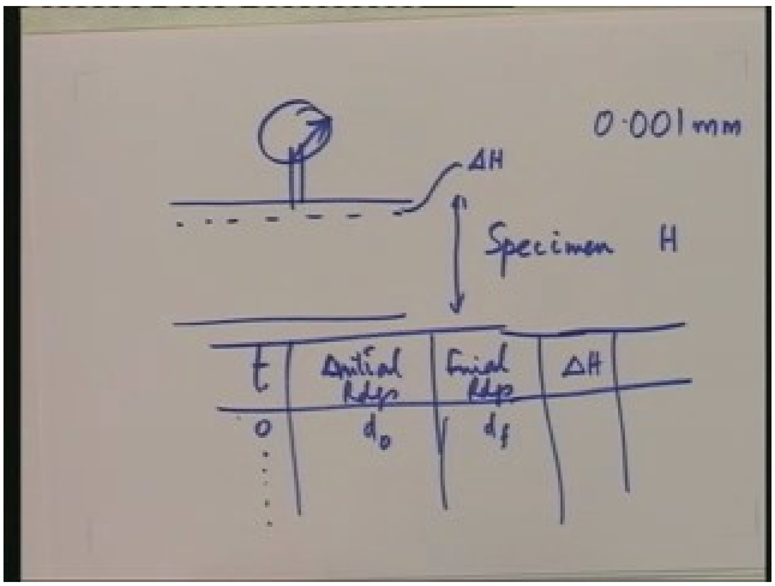

So we apply one increment of load, wait for the dial gauge readings to stabilize. This might take anything from 24 to 48 to 72 hours depending upon the type of clay that's in question, that is being tested. Then we apply the next increment of load and repeat this process with every increment of load and for each increment of load we will take readings from time t =0 to a certain value of time may be 24 hours or 48 hours and go on computing the change in thickness. Now this is effectively what we get from a typical consolidometer test. From this we can compute the void ratio.

Once you know the change in thickness since the change in thickness is essentially due to the change in void ratio, we shall be in a position to easily compute the change in void ratio e_1 - e_2 as a function of the change in thickness. This void ratio change since it is taking place due to a certain increment in stress we can also know what is the change in stress and what is the corresponding change in void ratio, change in thickness will lead to change in void ratio. And it is this information which is going to be of importance to us in computing in advance what's the change in thickness or settlement of that is going to takes place when a certain load increment is created due to the application of an external load in the form of an external activity.

Now this graph shows typical compression behavior of clay and sand to emphasize once again why we are particularly interested in computation of the settlement in clays only. Look at this graph, this shows how the compression takes place with time. Here the compression is expressed in terms of percentage of the total compression that takes place for any given load increment and you find that even after 60 minutes, this clay layer is showing considerable rate of compression. In fact in practice it is not in 60 minutes, this graph shows only the compression in percentage over 60 minutes but this is a phenomenon which goes on taking place over several hours even up to 48 hours. Whereas in the case of sands, the compression is very quick and within hardly 10 minutes the total compression has already taken place, 100% compression has already taken place.

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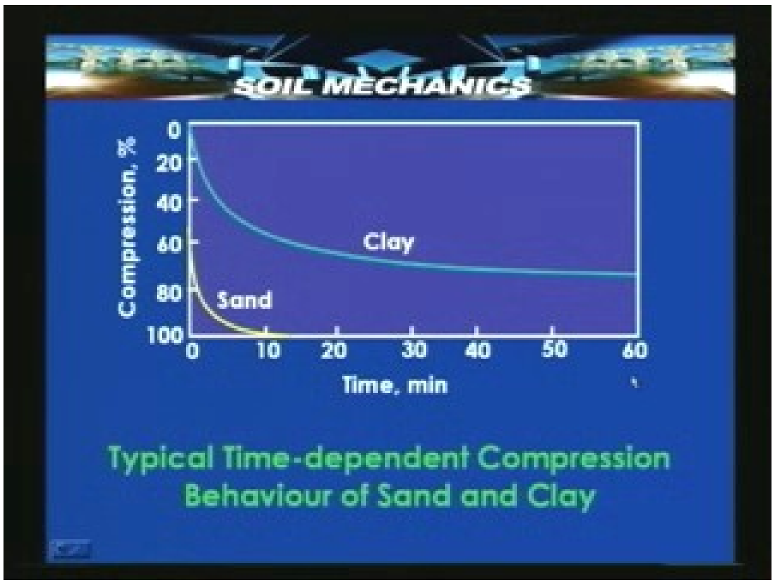

This is the reason why in clays we are looking for the time rate of compression and this as I had once mentioned is known as the hydro dynamic lag. That is there is a lag between the compression and the expulsion of water. As the water gets expelled out of the voids compression is induced. There is how ever a certain difference in time between the actual expulsion of water and the corresponding compression taking place. This time difference is known as lag and this lag is known as hydro dynamic lag because it's essentially a lag in between hydro dynamics and the resulting compression. That is the flow or expulsion of water and the resulting compression.

This hydro dynamic lag is what is primarily and essentially responsible for a slow compression, a compression that depends upon time and that's what this graph depicts. And in case of sands most of the compression is almost instantaneous and so we are more interested in initial settlement in cases of sands and other course grained materials, where the flow of water takes place relatively rapidly due to their high porosity or high coefficient of permeability.
And in case of sands, I might also mention here that very often the so called initial compression takes place fast and in fact during the very application process of the load or during the very activity of construction of a building. And therefore what ever adjustment is required takes place during this settlement, during the construction of the building itself

and hardly any compression takes place during the life time of the building and the building therefore functions very well in cases of sands or gravels. But in cases of clays even after completing the construction of the building, since the settlement can continue to takes place under the total load of the building, the importance of consolidation and the corresponding settlement arises.

Now we were talking about the oedometer test, the dial gauge readings and the computation of thickness change and void ratio. Now take a look at the typical oedometer curve. The oedometer tells us for any given stress that is applied what is the corresponding void ratio and how the void ratio changes with application of stress. This is what we get from the dial gauge readings of a typical oedometer test. Now if you look at this typical graph which is known as the void ratio versus effective pressure ratio graph, there are a number of important points to be understood.

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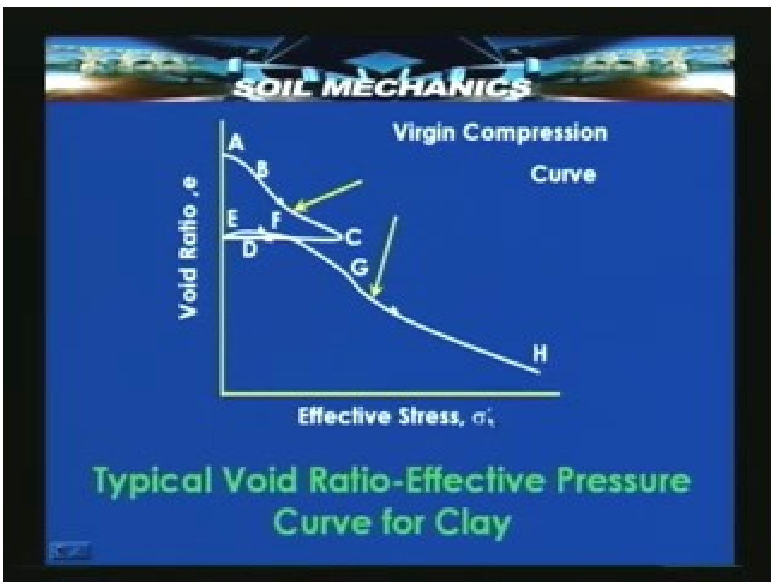

Suppose we start compression from a value of void ratio E corresponding to zero state or zero stress increment in the given soil. When there is no stress, when the soil is under its initial state, the void ratio has got a certain value corresponding to point A. Then as you apply the stress and the corresponding effective stress sigma dash then the void ratio keeps on decreasing, it reaches a value to a point corresponding to B and then goes on further decreasing, reaches a point corresponding to this C and this portion is known as virgin compression curve. Because this is a compression that takes place for the first time under this stress. Initially this compression had not taken place because the stress that was existing in the soil was corresponding to this zero state.
Actually this zero state corresponds to what ever initial stress or the over burden stress that is existing in the soil and therefore corresponding to the initial void ratio E, but any void ratio change that is taking place from A to B to C is essentially due to this increase in stress or the additional stress that has now been added due to the construction activity. And therefore this compression is taking place due to the stress for the first time and so it

is known as the virgin compression curve. Now suppose you have come to point C and you have decided to remove the load, then when you remove the load the void ratio will try to regain its original value and there will be a decompression curve such as C D. Now suppose you have reached the point E, you will notice that although you have removed the stress the void ratio is bouncing back to its original value. It doesn't actually reach the original value; it stabilizes at some value such as E and original value A is never reached.

This is precisely why we say that the compression in a clay layer is not an elastic phenomenon; it is a time dependant inelastic phenomenon. Therefore the original void ratio is never recovered as you go from C to D to E the void ratio E that is finally reached during this decompression part is never equal to A, it will always be much less than A. Now suppose you once again go from E, start applying the load then we are actually recompressing the soil which had already been compressed once. Therefore from E to F, the compression will gradually take place along a line which is almost parallel to this ABC and will reach a certain point G corresponding to the load which had been applied earlier. That means we had applied a load corresponding to this point C and then we had removed the load, decompress the soil.

Now when you recompress this EFG will correspond to the recompression curve and when the stress once again reaches a point G, that is corresponding to the same stress as the point C, once again that you will find that the soil is undergoing compression further compression under additional load for the first time, which means that this portion is again a virgin compression curve. This is typical of all clays and this is known as therefore a typical E sigma dash curve, very often this curve is known as the EP curve, P standing for pressure in general.

Now let us take another look at this curve. Here is another version of this curve; there could be minor variations in the nature of the curve. It could be slightly deviant from the curve which we saw in the previous slide but essentially it will always have this 3 components original virgin compression curve, the decompression and the recompression curve and then once again after the stress reaches the value corresponding to point C again a virgin compression curve going up to H. But now what is the difference between this graph and the graph which we had seen in the previous slide?

We saw in the previous slide that this phenomenon is a highly non linear phenomenon, although it appears to be linear some what in this ranges, it is relatively non linear in nature and therefore we prefer to plot this E versus sigma dash curve on a semi log graph. Void ratio is plotted to natural scale where as the stress change is plotted to log scale. So you will find now there is a small difference between the previous curve and this curve, here the virgin compression curve is almost linear.

It is always good to have such a graph where the relationship which is actually non linear gets converted into relatively linear relationship. That is void ratio versus sigma dash graph was non linear where as void ratio E versus log sigma dash graph is relatively linear and it now becomes much easier to establish a linear relationship between E and sigma dash which is very convenient to use.

Let us see next slide. This is how we establish the relationship between E and sigma dash. First we plot sigma dash to log scale versus E and from this E versus log sigma dash graph which is commonly known as E versus log P graph, we determine the parameters which are essential to describe this relationship between E and sigma dash. The relationship between E and sigma dash can be expressed in terms of this linear graph between E and log sigma dash. And what is the best parameter to depict any linear graph? The best parameter to represent this linearity, the relationship that is linear is nothing but the slope of this linear part of the graph which means in this case the slope of this line linear segment which is C_c, which is written here as C_c.

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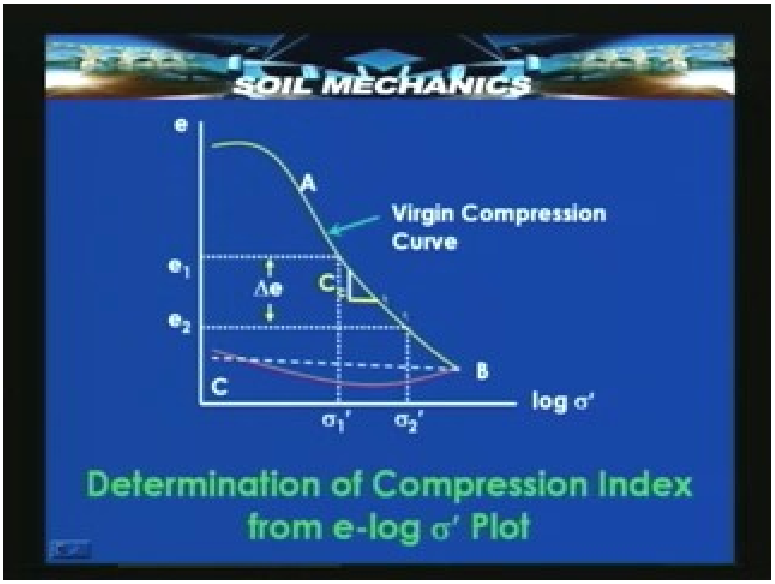

C_c is a parameter which depicts basically the slope of this compression curve drawn to semi log scale and this compression coefficient or this parameter which represents the slope of this graph is known as the compression index. That is it is an index of the compression and this compression index completely depicts the linear relationship between E and log P or log sigma dash and can now be used to relate change in void ratio with change in stress sigma or for that matter change in log sigma. Let us take any 2 values of E the void ratio and the corresponding stress and C. Suppose there is a stress increment from sigma_1 dash to sigma_2 dash, during any stage in the compression of the soil, let us say at some point of time the stress is sigma_1 dash and at a subsequent instant of time the stress is sigma_2 dash. That means we have increased the stress from sigma_1 dash to sigma_2 dash over a certain period of time and correspondingly the void ratio has decreased from a value e_1 to a value e_2.

So when e_1 to e_2 change takes place and corresponding stress changes from sigma_1 dash to sigma_2 dash, if the slope for this range or this segment of linearity is C_c, then we can express the relationship between delta E and delta sigma in terms of C_c as follows. Here this shows that C_c is a negative slope, that is minus of delta e by delta log sigma, logarithm of sigma_2 dash minus logarithm of sigma_1 dash is nothing but the logarithm of the ratio of sigma_2 dash to sigma_1 dash. And that's what is written here, the ratio of sigma_2 dash to sigma_1 dash and logarithm of that and this is the change in void ratio. Now we know that e_1 is greater and e_2 is lesser and once we express in terms of e_1- e_2 divided by log sigma_2 dash by log sigma_1 dash, C_c becomes a positive quantity and it is this positive quantity C_c which we can use in a relationship like this for computing the settlement subsequently.

Usually in order to estimate C_c we take a range of stress which is in the ratio 10:1. Let us see the graph again, here sigma_2 dash and sigma_1 dash are plotted to logarithmic scale which means that if I take sigma_1 dash corresponding to some unit and if I take sigma_2 dash corresponding to 10 times that unit, then this log sigma_2 dash by log sigma_1 dash will become log of sigma_2 dash by sigma_1 dash which is just equal to log of 10 or unit. That means for unit change in stress along this axis, we find the change in void ratio and get the slope which in fact is nothing but the compression index.

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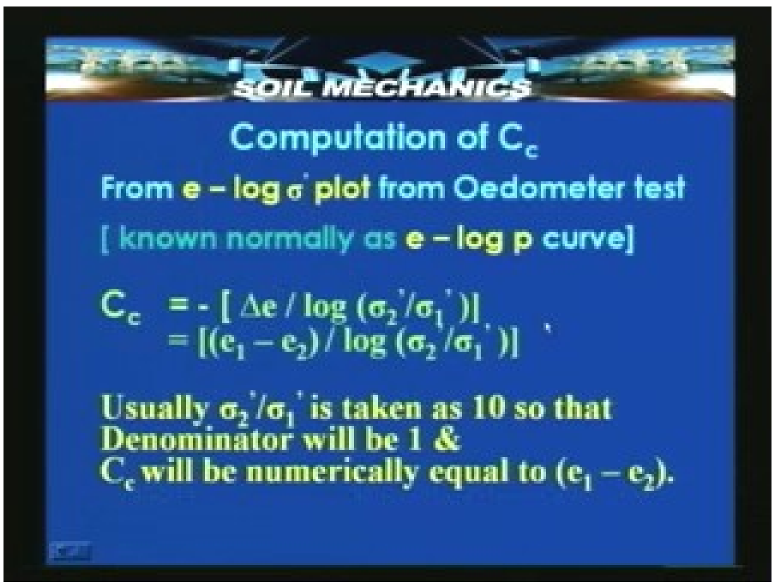

So taking 10:1 ratio between sigma_2 dash and sigma_1 dash we will be able to find out C_c which will be nothing but numerically a value equal to e_1- e_2, e_1 and e_2 are non dimensional and therefore e_1- e_2 represents a non dimensional slope C_c. Now let us see how we make use of this e log p relationship in computing the total settlement. We shall initially confine ourselves to the computation of the total settlement and then subsequently take up the problem of computing the rate at which the settlement takes place.

So now so far we have seen that the total settlement can be computed if we know the change in void ratio and we can get the change in void ratio if you conduct an oedometer test and measure the change in thickness and from a plot of void ratio change versus change in stresses and the corresponding slope we will be in a position to obtain the relationship between the change in void ratio with change in stress. So imagine a situation where we have got a soil layer which is let us say clay and is saturated. We now construct an object on this which causes a change in stress from the original stress. The original stress is essentially due to the over burden and from the original over burden stress, with this additional stress that is being imposed we get a new final stress and original void ratio which is e_0 corresponding to the initial state of stress due to the over burden, now changes to a new value e_1.

If we know the change in stress because it is possible to know because we know the stress change that we are going to impose due to the construction activity. We will know what is the corresponding void ratio and corresponding settlement. If this settlement is now excessive beyond certain permissible values, we go backwards. We in order to reduce the settlement we reduce the change in void ratio and that means we change the stress change, we reduce the stress change which means that in practice we will have to actually reduce the stress levels that are being transmitted to the soil. One way to reduce the stress level which is being transmitted is to increase the dimensions of the foundation over and above what had originally been assumed in the preliminary design of the foundation of the building.

Let us take an example and see how all this works out. To begin with let us take a simple instance where we prepare the ground for a construction activity. We know that the natural ground is never leveled, so it’s a very common practice to level the ground before we build the building. For leveling the ground we usually use all kinds of material, waste material construction debris for example and we lay it in the form of a layer over the existing natural ground and then compact it and make it level. We can understand this when I show you a diagram in the next slide.

Suppose there we prepare or lay a fill of this kind with waste material which is 2 meters in thickness and we compact it to a unit weight of 22 kilo Newton per meter cube. Then let us now assume that this layer over lays a natural succession of layers which has already been existing there and that natural succession consists of a saturated clay layer bounded on both sides by sand layers. Now what is required here is, what is a kind of settlement that will emerge due to this fill material itself. Now this fill material has its own weight and therefore for all practical purposes it acts like a building and it imposes stresses on the clay layer and it causes the settlement and that settlement itself is important from point of view of knowing, what is the consolidation behavior of the claim. It’s a different matter that this fill material is a flexible material, this layer is a flexible layer and even if there is a lot of settlement in the succession of natural soil layers which are below, the fill layer can still adjust. But on the other hand if we put a building on that and if the settlements are excessive, the building cannot adjust itself to the excessive settlements where as this fill layer can adjust itself.

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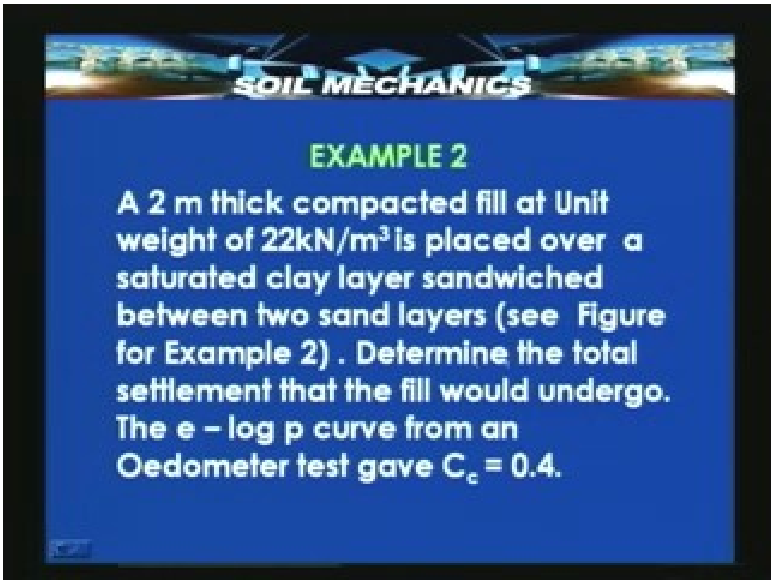

And therefore we shall compute the settlement due to this fill layer and we shall not bother at this stage as to whether it is excessive or within limits and how to contain it within limits. Let us just go over the mere process of computing the settlement. Here is the succession of layers that I am talking about. In all there are 4 layers, the first layer is the fill material of 2 meters thickness which has been laid and compacted over the natural ground that is existing through borehole investigations, sub surfaces investigations. Let us assume that it has already been established that the sub surfaces consists of a 6 meter layer of sand, underlined by an 8 meter layer of clay, further underlined by a draining layer.

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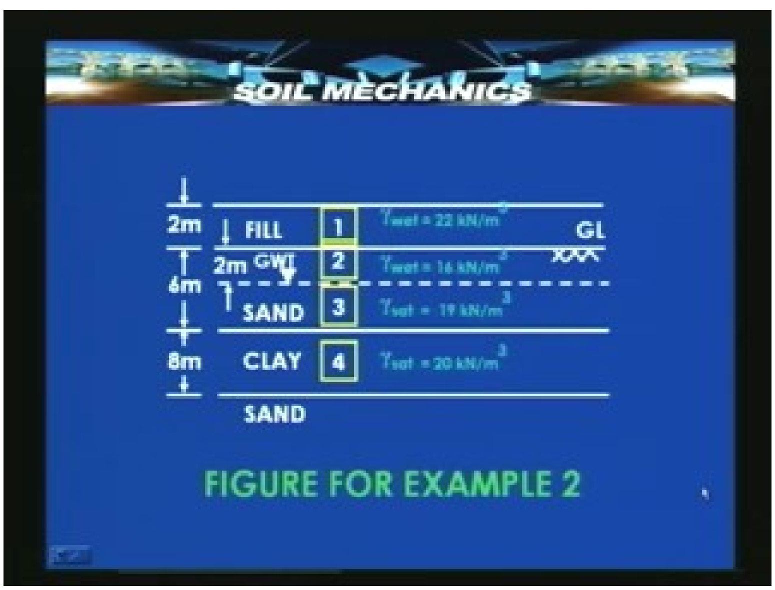

We need to make assumptions like this, from point of view of drainage. The reason why we have taken sand layers above and sand layers below is we are going to assume one dimensional consolidation that is there is going to be a flow of water in the vertical direction in one direction and corresponding compression also in the vertical direction. And the water can flow, it can be expelled only if there are porous materials, porous layers above and below. And that's the reason why we have assumed a natural succession of layers consisting of 2 sand layers between which a clay layer has been sandwiched. Now further we have one more detail added here that is the ground water table is not right up to top of the ground surface but it is 2 meters below the original ground level. That means a 2 meter part of this sand layer at its top is just moist or wet but not saturated and the fill layer which is above is also moist or wet because it has been compacted by adding water to it and therefore the top two layers, numbers 1 and 2 are moist or wet layers where as layer 3 and layer 4 also are both below water level and therefore are completely saturated.

This detail is important for computing the initial state of stress that exists in the clay layer. Let us see how to compute the initial state of stress or how to solve this problem in general. The solution consists of a series of steps, there are as many as 8 steps as you will see shortly. The first step is understanding the problem, since it's a clay layer that's undergoing compression, the compression in sand layers is not of any consequence. We shall compute all stresses or stress changes and the void ratio changes in the clay layer only. Since clay layer has got a certain thickness, we will compute the stress changes and the void ratio changes at the middle of the clay layer so that we get an average value over its entire thickness.

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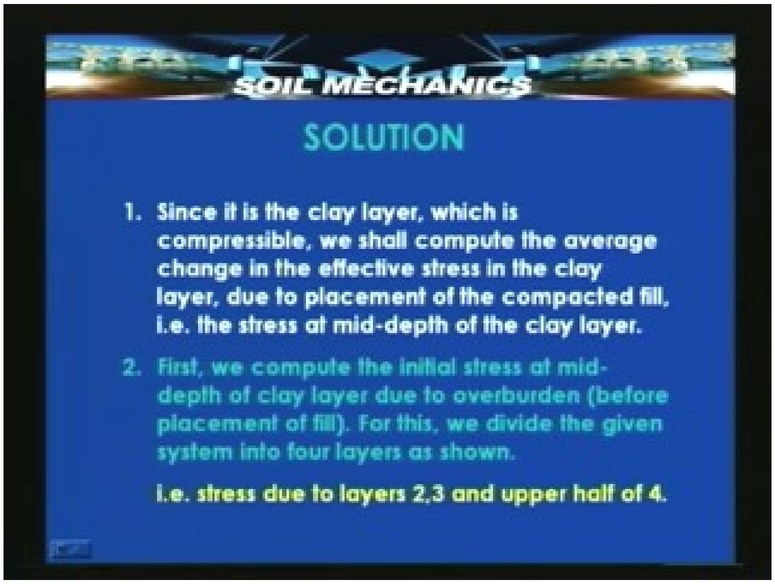

So for all practical purposes we will assume that the clay layer is homogenous and an average value of stress change or void ratio can be obtained by simply considering a point at mid depth of this clay layer.

We shall compute the average change in the effective stress in the clay layer due to placement of the compacted fill that is the stress at mid depth of the clay layer. First what we do is we compute the initial stress that is already existing before placement of the fill. Again at the mid depth of the clay layer, for these what we do is we divide the given system of layers into those 4 layers, 1, 2, 3, 4 as I showed in the previous diagram. Out of these 4 layers 1, 2, 3 and 4, 1 initially does not exist where as 2, 3 and 4 exist. Layer 2 is moist or wet it is not fully saturated, layer 3 and layer 4 are fully saturated.

And therefore in computing the initial stress at the mid depth of the clay layer, we have take due note of the fact that the unit weight of the layer 2 although it is also a part of the sand layer is different from the unit weight of the layer 3 both though 2 and 3 together constitute the same sand layer. So we shall be computing the stresses due to the layers 2, 3 and the upper half of 4 because we are considering the mid point of the layer 4. What shall be the stresses? Layer 2 has a thickness of 2 meters and its moist unit weight has been given as 16 kilo Newton's per meter cube.

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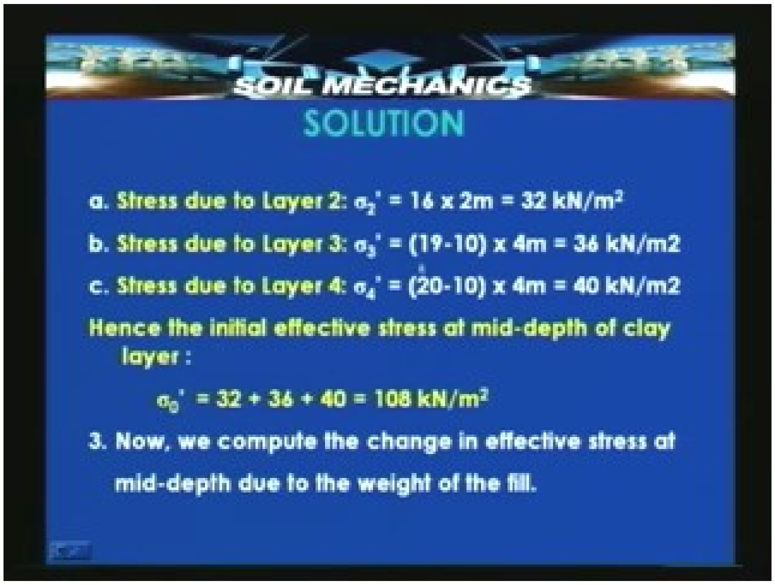

Therefore the corresponding stress at mid depth of clay layer due to this overlying layer of wet sand is 16 × 2 = 32 kilo Newton per meter square. Now the third layer is fully saturated and therefore the unit weight that is responsible for computing the effective stress in this layer shall be the submerged or the buoyant unit weight. The effective stress at mid depth of the clay layer due to layer 3 which I am calling as sigma$_3$ dash is going to be therefore the saturated unit weight of this layer minus unit weight of water. So that we get the buoyant unit weight 19-10 in to the saturated depth of the sand layer that is 4. So 19-10 in to 4 that is 36 kilo Newton per meter square that is the stress that arises at the mid depth of the clay layer due to the weight or the self weight of the lower part of the sand layer.

Now in this we have made one small assumption which although mentioned in the slide, I had not elaborated upon that is we assume that the loading is of a very large extent and for all practical purposes the self weight of the layers can be considered to be transmitted to the mid depth the clay layer with out any change. Let us take reference to the Boussinesq theory and the stress distribution theory that we saw in some of the previous lectures. We saw there that if there is a load that is applied to the surface of a soil layer, there is a distribution of the stresses and at any point here we have to compute the stress due to this applied load through boussinesq theory because there is a dispersion of stresses. But here since the layer is uniform and is of a very large extent, the sand layer for example at mid depth of the clay layer what ever stress arises due to this sand layer we take as equal to the weight of the sand layer itself without accounting for any reduction due to dispersion.

This is valid because we are assuming a very large extent of loading as part of our over all assumption that the phenomenon of consolidation that we are considering is a one dimensional phenomenon. So subject to this assumption sigma$_3$ dash or even sigma$_2$ dash will all be merely be equal to the self weight of the material distributed uniformly with out any reduction or dispersion within the clay layer. So now the stress at the mid depth of the clay layer due to the clay layer itself, the upper half of the clay layer which is 4 meters in thickness which has a unit weight of 20 is also saturated and therefore the buoyant unit weight applies here also. So 20-10× 4 gives you 40 kilo Newton's per meter square this means that the initial effective stress before the application of the fill layer is sum of these 3 effective stresses that is 32+36++40. That's going to be 68+40 or 108 kilo Newton's per meter square.

Now this initial state of stress has a corresponding void ratio and that's the starting level and beyond this when we apply the fill layer there is an additional stress that arises and correspondingly a reduction in the void ratio. So now we compute the effective change rather the change in the effective stress at the same mid depth of the clay layer but now due to the weight of the back fill. The fill layer that is assumed also to be of large extent transmits entire self weight to the mid depth of the clay layer. So again because of the one dimensional consolidation assumption. So this stress change or stress increment that arises due to the fill layer at mid depth of the clay layer will be equal to the weight of the fill layer which is 22 kilo Newton per meter cube which is the unit weight, wet moist unit weight because that fill layer is not saturated into the thickness of the fill layer which is 2 meters and therefore the stress change is 44 kilo Newton per meter square.

Now therefore the final effective pressure at mid depth of the clay layer after the activity of the placement of the fill will be equal to the sum of sigma$_0$ dash and delta sigma dash that is 108+44 that's equal to 152 kilo Newton per meter square. Now corresponding to this there are 2 ways of computing the settlement. Suppose we know the initial and final void ratios corresponding to these 2 levels of stress, that is corresponding to what ever we saw in the previous one, corresponding to this 108 kilo Newton per meter square and corresponding to final stress of 152 kilo Newton per meter square, then we can calculate the settlement.

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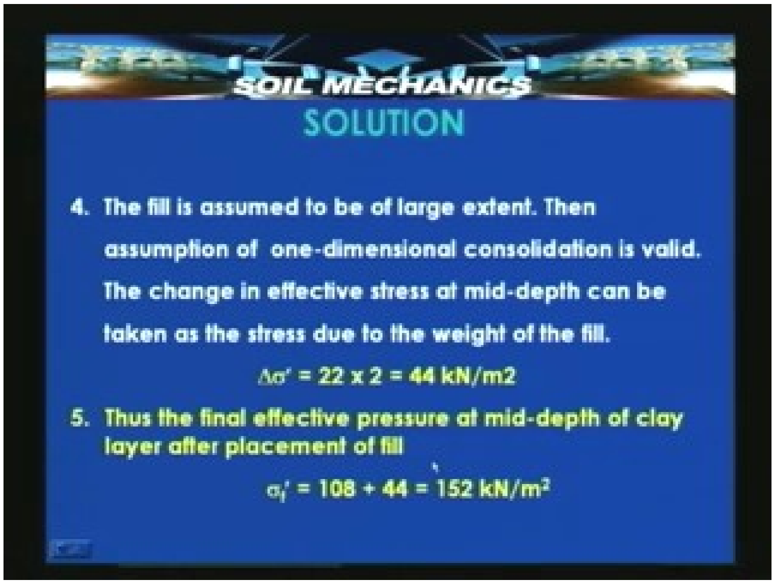

Let us say that the void ratio corresponding to the 108 kilo Newton per meter square is 0.555 and that corresponding to the final load is 0.500. Then as per our formula for computation of settlement, we will get S is equal to change in void ratio that is 0.555 minus 0.500 divided by the original volume that is 1 + 0.555 multiplied by the original thickness of the clay layer which is 8 meters, this will give you 0.283 meters as the settlement that takes place and that's equal to 283 millimeters. Now this settlement has taken place because of a change in stress from 108 to 152 kilo Newton per meter square. In this computation since we knew the void ratios, initial and final we have made use of them to compute the settlement.

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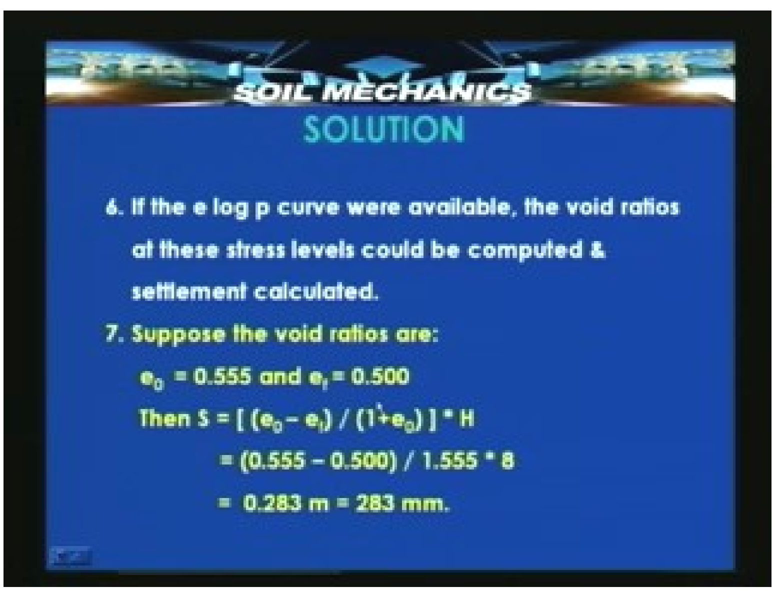

How ever we can also compute this settlement in terms of the stress changes that is by using a formula which computes the settlement in terms of the relationship between void ratio and logarithm of sigma. We have seen that C_c which is the slope of the compression curve can be computed and suppose the value of C_c that we get for this particular problem is 0.38 then using this formula, that is we shall be replacing e_1- e_2 that in terms of the stress change.

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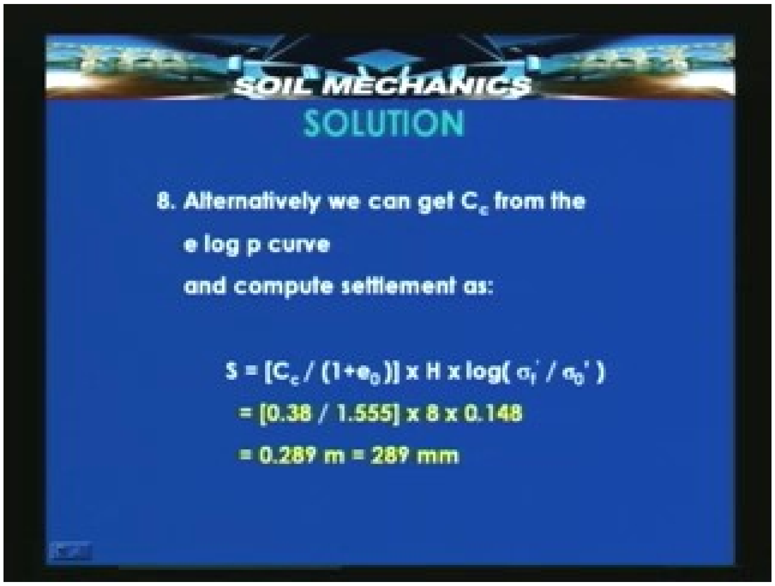

What ever void ratio change is there is now expressed in terms of slope C_c and the stress change in logarithmic terms. This gives us a value of settlement equal to 289 millimeters. So we can compute the settlement if we know the dial gauge readings or the void ratio changes from the oedometer test and if we have the e log p curve, we can determine the C_c value and then the corresponding total settlement. Thus from the e log p curve we can get the slope of the linear plot to the curve and get the corresponding void ratio change and settlement. Now what value of C_c should be used, actually for all practical purposes C_c can be taken as constant.

How ever if we want to be a little more precise we can calculate C_c corresponding to the load change or the stress change that takes place in an actual situation. But if we want to use an average value as we said earlier, we can choose 2 stress values, the second value being ten times the first value. So that we get the distance here or a logarithmic scale as one unit. Now this is not the only parameter that depicts compression. As I have been saying we also need to calculate the rate of consolidation and for that we need other compressibility parameters and there are 2 other compressibility parameters which are defined with respect to e and p relationship, one of those compressibility parameter is also determined from this e sigma dash curve but drawn to natural scale and not to log scale.

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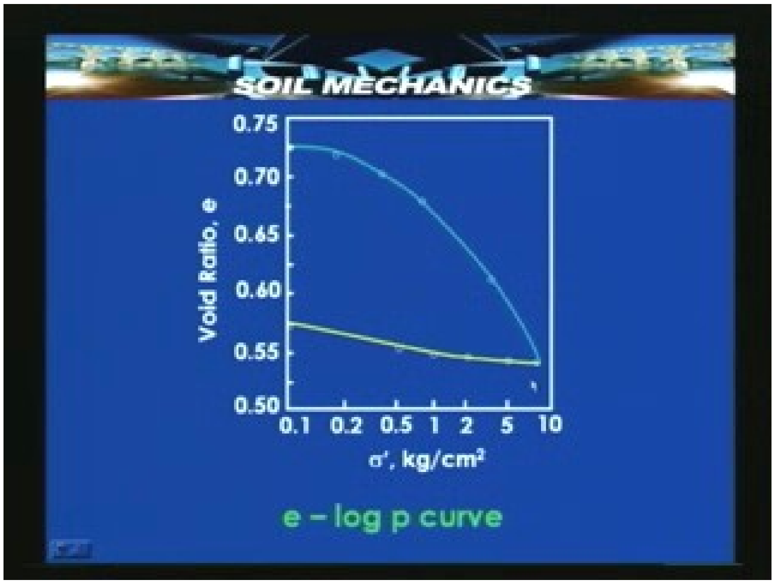

For example that parameter is known as the coefficient of compressibility and that's equal to the void ratio change divided by not the logarithm of stress change but the stress change itself. Now we also have another parameter known as the coefficient of volume decrease or volume change or volume compressibility which is nothing but the change in void ratio per unit void ratio divided by delta sigma dash that is a_v upon $1+ e_0$.

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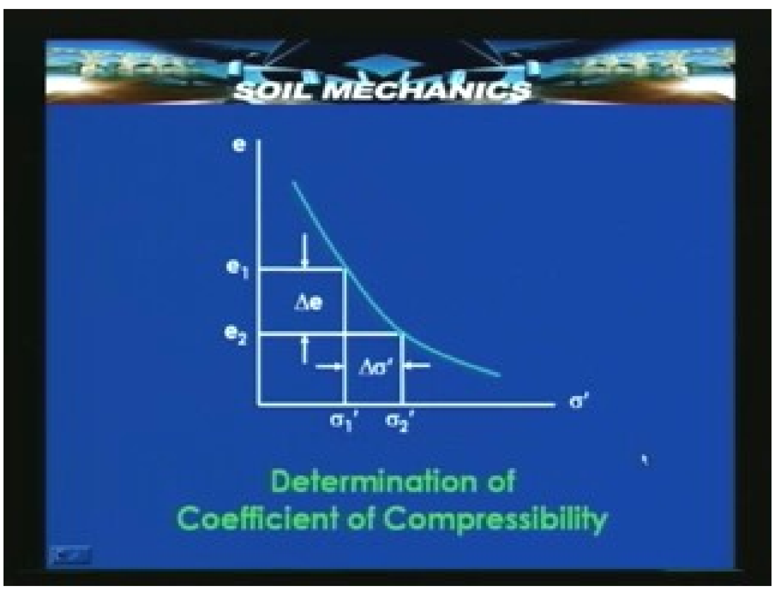

These 2 parameters are particularly useful to us for computing the time rate of compression. Because these ep curve which is non linear has values of a_v and m_v which go on changing with time as the stress changes.

And therefore there is a way here to relate the change in stress with time to change in void ratio over the same period of time. And thus comes the relationship between e and sigma which is time dependant and from which we can calculate the time rate of settlement.

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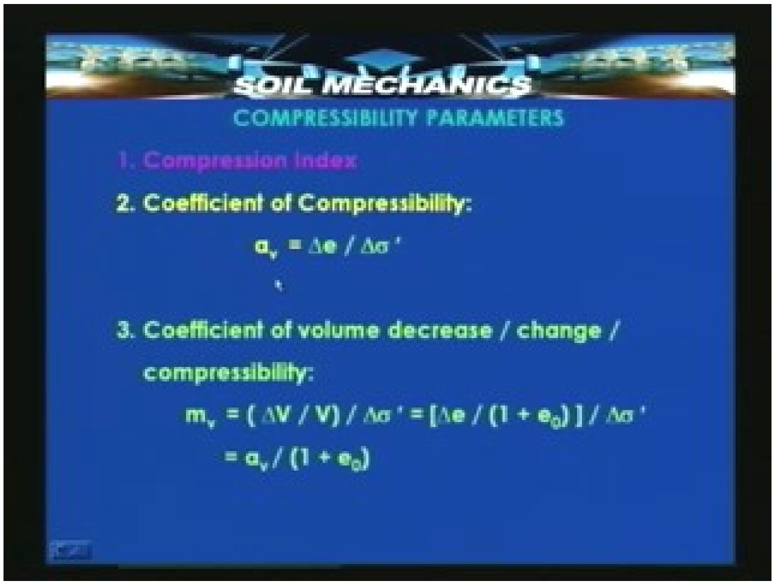

There is one other important concept that is we have been talking about decompression and recompression and when we recompress up to some point of time the stress is within the value of the stress with to which the soil has been compressed earlier. And that part that stress to which it had been compressed earlier is known as preconsolidation pressure.

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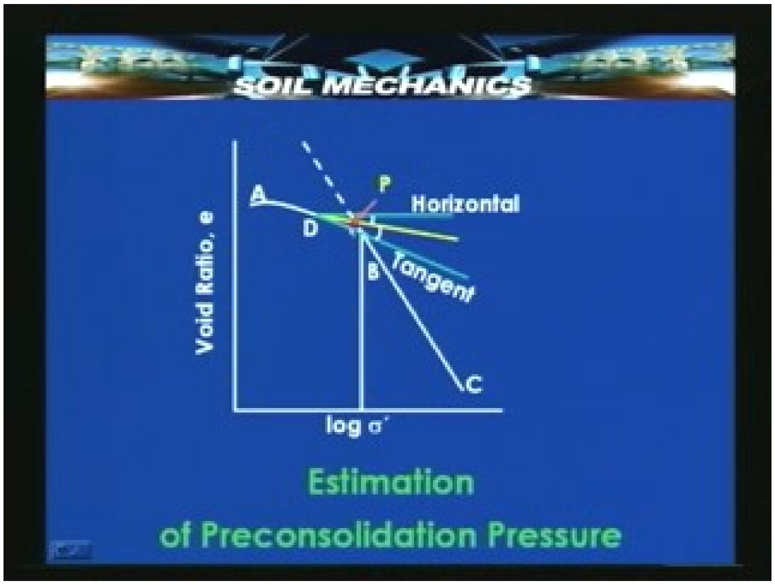

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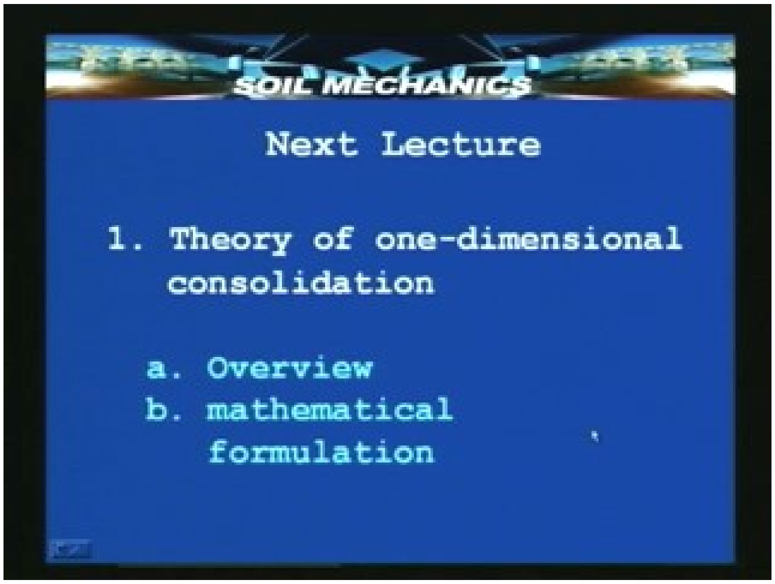

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And it is very often important to know this preconsolidation pressure, there is a measure for computing this which we shall see in the next lecture. So in this lecture we have seen what kind of results we get from the oedometer test, how we can use this for computing the compression and how theory of one dimensional consolidation has been useful in computing settlement. We will see in the next lecture how we can compute time rate of settlement, we shall have a quick overview of theory of one dimensional consolidation. And see the mathematical formulation that leads to computation of settlement with time. Thank you.