Soil Mechanics
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Lecture – 35
Consolidation and Settlement Lec No. 2

Students we meet again today for the second lecture on consolidation and settlement. As this is the practice I will briefly review what we have already gone through in the previous lecture. Further more this topic is of much practically importance, this affects every building that is build on soft soil and such buildings are many on water front in particular where you find marine or river in clay deposits. In view of this importance of this topic it is absolutely necessary that the very basic fundamentals regarding consolidation behavior of clay is well understood. Therefore I will go over some of these basic concepts once again.

Lets us take a look at the slides to begin with. In the last lecture we gained a fundamental idea about the consolidation phenomenon that is what is this phenomenon all about, what does it consist of, how does it takes place. And we also saw towards the end of the lecture how to compute the effect of this consolidation behavior that is how to compute the amount of settlement that a building will undergo. So we started with answering some basic questions essentially, we answered 2 questions out of 5 which I had raised which I had post. The two basic questions that I had raised were what is consolidation and what is settlement. Until we really understand what is consolidation or what is settlement it is very difficult to understand that relative importance, understand where it is really important and also to know how to make reliable computations about the effect of consolidation in any given situation. So what is consolidation? There are many different ways in which we can probably explain this.

Let us see what causes consolidation once again briefly and then come to the formal definition of consolidation. Let's take a look at the next slide. What is consolidation? It's a form of stress strain behavior that is you apply a stress there is going to be a strain. So consolidation is all about application of a load and the resulting deformation or the application of a stress and the resulting strain. So stress strain behavior results in consolidation. It is obvious that different soils even clays themselves will have different stress strain relationships although the basic pattern may be the same, the actual stress strain relationship could be different from clay to clay and therefore the degree to which the consolidation will take place under a given load will vary from place to place. And it is required therefore to have a unified theory which will explain to us, for a given stress how we can possibly evaluate what strain will result. So what is consolidation once again? It is nothing stress strain behavior and what is settlement? It's a form of compression. When a stress is applied, when strain takes place or when deformation takes place there is going to be a compression of the soil under the acting load and this compression is what is known as settlement, settlement is a result of consolidation. As I had mentioned in the last lecture terzaghi has pointed out there are basically two different classes of problems in soil mechanics. Those which can be considered as stress strain deformation problems and those which can be considered as stability problems. For example if you take the stress distribution problem which we had dealt with in some detail in one of my previous set of lectures is a typical elastic stress strain behavior. This elastic stress strain behavior indicates that the strains are recoverable when the stress is removed and essentially the equilibrium or the stability is not disturbed. The equilibrium in fact was ensured when we talked about stress distribution by tacitly assuming that every element of soil in a medium is in equilibrium. On that basis we derived a set of equations which told us how stress is distributed.

So stress distributions problems inherently imply that there is equilibrium where as on the other hand there are stress strain time relationships in which given a stress, the strain goes on varying with time or some times given a strain the stress goes on varying with time. And such problems where the strain may vary can be described as viscous elastic crib behavior and so on. These are terms which we had briefly gone through in the previous lecture. Under this class of problems where stress strain time behavior is involved, again there are two different problems one which can be called as the consolidation problem another the stability problem. This consolidation problem is a problem of large deformations or large strains where as slope stability or foundation stability or problems were there are again large deformations but these deformations indicate failure of the structure. So we have problems in which shear stresses are less than the shear strength but displacements are large. Such problems are consolidation problems and we have problems were shear stresses exceed their strength of the soil and such problems are known as stability problems.

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So in a nut shell consolidation problems are problems where there is no failure, there is no question of stability but there are large deformations and time dependant deformations. In order to understand this consolidation phenomenon we had gone to the very basic aspect of how a soil is made of or made or what it consists of. We all know that an actual soil consists of a number of soil particles or solid particles within which there are voids. We know that although there are solid particles and voids present inside them some times they may be filled with water for purposes of understanding stress strain behavior it is convenient to idealize this situation and consider what is known as a three phase module. It is a well known model I am very sure you must have been already told about this in some earlier lecture by some other speaker. Let us take a look at this three phase model. This three phase model consists of solids that is the solid particles constituting the soil. They constitute water and air which together fill the voids which make up the voids.

So essentially there are two components solids and voids and within voids again there are two components water and air or in more general terms fluid and gas. Now the part which encompasses solids and the voids together is known as the skeleton of the soil. So the skeleton of a soil which is nothing but the three phase model consists of solids, water and air and if the soil is saturated that means the air is replaced by water then there are only two phases the solids and the water.

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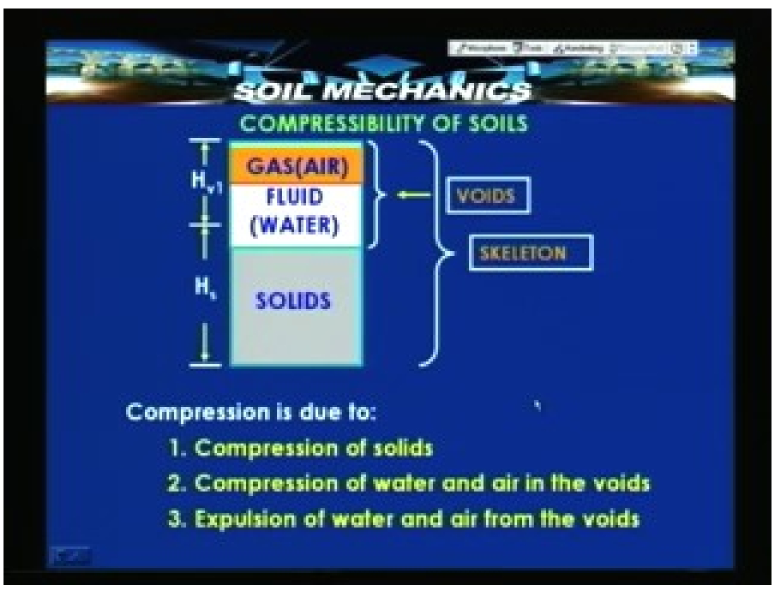

Now this is fundamental to understanding compressibility of soils. This is fundamental in the sense that compressibility of a soil depends upon the compressibility of its constituents. There are three constituents the solids, water and the air. Each one has its own compressibility behavior. For example suppose a load is applied on this three phase model then first let us take gas. Gas is compressible, when a pressure is applied gas is compressible and it does compress but if gas is not there then we are left only with water and solids. Is water compressible? Normally water is not a compressible fluid, it is an incompressible fluid and therefore if load is applied to water it cannot deform and the only way it can withstand the load is by movement and that is what you are going to see which is responsible for the consolidation and settlement.

So water can be taken as the incompressible then what about the solids. The solids are also relatively incompressible under the loads to which we normally subject a soil through some civil engineering activity like a dam or a building or a retaining wall or what ever. The requirement in any civil engineering actual structure is that it should not load the soil to such an extent as to cause a failure. We are not dealing with stability or failure problems, we are only dealing with the problems where the strength is not exceeded and only large deformations takes place. So the stresses are all within such limits as not to cause breakage of particles not to cause compression of particles which means that the water is incompressible, the solids are also incompressible within the range of loads that are applied.

Then how does compression take place and there is no gas, how does therefore compression takes place? Compression can only take place if water is expelled out of the voids and the particles orient or move, shift and reorient or readjust themselves. This in fact is the phenomenon or this in fact is the action that is responsible for what is known as consolidation phenomenon. So let us take a look at what is written here. Compression is due to first the compression of the solids but that is ruled out, compression could be due to water and air in the voids but if air is not there compression of only water which is again ruled out which means that expulsion of water and air or only water from the voids and readjustment of particles can only be the reason for compression to occur. So now we can say that consolidation can be formally defined.

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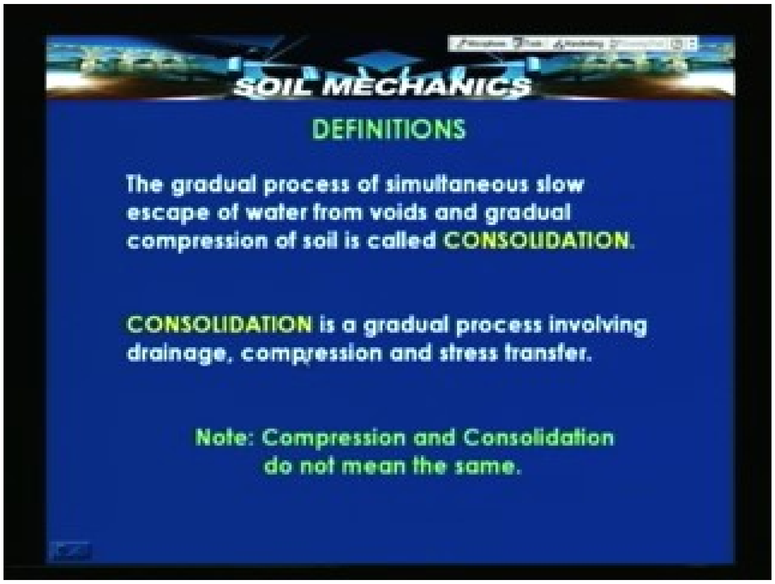

What is their formal definition? Let us read, the formal definition of consolidation is it's a gradual process of simultaneous slow escape of water from voids and gradual compression of soil. The word slow escape and the word gradual compression are very important because consolidation is a phenomenon where the load is applied gently. That is no impact load and when the load is applied gently the water takes its own time to get expelled and the particles take time to get readjusted and so the resulting process is slow escape of water and gradual readjustment of particles or gradual compression of the soil. So three aspects are there, gentle application of load, gradual flow out of water and gradual compression of soil. This gradual flow of water out of the voids is what is responsible for the time dependency of the consolidation phenomenon. As we saw in one of the earlier slides it is a stress strain time behavior and the time aspect comes in mainly because of the presence of the incompressible water which can take load or which can pass on the load only by moving out. And how does it move out? Now we must remember we are here considering saturated soil and suppose we are considering clays. We all know that the permeability of clays is very low, it could be of the order of 10 raise to minus 6 centimeter per second which is a rather low value, it could be even lower. With such a permeability value and with very small voids the water has to necessarily take time to flow out of the soil.

The process of flowing out is in view of this permeability is very slow and that takes place over periods of weeks and years some times in an actual case depending upon the load and the soil. And this is what is responsible for the time dependant deformation which is known as consolidation. Now another definition for consolidation is it's a gradual process involving drainage, compression and stress transfer. The meaning of the word stress transfer needs a little explanation. Suppose we have all these particles with voids in between them and water occupying these voids, when you apply load since the water is flowing out it could even flow outwards like this against the load. When the water flows out the particles are readjusting themselves and therefore water cannot take load. Since it is not residing in its original position since it is moving out, what really happens is the applied load ultimately gets transferred to the solid grains as the water goes out again gradually and as the particles come closer and closer and coming to contact with each other, a distribution of the load finally takes place in the form of certain kind of stress distribution.

So that is known as stress transfer, more of it we will see a little later when we look at a mathematical or a physical model which explains how the stress transfer is taking place. At this point of time it is enough to know that the gradual process of moving out of water in turn is responsible for a gradual process of stress or the applied load getting transferred to the solid particles little by little. So these are two formal definitions of consolidation phenomenon and I might emphasize at this stage once again that this phenomenon is important therefore only in saturated clays. In the case of sands this compression is not time dependant as you will also be seeing a little later and hence the phenomenon of consolidation is important mainly only in saturated clays.

Now we have been using the word compression, compressibility, consolidation rather freely from this definition you would have seen that the word consolidation explains a certain kind of phenomenon. Where as the word compression explains a certain kind of resulting action or resulting effect rather from an action. This was the background which we had covered in our earlier lecture. Now we are ready to go forward, in today's lecture we will see further how to compute the settlement. When given a load, given a soil, given certain conditions how to compute the settlements, what is the simplest method or what is the mathematics involved in that? And we will also see the theory of consolidation can be possibly describe this consolidation in terms of some theory. These are mainly what we are going to see in today's lecture. By enlarge there are two aspects which are important when it comes to the consolidation phenomenon and computation of settlement. The two phenomena are when a foundation rests on a soil let us say and stresses are applied on to the soil. What happens is it settles. When does it settle? It settles as the water goes out. The water goes out gradually so the settlement is also gradual, this also gradual that means there is an implication of time involved in the settlement. This means that under certain load, under certain soil conditions the settlement is going to take place as a function of time. Now the question arises, will it take place indefinitely, how long will this settlement take place? Well practice or experience shows that this settlement will go on taking place theoretically up to infinite time but in practice it stabilizes after certain amount of time.

And that is the total or the final settlement corresponding to a given load, a given structure and a given soil condition. It is possible to calculate that total settlement that is one type of computation. But in practice it is not the total settlement alone which is important, we also want to know how, at what rate this settlement takes place. Suppose we are in a position to compute the total settlement and we find that the total settlement is let us say 6 centimeters, well that alone is not sufficient. Because we would like to know in practice for a given building for a given load these 6 centimeters will take place over what period of time. Suppose 10 years then this building is going to undergo deformation for a period of over 10 years and the settlement is very gradual and probably the building will be able to withstand this gradual settlement adjust to it without undergoing distress.

But imagine a situation where this 6 centimeters settlement takes place say in one year. The 6 centimeters settlement taking place in one year is rather fast and the building may or may not be able to adjust itself to this rate of settlement and therefore it may be that the total settlement is within some reasonable limits which the building can tolerate but if the rate is fast then the building could show some distress. But a question will arise how can the rate be fast? We have just now defined consolidation as a gradual process but now the word gradual or the words fast are relative words. Relative to the building if the settlement rate is fast then the building may show distress. If the building is such that a certain rate of deformation can be tolerated by it then we will say that rate is slow. Obviously it depends upon the rigidity of the building.

Imagine a building versus an earthen embankment. In the building of this type which I have drawn here, the settlement could be relatively rapid for a building which is quite rigid. Consider on the other hand an embankment, suppose I have a road embankment made of soil. This road embankment is obviously flexible, this being flexible when it undergoes settlement rather takes a shape as shown here. Even if the settlement is relatively rapid that is 6 centimeters in one year, this being a flexible structure it can with stand that and maintain certain amount of stability with out cracking or without undergoing distress. And this is what it dictates the importance of knowing the rate of settlement, the rate at which settlement will take place. We are generally not very much worried about settlements that take place below a road, unless they reach excessive limit. But we are certainly worried not only about the total magnitude of settlement undergone by a building but also the rate of settlement. Therefore depending upon the structure the total settlement is of course important but the rate of settlement might also be important in structures where the adjustment is not easy. In order to compute this settlement both the total magnitude and the rate of settlement, we will make a simplifying assumption. I made a brief reference to it in my last lecture. The assumption that we make is that the settlement process is one dimensional or the consolidation takes place in only one dimension, strictly speaking consolidation is a three dimensional phenomenon.

Imagine a square or a rectangular or a circular foundation, a rectangular loaded area when it transfers its stress to the soil, settlement is definitely going to take place not only vertically but due to Poisson's effect there could also be lateral moments and the problem really is three dimensional. Not only that we just now saw that it is the movement of water and readjustment of particles which is responsible for consolidation. Now the movement of water, the flow of water inside the soil need not necessarily be in only in one direction let us say vertical, it could be also moving in the lateral direction. In view of these considerations the settlement phenomenon or the consolidation phenomenon is a three dimensional phenomenon.

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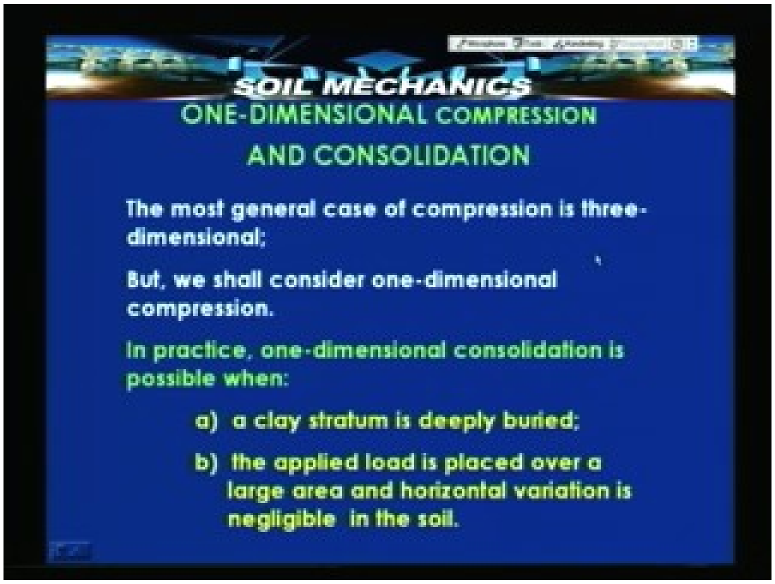

But in practice it is seen that for many applications it is sufficient to simply this problem and consider a one dimensional problem. That is if this is a soil surface and if this is the load transmitted then we say that the settlement is only in the downward direction in the direction of the load even though water may be moving out this way, this way and this way. Irrespective of movement of water as long as it is in one plane, in the plane of the paper and as long as the settlement is in the direction of this load we say that it is one dimensional consolidation.

Now under what circumstances we can say that the movement of water will be in one plane, the direction of the movement or settlement of the foundation is also unidirectional. It is possible to assume these ideal conditions when certain requirements are met with. See here in this slide we have the most general case of compression which is three dimensional which can be reduced to one dimensional under certain conditions to name one of them, when the clay stratum is deeply buried or when to name a second reason, the applied load is placed over a large area and horizontal variation is negligible in the soil. That means there is not much variation in the horizontal direction in the soil and the applied load is placed over a very large area.

So that in the region of loading it is reasonable to assume that all the movement of both water and the footing is in one direction, when the clay stratum is deeply buried. When it is closer to the surface this may not be valid. So a clay stratum which is deeply buried and is subjected on the surface to a very large load covering a very large area then the chances are that the compression takes place in one direction and the so called one dimensional consolidation could be assumed to be reasonably valid. Now this considerably simplifies the problem of consolidation because it's a problem of flow of water in only one direction.

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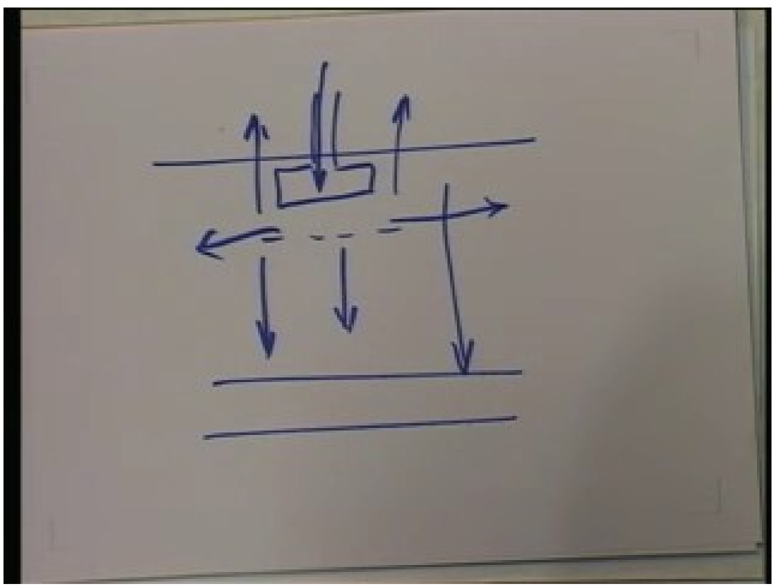

Let us see next. What is the kind of problem that we face in reality, in real life? If you look at this slide there will be a compressive layer. This is a compressible layer, very often this compressible layer need not necessarily be the surface layer. Very frequently this compressible layer may be over lined by a relatively less compressible or incompressible layer and at the bottom also it may be underlined by either a less or an incompressible layer. For example it is very common to find clay deposits sandwiched between sand or a gravel layer and sand or a rock layer. Remember that clays are sedimentary deposits, they are derivatives of sedimentary rocks.

These are formed under water by, layer by layer deposition of material which is transported from elsewhere and brought by water which acts as a transportation agent.

And therefore at different periods of time according to the law of floatation, different particles will settle with different velocities. Usually the courser particles will settle down faster in water especially when the water is stagnant and finer particle will continue to float for some time and then settle down gradually over a much longer period of time. It is therefore very common to find that there is sand or a rock layer that is course grained material above which there will be a finer grained material. It is possible that after a long gap or along period of time, once again deposition takes place and we get over these fine grained layer another layer which could be course grained.

The fine grained layers are the one which are going to cause problems, they are the one where the permeability is low and the water flows out gradually where consolidation results. Whereas in the courser grained materials consolidation is not that a serious problem because the permeability is high. So by enlarge in practice, we often come across a situation where there is a compressible layer which is usually clay which is sandwiched between two layers which are relatively more pervious and relatively less compressible. And on such a layer on the surface we may apply a load, this load could be in the form of a fill that is you all know that whenever we want to develop a site for constructing a building we will level the site first. So if the site is not leveled we will put a fill layer and compact it.

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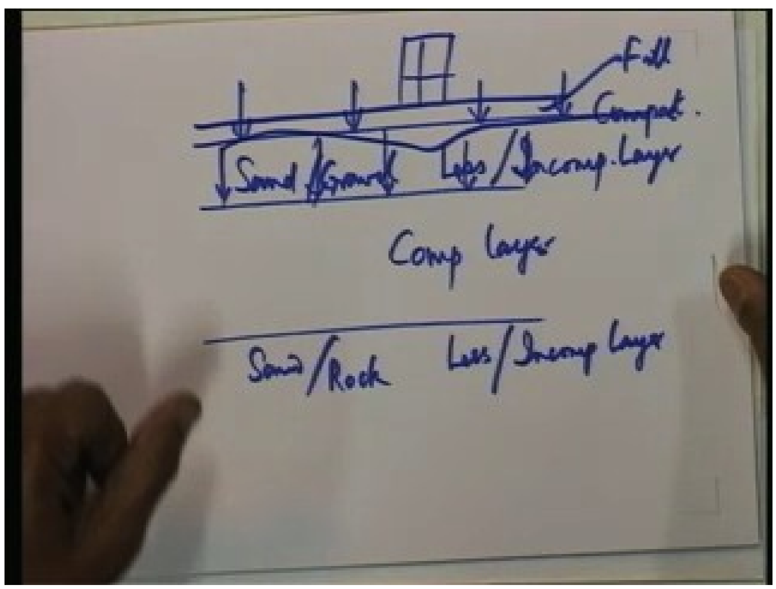

We will put a layer of loose fill and compact it and thereby make the ground level assuming that the original surface is not level. And this fill material also acts as a load effectively not only the building that is going to come above. So there could be a load due to these leveling material, there could be loads arising due to the buildings and below them there could be a set of layers one of them may be a compressible layer.
Usually it is sandwiched between other pervious layers but need not necessarily be always so, in the diagram which I have shown here I have shown only the compressible layer. That is I have assumed that some load has been transferred up to the sand layer and

now I am only considering the load that has been transferred to the top of the compressible layer.

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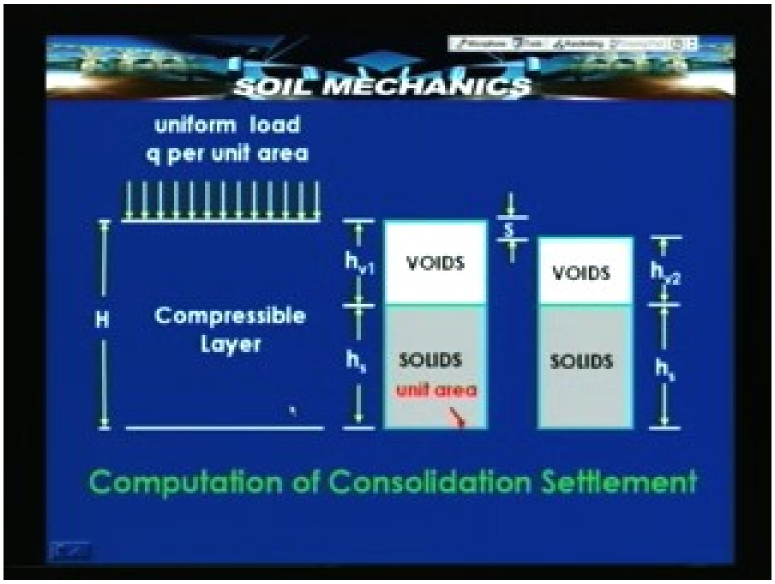

Suppose the compressible layer is subjected to a uniform intensity of loading q over a very large area, so that its compression can be considered to be one dimensional. What does this mean? Let us again go back to the three phase diagram. Effectively two phases, solids and voids. Voids are filled with water, the solids have a height h_s, the voids have a height h_{v1} to begin with, at time instant one we have h_s and h_{v1} as the heights of the soil skeleton, solids and voids we are assuming unit area. So if I consider a column of soil with unit base area then the height virtually represents the volume and the solids have a height h_s and the voids have a height h_{v1} let us say to begin with.

Now the load q is acting on this, as the load q acts the consolidation phenomenon starts taking place. Solids are incompressible, only the voids are compressible and they are compressible in the sense since water is not compressible it has to flow out and then the voids will shrink. Water flows out gradually and the voids decrease gradually leading to a slightly compressed skeleton at a time instant two. So let us take a look at the next diagram drawn side by side. We have again the solids, note here that h_s remains the same height of solids remains the same indicating that the solids are incompressible whereas the voids h_{v1}, the height h_{v1} has now reduced by an amount s and taken a new value h_{v2}. It is this decrease in height which is known as settlement and it is this settlement which we are interested in computing. We want to compute a settlement in advance so that the building can be so designed as to adjust depending upon the amount of settlement that is anticipated. Therefore this value of s which is the resulting decrease in height of the voids due to a given building is what is to be determined or computed. How do we do this?
Let us see how these changes in voids takes place. Take the first diagram once again I am calling solids h_s as before, I am calling the initial state of the voids as h_{v0} zeroth state, the red line here in the first diagram represents the subdivision within the voids that is water

and air.

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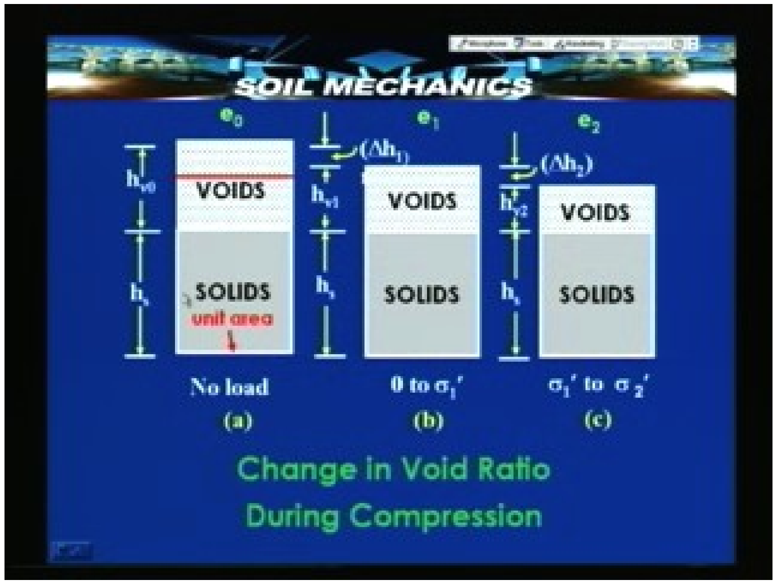

Water particles are incompressible so it's only the air which undergoes compression. The only other way to compress is water flowing out and let us say as the load increases from zero that is no load to an equivalent stress value of sigma$_1$ dash then solid remaining constant, the voids decrease to a new height h_{v1}, there is a decrease of delta h_1 and the new void ratio is e_1. Suppose the stress is further increased from sigma$_1$ dash to sigma$_2$ dash, solids still remains the same h_s, the heights still remains the same h_s. The voids further decrease to a value h_{v2} or there is a settlement equal to delta h_2 and the new void ratio is e_2. So now we find that as the stress goes on increasing there is a reduction in height, there is a reduction in voids ratio and it is this void ratio and the resulting decrease in height which we are interested in knowing. Change in void ratio is what we want to know.

In the field it is difficult to determine the change in void ratio, there are no convenient methods to determine the void ratio under an applied load as it goes on changing. So what we resort to in practice is to take a small sample of the soil, make a specimen out of it in a laboratory and test it under load. The equipment that is used for testing a sample in the laboratory is known as the oedometer. Oedometer is used for simulating the effect of an applied load on a clay layer and study the decrease in thickness of the clay layer and decrease in void ratio of the clay layer. So that we can see how much settlement will take place or how much void ratio reduction will take place under a certain known change in the applied stress. Take this figure, this is a diagrammatic sketch of an oedometer or a consolidometer.

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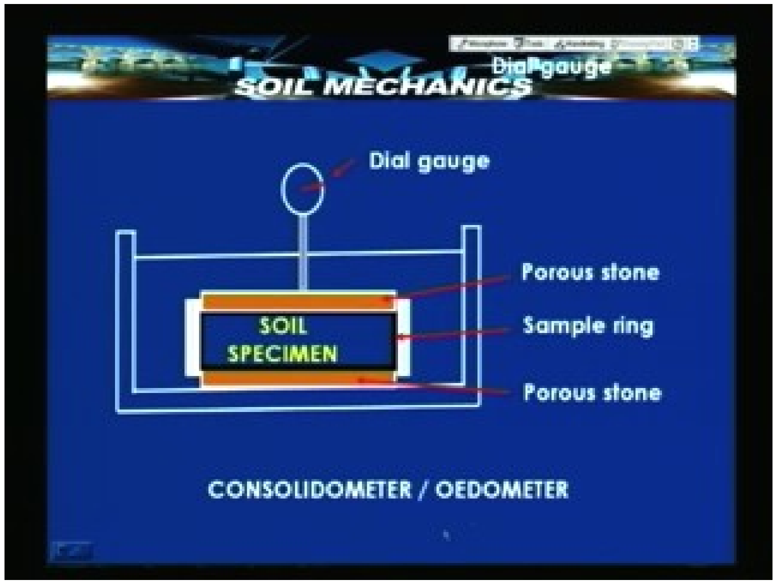

There is a container within which there is one porous plate and then a sample ring this white one is a ring. In the annular space inside the ring there is a ring like specimen a cylindrical specimen of known height usually 25 mm is kept and above that again there is another porous stone and the whole thing is kept in water. This entire container is later on filled with water, we can immediately connect this with what we saw in the previous diagram as representative of practical situation. The soil specimen here is bounded on both sides by relatively pervious materials, a porous stone at a top, a porous stone at the bottom. So this simulates a compressible clay layer sandwiched between two relatively less compressible or porous layers.

And further we have an arrangement for applying a load and to measure with the help of a dial guage that decrease in height of the soil specimen. So the components here are an outer container, an inner ring, soil specimen within the inner ring then the porous stones then a dial gauge and load application. What happens when you apply load like this to a specimen in an oedometer? The void ratio changes in the oedometer test, as the void ratio changes it is possible to estimate the change in void ratio because we saw in one of the slides earlier that in practice the decrease in height is due to the decrease in void ratio and the decrease in height or the settlement is what we are interested in and if we can find the change in void ratio, we can certainly find the change in the height or the thickness which is what the settlement is all about.

So take here this combination of diagram, once again at no load skeleton height is h_s, initial height of voids is $h_{v0,}$ void ratio is e_0. At certain load or at a certain load increment equal to say delta p as the load changes from zero to sigma$_1$ dash, we have solids with same height h_s as before and voids with a new height h_{v1}. This continues further to e_2 as the stress increases to sigma$_2$ dash and what we find now is that with every increase in load there is a decrease in void ratio which means that there is a certain relationship between the decrease in void ratio and the decrease in the thickness of the soil specimen.
If we can therefore put a soil specimen inside a consolidometer, apply a load and go on studying the change in thickness that is delta h, there is a way to know what is the

corresponding change in void ratio. How do we do that? The solids and the voids which constitute an initial height of h_0 total height where the solids have height h_s and voids initially have a height h_{v0}. Let us now translate these heights into volumes. We know that the base area is unity, we are considering soil columns of unit area. These heights can be straight away translated into volumes for example the height h_0 the total height of the skeleton will correspond to a total volume v_0. The height h_{v0} will correspond to a volume of voids v_v and the height of solids h_s will corresponds to a volume of solids v_s. The area being unity, height multiplied by unity will simply give you the volumes and the void ratio is e_0. We know how void ratio is defined, the fundamental definition of void ratio is e is volume of voids divided by volume of solids.

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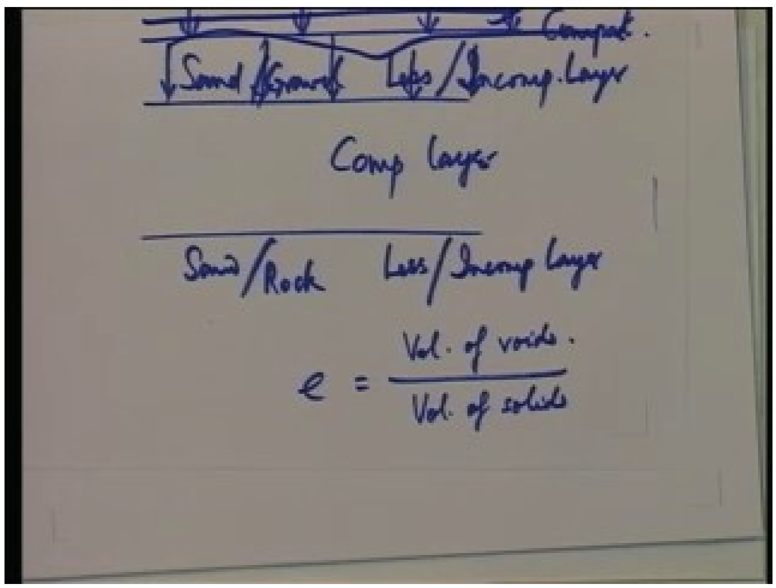

The reason why we defined this as you probably already know is when we want to compare different states of compression or reduction in thickness or change in void ratio, if we have a parameter in which the denominator or the basis remains constant then comparison becomes possible. So void ratio is defined in terms of volume of voids divided by the constant volume of solids. Solids are incompressible, so the volume of solids remain same and this is particularly useful in comparing the degree of compression that a soil has undergone at different periods of time or different states of stress. So here for example there is a change in void ratio from e_0 to e_1 when the load increases from zero to sigma_1 dash and as the load increases further to sigma_2 dash then the void ratio decreases to epsilon_2. In every single case this void ratio can be calculated as the volume of voids here that is h_{v1} or h_{v2} divided by h_s the volume of the solids. Both h_{v1} and h_{v2} are measurable, when you have a soil specimen in the oedometer if this is the oedometer, porous plate and the soil specimen when you apply a load and when you have a dial gauge, it is possible to measure the amount of compression that takes place in the soil specimen, that is its change in thickness.

So delta h whether it is delta h_1 or delta h_2 depending upon the load increment it is possible to determine. So in fact, in practice a series of loads is applied. The load initially is let us say some p_1 it is gradually increased until it reaches a certain high value which simulates the load that is expected to come on a real soil condition due to a real structure. What are we trying to do with the help of this oedometer? With the help of this oedometer all that we are trying to do is to simulate a certain field condition. So in this what we do is we take an actual soil sample from the field, cut a specimen of known specific dimensions in this case 75 mm diameter and 25 mm height and we put the specimen and subjected to load and keep on measuring the change in height.

And so we can go on getting the different values of delta h_1 delta h_2 by measuring h_{v1} and h_{v2} corresponding to various loads sigma_1 dash sigma_2 dash sigma_3 dash and so on until we reach a value of sigma which corresponds or almost is equal to the stress that is likely to be imposed by the load that is going to come due to a building that is likely to be constructed on that soil. And there are methods of computing stress distribution as we have already seen and therefore what is the load or what is the stress sigma which is going to actually come over the soil at the sight due to a proposed or envisaged activity can be easily computed in advance and that can be used here in the consolidometer as the stress up to which a soil specimen should be loaded. And in each case we measure the change in thickness, actually we measure the new thickness every time after every passage of certain amount of time and then we compute the change in thickness.

Once we know the change in thickness, since height translates as volume when the unit base area is constant, the change in thickness also corresponds to change in volume. So we can write a small equation of the type I have written here. Take the initial and the second or the final state in the given problem. The final state corresponds to a stress of sigma_2 dash, a total of h_2 with void height h_{v2} and decrease in thickness delta h_2. We can write down the change in volume from state zero to state two as v_2 minus v_0, actually v_0 is higher so we could have written v_0 minus v_2 and reference it with respect to the original volume v_0 so that we will know, change in per unit volume, original volume. So v_2 minus v_0 by v_0 should correspondingly be equal to the height h_{v2} of the voids minus the height h_{v0} of the voids at time zero. Actually this will be minus and this will also be minus and therefore it is as good as subtracting second volume from the first volume. Instead of dividing by v_0 we now divide by h_{v0}, the original height of the voids.

We could also divide by the total height but then it's only the volume of voids which is changing. Therefore it is appropriate to relate the change in height to the original height of the voids only rather than h_s plus h_{v0}. It is advantageous or it is more appropriate to relate the change in height to h_{v0}. This would mean that the total volume can be expressed in terms of volume of solids plus the void ratio, so $1 + e_2$ minus $1 + e_0$ the new volume original divided by the original volume $1 + e_0$. So now what we have achieved is we have expressed the change in volume in terms of change in void ratio. So it is $1 + e_2$ $-1+ e_0$ divided by $1 + e_0$.

Let us proceed further. This means it is equal to delta e upon one plus e_0, e_1 minus e_2 or e_2 minus e_0 upon one plus e_0 or the change in thickness which is nothing but the settlement which I may express as say delta s. It is nothing but the change in void ratio divided by the original void ratio multiplied by the original thickness h_0. So now further we can generalize this expression as s is equal to change in void ratio by original volume which is 1+ e_0 multiplied by the original thickness of the original clay layer.

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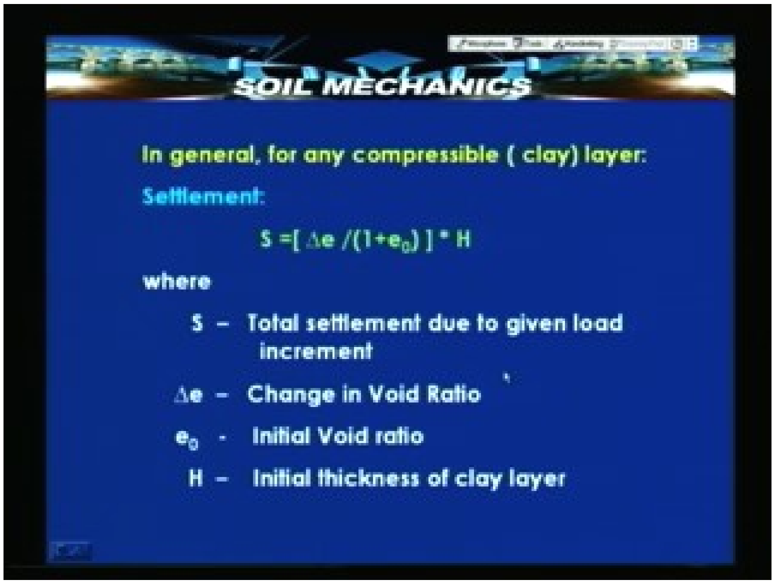

So s is the total settlement due to any given load increment, delta e is the change in void ratio, e_0 is the initial void ratio and capital H is the initial thickness of the clay layer. This is how we compute the settlement in terms of the void ratios.

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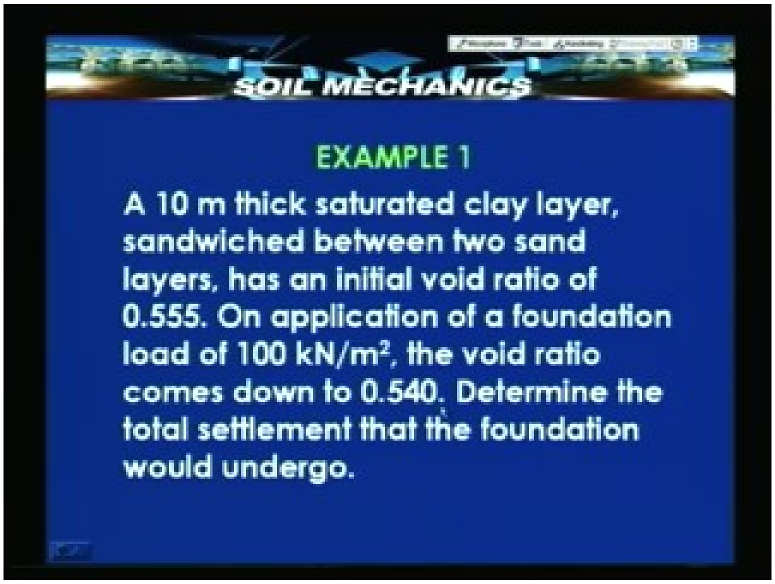

Suppose we take one simple example. A 10 meter thick saturated clay layer sandwiched between 2 sand layers has an initial ratio of 0.555, a final void ratio of 0.540 and a load applied equal to 100 kilo Newtons per meter square. What will be the corresponding settlement? The corresponding settlement will be change in void ratio divided by the original volume which is 1 + e_0 multiplied by 10, that is 0.096 meters or 9.6 centimeters.

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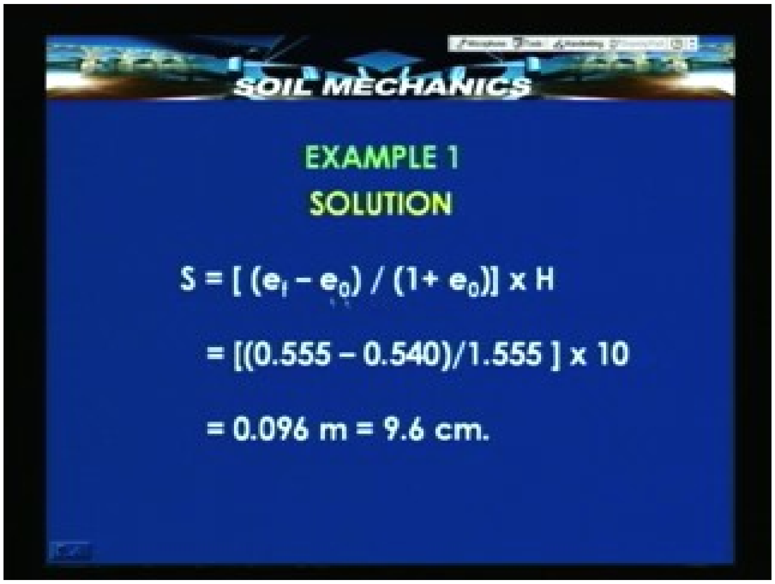

Now the total settlement depends on e_0 and e_f and e_0 and e_f in turn depend on the stresses sigma$_0$ and the finally applied stress. And hence in order to proceed further, we need to establish relationships between sigma and the void ratio e. Once we establish relationship between sigma and the void ratio e, we can have a method by which knowing the anticipated stress change we can find out what is the anticipated void ratio change. Once we know the void ratio change we have already seen how to compute the total settlement. So the next step shall be to relate the void ratio change with the stress change, so that knowing the anticipated stress change we can still compute the anticipated settlement. Thank you.