Soil Mechanics
Prof. B.V.S. Viswanathan
Department of Civil Engineering
Indian Institute of Technology, Bombay
Lecture – 42
Consolidation and Settlement
Lecture No. 9

Students we had eight lectures so far on this topic of consolidation and settlement. Today we come to the last and the ninth lecture on this topic, I plan to wind up this topic with today's lecture by giving you a few examples of solved problems and highlighting some special instances of consolidation and settlement. I will be going mostly by slides and let me start with the first slide now. As usual we will take a brief review of what we have seen in the previous lectures. If you remember in the last few lectures we talked about to begin with the total settlement and its computation.

As you remember computation of the total settlement is very straight forward, simple and does not require any elaborate knowledge except the void ratios at the beginning of the application of load and at the end of the application, whereas computation of the rate of consolidation or the rate at which the settlement progresses requires a lot more knowledge, it requires either the knowledge of so called coefficient of consolidation and how it varies with time. And essentially it depends upon determination of certain parameters of compressibility from the odometer test. So if you remember we saw the details of odometer test how to compute the compressibility parameters from them and then how to compute the rate of consolidation, primary consolidation in particular. Then I also introduced the concept of secondary consolidation and finally radial consolidation.

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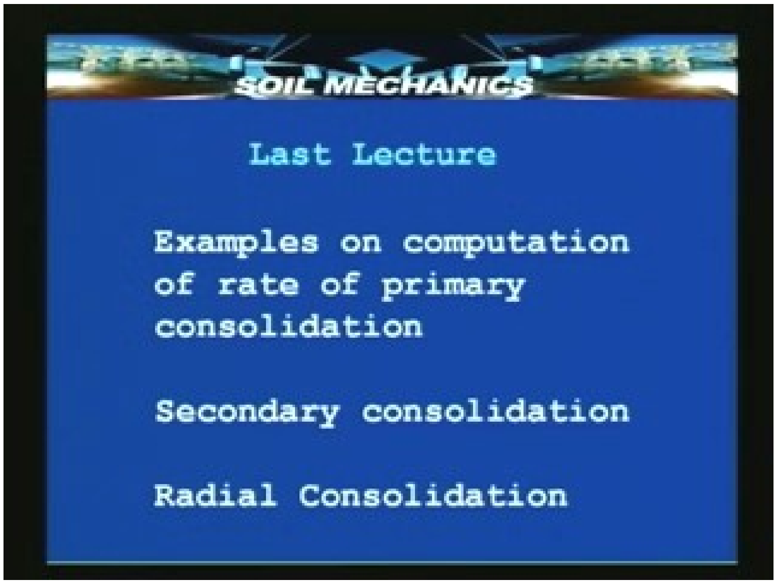

If you remember the secondary consolidation is nothing but a consolidation which takes place in the form plastic lag. That is after the hydrodynamic lag which is arising due to smooth flow of water is competed, the plastic flow particles and their readjustment starts, load remaining same this readjustment goes on for two days three days at times and that's the secondary consolidation part. We also saw an exponential equation with the help of which we can compute the magnitude of this secondary consolidation. And lastly I introduce three dimensional consolidation concepts. Although the concept of three dimensional consolidation was introduced, I considered only a very specific instances of three dimensional consolidation and that is the radial consolidation. Let me see.

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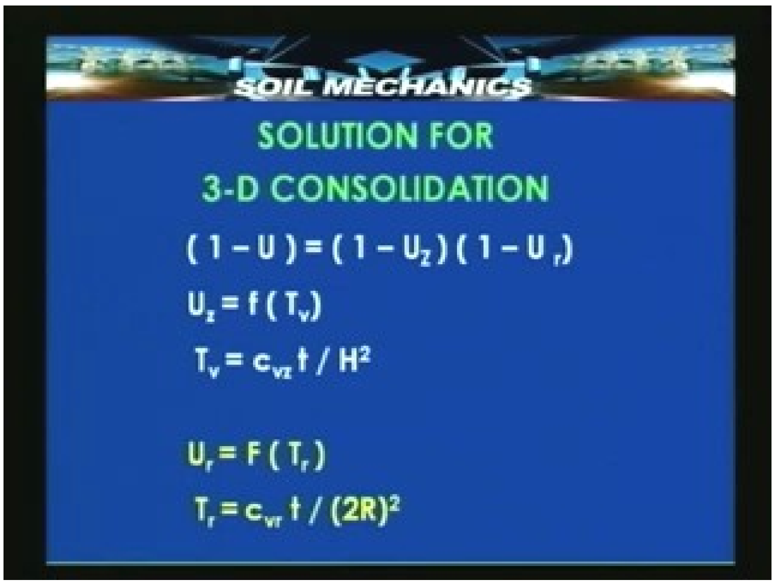

What we discussed was that three dimensional consolidation basically involves consolidation in the vertical directions. Suppose this is the surface and you find that due to some load consolidation takes place, in order to facilitate this consolidation if you install what are known as sand drains we had discussed this also in the past lecture. Then the flow of water takes place due to excess hydrostatic pressure not only in the upward and the downward direction, if the downward layer is also pervious but it also takes place radially. In view of this there is a tremendous amount of acceleration in the rate at which the consolidation process takes place.

Now how does one estimate the total consolidation that takes place when there are two components to it? The vertical component is straight forward can be computed by the same one dimensional terzaghi's consolidation theory which we had seen in very great details and for which we had seen few examples as well. The radial consolidation also we had discussed where we calculated U_r as function of time factor T_r. If you take a look at this equation you will find that vertical consolidation, average consolidation is given by U_z, z standing for vertical now.

If you remember I had used the same notation U_z earlier to denote the degree of consolidation at depth z, whereas here this U_z stands for the average consolidation in a layer but in the vertical consolidation, vertical direction is taken as z. This is a function of T vertical, T_v is c_v vertical that is c_{vz} into small t upon H square.

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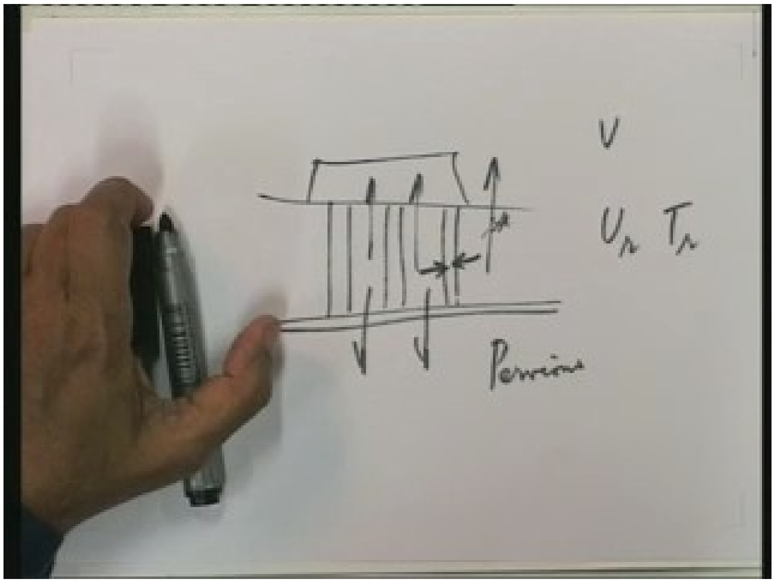

Similarly, analogously radial consolidation the degree of consolidation and the time can be expressed by identical equation. In place H we have 2 R. Now how does one get total consolidation which is given by this equation 1- U where U stands for the total consolidation is a product of 1- U_z and 1-U_r.

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We saw that in order to solve this equation of radial consolidation, we could make either an assumption of free strains in the median or equal strains under the applied load due to the preload embankment. We generally use the equal strain technique which is a much simpler equation to handle and the solution to this was given Barron which I mentioned in the last class, in the last lecture.

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And the chart or the table which Barron has given for computing U_r as a function of T_r is under equal strain condition is this table. Here for example if you know U_r, for different values of N you can find out corresponding T_r. Now what is this N which is nothing but the ratio of the radius of influence by the radius of the sand drain.

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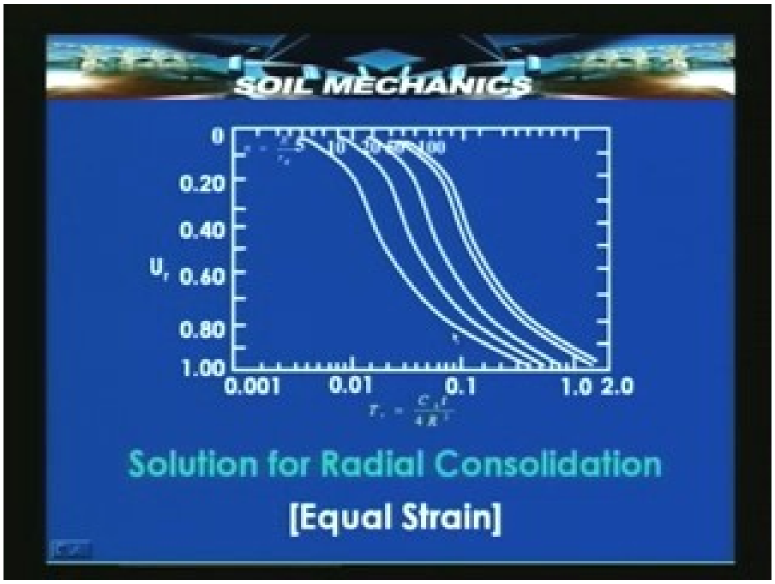

Now the same information is also given in the form a graph, this graph shows along the x axis T_r and along the vertical axis U_r. So if you know any given time T, knowing the compressibility characteristics C v r of the soil and the geometrical characteristics and resulting R of the sand drain, you can calculate U_r the radial degree of consolidation.

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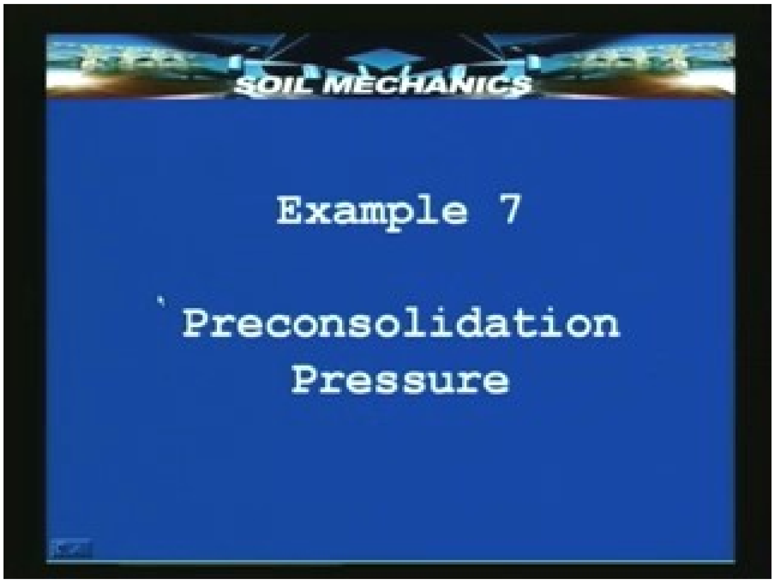

Now we also saw if you remember, one simple example on reconsolidation pressure. If you remember I had mention that pre consolidation pressure can be computed from e versus log sigma dash graph. If this A B C is log sigma dash graph, pre consolidation pressure is determined with a help drawing a tangent to this straight line portion then a horizontal, then a bisector and where this bisector intersect this projection of this straight line portion is the point which corresponds to P the pre consolidation pressure. That's the maximum pressure to which the soil has been subjected in the past.

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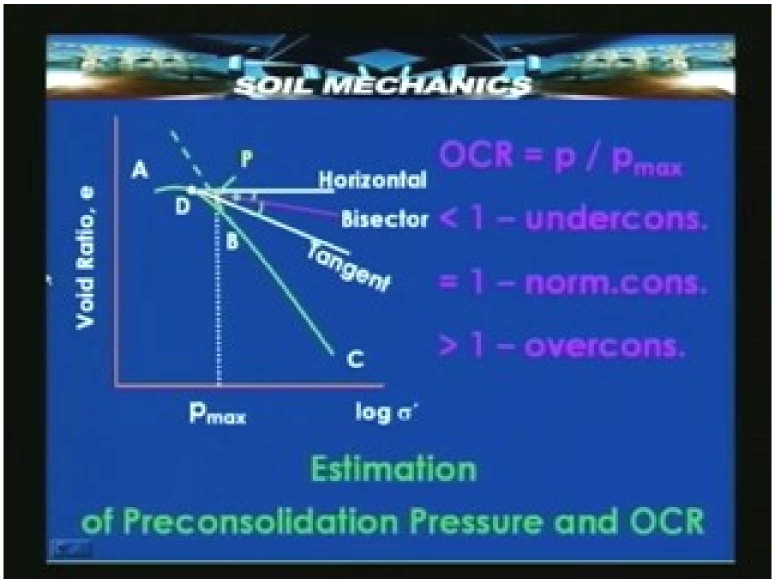

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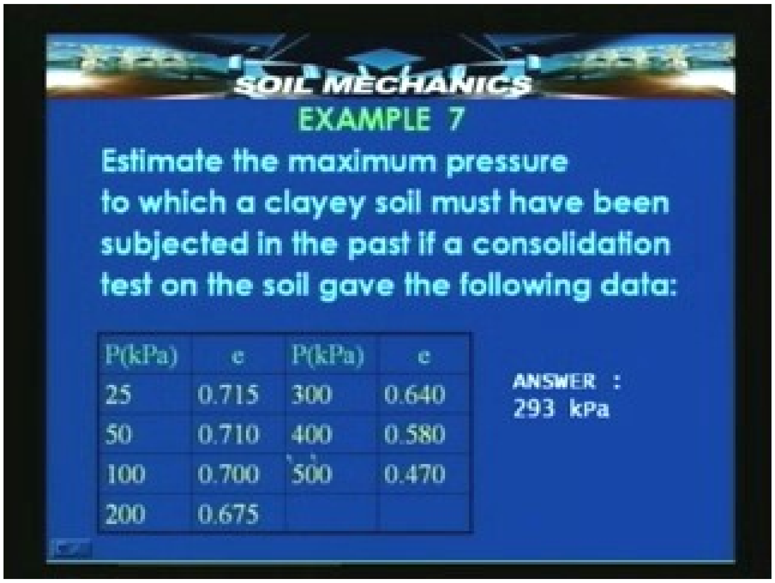

P(kPa)	e	P(kPa)	e
25	0.715	300	0.640
50	0.710	400	0.580
100	0.700	500	0.470
200	0.675		

Now with this we also saw the example of how to the pre consolidation pressure, given the various e P values. The method is of course plot e long P graph and following the geometric construction which we saw in the earlier slide, you can calculate. Now you may work this out this example, you will find that a pre consolidation pressure as 293 kilo Pascal's.

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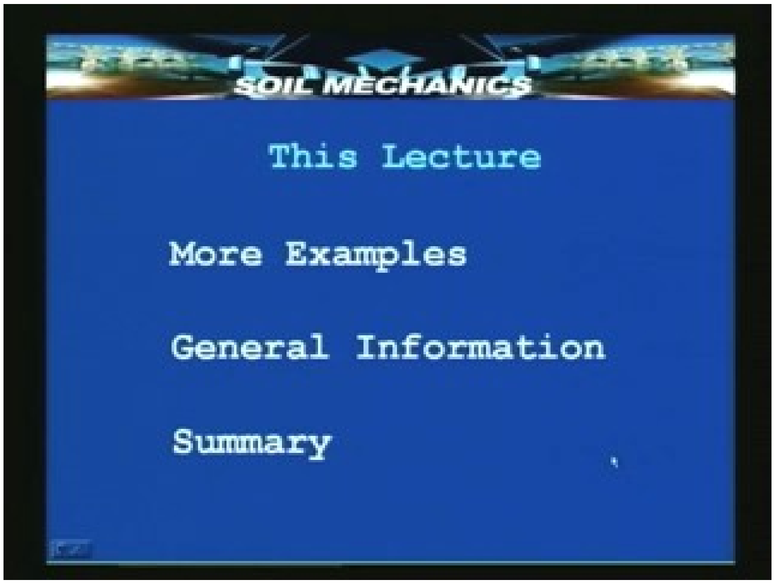

Now with this we will move on to fresh materials in today's lecture. What I proposed to cover in todays lecture is a few more examples on rate of consolidation then radial consolidation with and without sand drains, with preload and then some general interesting information about consolidation and settlement from different instances from the world and finally a summary, with that I will be winding up.

Let’s take a look at the next slide. We will see two examples now on primary consolidation, one is on present consolidation calculation and another will be rate of consolidation. Let us take example 8; you may need to read it carefully.

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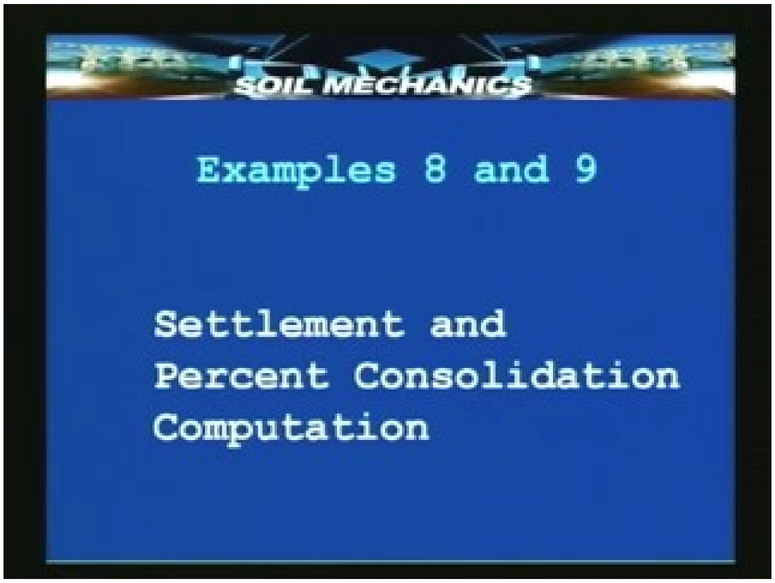

The dead load on a column due to a chemical plant is 800 kilo Newton s while the live load is 300 kilo newton, that’s the total load. Let us assume that the live load is acting all the time let’s assume that the construction of the structure is over, the live load has come on the structure and therefore 800+300 kilo Newton or 1100 kilo Newton is the total load under which the settlement is going to take place. The foundation is an ordinary fitting of width 7 meters that is the area is 49 square meters. The sub surface profile at the ground conditions below the foundation is shown in a figure which will follow in the next slide.

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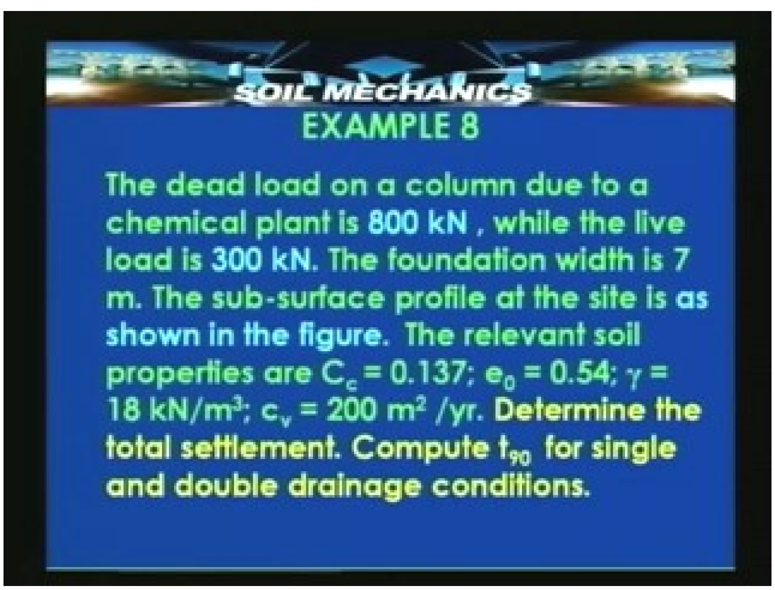

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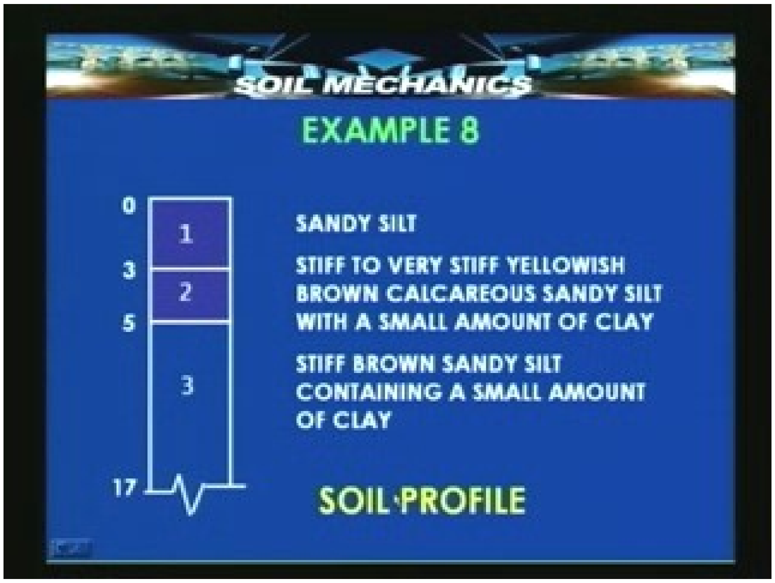

The soil properties which are important from point of view of consolidation are all known for example, compression index is known as 0.137; obviously it is determined for the compressible soil with the help of an odometer test, that is you will see a soil profile shortly. Samples were extracted from the compressible layer of that soil profile and they were tested in the odometer to get the compression index. The compression index, the initial void ratio of the soil, the unit weight, the compressibility parameter c_v are all known. Now what is required is whats the total settlement and what's the time required for 90% of the total settlement. How do we solve this? This is the soil profile, it consists of sandy silt then a very stiff yellowish brown calcareous sandy silt and then followed by sandy silt containing a small amount of clay.

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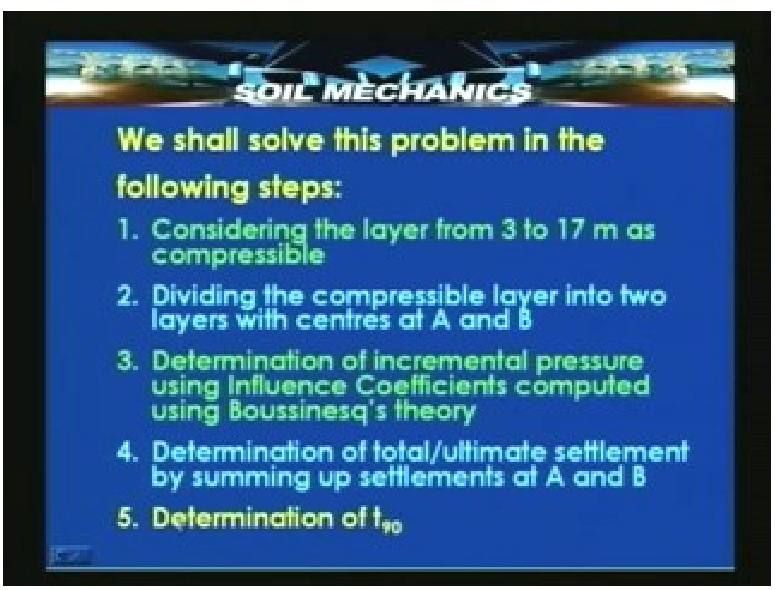

Let us take the layer 3 ranging from 5 meters to 17 meters and to some extent the layer 2 which also contain little clay to be compressible. That means we will take the total thickness of the compressible layer to be 3 to 17 or 14 meters. We shall solve this problem sequentially. Now what are the typical steps which are involved? Number one is identifying the compressible layer which I have just now mentioned, 3 meters to 17 meters is the thickness, 14 meters is the thickness of the compressible layers. Then this compressible layer is divided into parts here, so in this case we shall be dividing this into 2 parts and let the centers of this two parts, subdivision of compressible layers be at A and B.

Then next thing is to determine the increase in pressure that is the incremental pressure that is coming at A and B due the applied load of 1100 kilo Newton's. This incremental pressure we will be calculating using boussinesq theory and by finding out influence value. Then the total or the ultimate settlement we will calculate at point A as well as at point B, the sum of the two will give us the total final settlement in the entire clay layer and after this of course knowing the value of c_v we will determine t_{90}.

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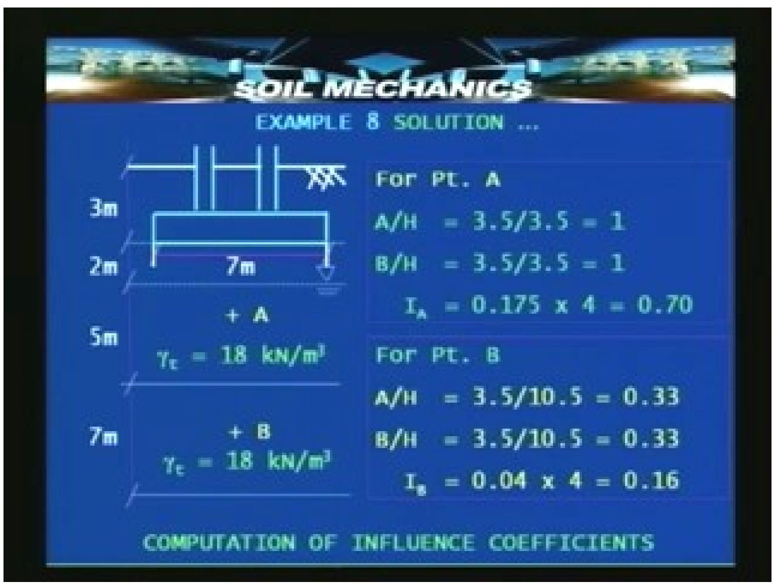

How do we determine the influence coefficient? It's very straight forward, we already seen the details of the business theory. Here is the foundation in our case it is 7 meters by 7 meters. The layers involved are 3 meters and then 5 meters, 7 meters and so on. If you remember the foundation kept at 3 meters depth and that means there is a 2 meters thin layer just below the foundation and water table is at depth. This is as per the data collected during the sub surface investigation.

That means below the foundation 2 meters of soil is dried or may be capillary saturated, we shall take it as dry and below that the soil is saturated. Now for point A, if we want to calculate the influence coefficient as you know we will calculate A upon H where A stands for half the width of the foundation and H stands for the depth at which we want the influence value. So in this case A upon H will be 3.5 by point A is also at a depth of 3.5 meters and so we have 3.5 by 3.5 equal to 1.

That means the other dimensions B upon H also will be 3.5 by 3.5 because this is a square foundation incidentally and for A upon H is equal to 1, B upon H is equal to 1. If you see the boussinesq chart, you will find that the influence value is 0.175. Now this is for one rectangle, you know the loaded area is divided into 4 parts and we are finding out the influence value for this one corner. So influence value for the total loaded area will be 4 times this and that is 0.7. Identically we can find for point B and that will be 0.16.

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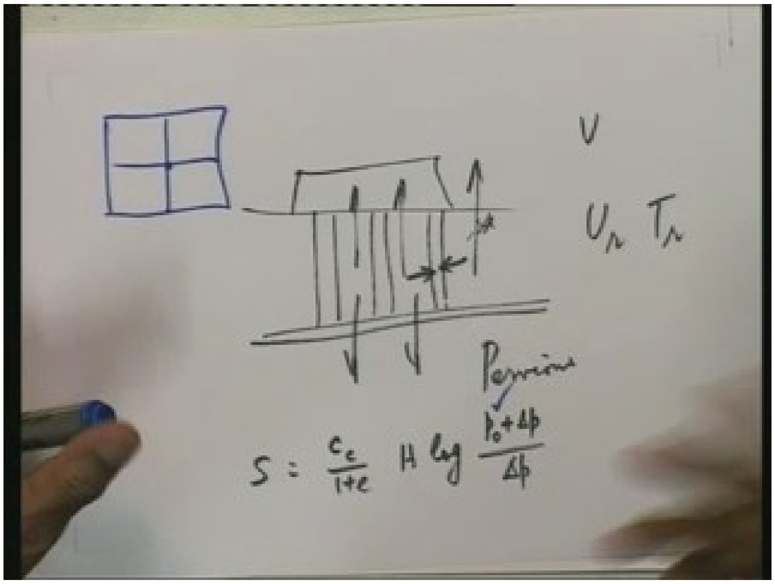

Next we know the value of C_c it is given and we have divided the layer into two, A and B. Now the total load of 1100 kilo Newtons is distributed over a foundation area of 49 square meters that means the loading intensity is 22.5 kilo Newton's per square meters and the depth upto point A or point B as the case may be or let us say h_1 and h_2.

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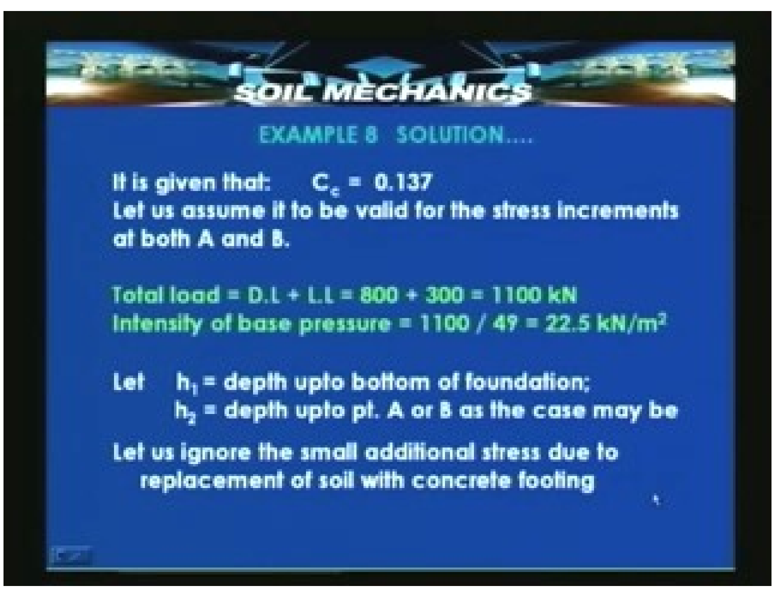

Now there is a settle points which needs brief explanation here. Actually when you put the foundation, we will be removing some soils and replacing with concrete and then of course back filling. This is back fill that means in this portion now which is being occupied by the concrete foundation, since the unit weight of concrete is more than that of the soil there is a small increase in the stress level. It is possible to take this into cognizant but however for illustration for the computation I shall be ignoring the increase in the stress that is arising due to concrete.

I shall take the stress as purely that due to the soil but however the increase in stress due to concrete replacement of soil by concrete can be very easily taken into account in the same procedure. Now what's the vertical stress at A due to the over burden? Remember that there is a dry soil layer and a saturated soil layer, water table is somewhere in the middle and wherever the soil is saturated and below the water table you have to take the buoyant unit weight. And therefore the intensity of pressure at A due to the over burden will be gamma t into h_1 for the dry part and gamma buoyant into h_2 for the buoyant part that is 102 kilo Newton's per meter square.

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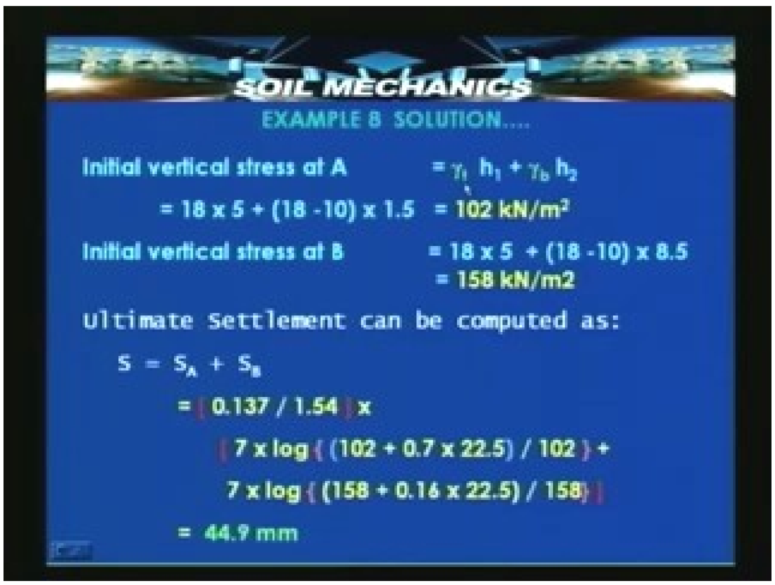

And similarly at B you can calculate the intensity of stress due to over burden as 158 kilo Newton per meter square. What is the settlement therefore? Settlement is summation of settlement at A and settlement at B. What is settlement at A? C_c upon 1+ e_0, e_0 is given to be 0.4, so 0.54. So 1+ e_0 is 1.54 into the layer let us say is doubly drainy then the drainage path length which comes here is only 7 meters, log of P_0+ delta P upon 102+ 7 into log 158+0.16 into 22.5 where 0.7 into 22.5 is the influence coefficient square into the intensity of pressure below the foundation. Similarly at point B, 0.16 is the influence coefficient and 22.5 is intensity of pressure so this gives 44.9 millimeters.

I must mention here that the settlement calculation involves the total thickness of the soil layer whereas the rate of settlement includes the length of the drainage path. We are at the moment calculating the total settlement and therefore the value of 7 that has been used here and the value of 7 used here are both nothing but thicknesses of the upper layer and the lower layer respectively.

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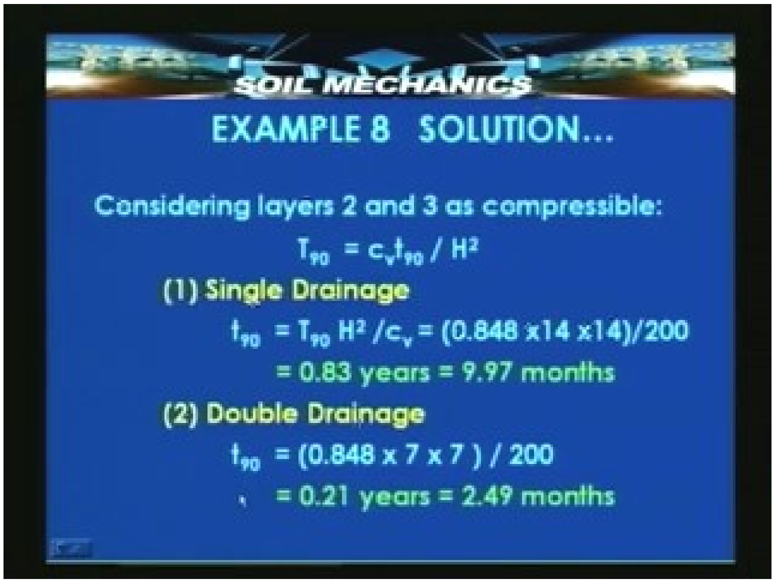

To continue the solution, if you remember there was one more aspect which was asked for. That is what is the time rate of settlement, if there is one way drainage and if there is two way drainage or it's also called single drainage or double drainage, as you know the difference only comes from the length of the drainage path. If it is single drainage the length of the drainage path is the total length of the layer or rather the total thickness of the layer whereas if it is doubly draining half the thickness of the layer is the length of the drainage path. Accordingly we know there is a formula for $T_{90} = c_v\ t_{90}$ upon H square and t_{90} from theoretical computations in one dimensional consolidation theory comes out to be 0.848 as we very well know.

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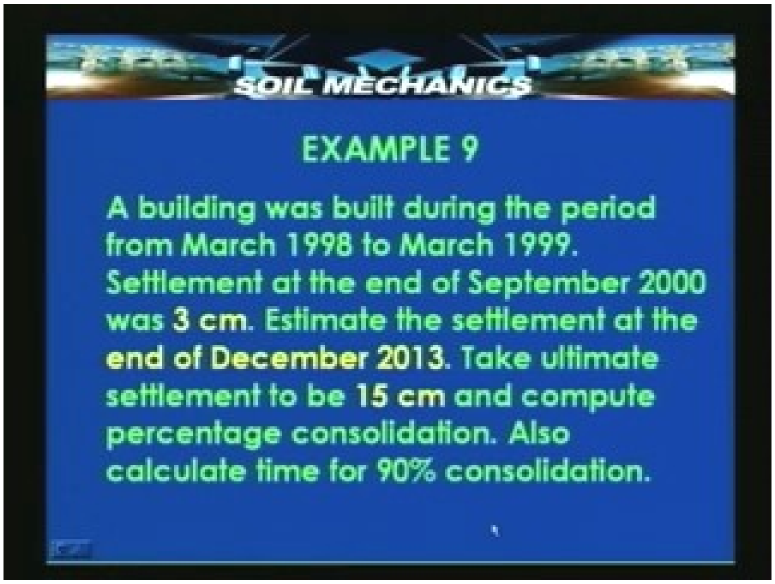

So using that value 0848 into 14 into 14 t_{90} into H square that is divided by the given value of c_v that is 200 meters square per year will give you 9.97 months as the time required for 90% consolidation in the worst case that is single drainage case. In the better case of doubly draining one, it takes place much faster and it only takes 2.49 months. Let us take one more example on percent consolidation. I am still taking about primary consolidation. Here a building was built during a time period starting from March 1998 to March 1999, the settlement at the end of September 2000 was 3 centimeters that is after the construction was complete the settlement was being monitored and it was found that at the end of the September 2000 the settlement was 3 centimeters.

Now can we predict this settlement at the end of December 2013, today we are in 2006, can we predict the settlement at the end of December 2013 for this building, certainly we can. Now it is given that the total settlement is 15 centimeters theoretically it takes place in infinite time. So given this total settlement 15 centimeters, how much of it will takes place in 2013 can be estimated and also that means compute the time required for 90% consolidation? So how do we solve this? Now you see here, the load varies from zero to its final value during construction and therefore whats the really load and what can be considered as the starting point for the application of the load.

Since the load varies from zero to its final value over a certain period time say t, it will be reasonable I am sure you will agree with me to take t by 2 as the time at which we can take the total load to have become effective. That is the average load is acting at t by 2 and so since the load is varying from zero to its final value we can take the load to be acting at t by 2, total load to be acting at t by 2. Now what is t by 2? It turns out to be beginning of September 1998 because the construction varies from March 98 to march 99.

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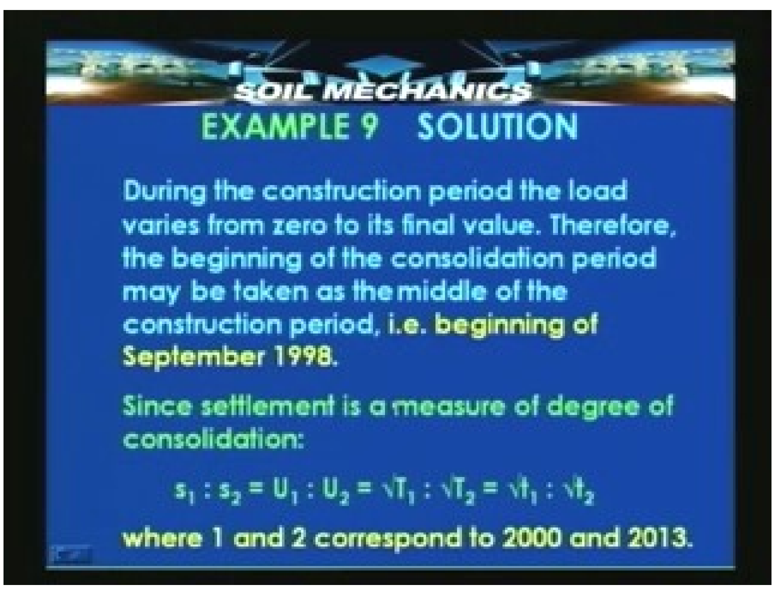

If beginning of September 98 is the point at which the load application takes place then it is given that 3 centimeter settlement takes place at the end of September 2000. So beginning of September 98 to end of September 2003, 3 centimeter settlement has taken place.

What is this settlement that will take place in in the year 2013 at the end of the month December? We can follow a simple relationship which follows from one dimensional consolidation theory, that is settlement one divided by settlement two that is settlement at the end of September 2000 to settlement at the end of December 2013 which is required obviously it is directly proportional to the degree of consolidation that takes place in the first instance to the degree of consolidation in the second instance. And we know the degree of consolidation is proportional to the root of time factor and therefore you can say U_1 : U_2 is as root of t_1: root of t_2 and capital T is directly related to small t and therefore we can say s_1: s_2 is time take for $s_1$under root to time taken for s_2 under root where one and two corresponds to the years 2000 and 2013. Here $t_1$is 25months that is if you start counting from the point of application of the load and count up to end of September 2000 you will get a total of 25 months.

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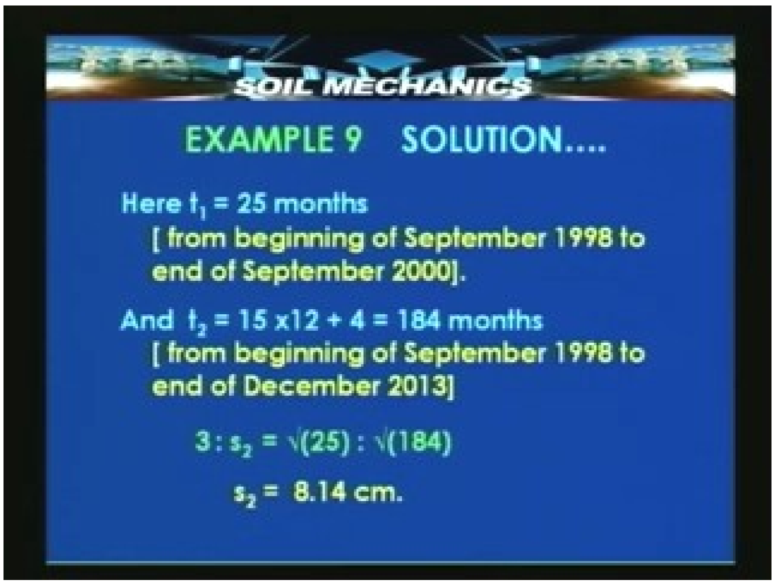

Then if you calculate further upto December 2013 from the beginning of the application of the load, you will find it involves 184 months. So if at the end of 25 months, 3 centimeters is the settlement. At the end of 184 months what is the settlement? Obviously it will be 8.14 centimeters. Now we still need to compute the time taken for 90% of consolidation, we know the total consolidation 15 centimeters. We just need to calculate the consolidation that takes place, that is the time taken for a consolidation of 90%. We know that 8.14 is the settlement that takes place at the end of the December 2013 and the final settlement is 15. Obviously it must be in the same ratio as U_1: U_2 were U_2 now is 100% because 15 centimeters is corresponds to 100% settlement.

So from this we find that the degree of consolidation at 8.14 centimeter settlement is 54.26% (Refer Slide Time: 25:57 min), if that is 54.26% again using the same ratio we can say that 90% of 15 centimeter settlement will corresponds a t_{90} of 42 years and 2.1 months. Now this is a dramatic indicator of how slow a consolidation process can be? You just see here, since no sand drains are used, this building which is constructed over a some period of some one year or 13 months continues to settle for a period of upto 42 to 45 years, 100% consolidation theoretically takes place in probably infinite times but in practice it may be as highest in 50 years.

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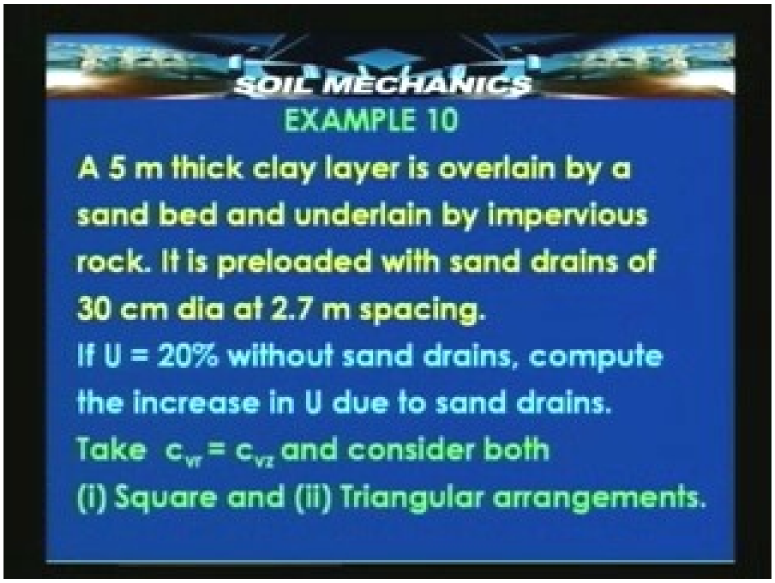

This could be very critical or very dangerous for the structure and a structure may not necessarily be able to withstand this. So it is for such instances that we go for preloading and radial consolidation. Let us take a couple of example on radial consolidation now, example 10 and 11 will be on radial consolidation. Let us read example 10. There is a 5 meter thick clay layer and above that a sand bed and below that an impervious rock immediate indication is that it is a one way drainage situation it is preloaded with sand drain of 30 centimeter diameter 2.7 meters spacing without sand the degree of consolidation is 20% at any given time. What will be the increase in degree of consolidation if we install sand drains? For convenience let us take c_v for vertical direction as well as the radial directions as equal and as far as the sand drains are concerned which are of 30 centimeter diameters.

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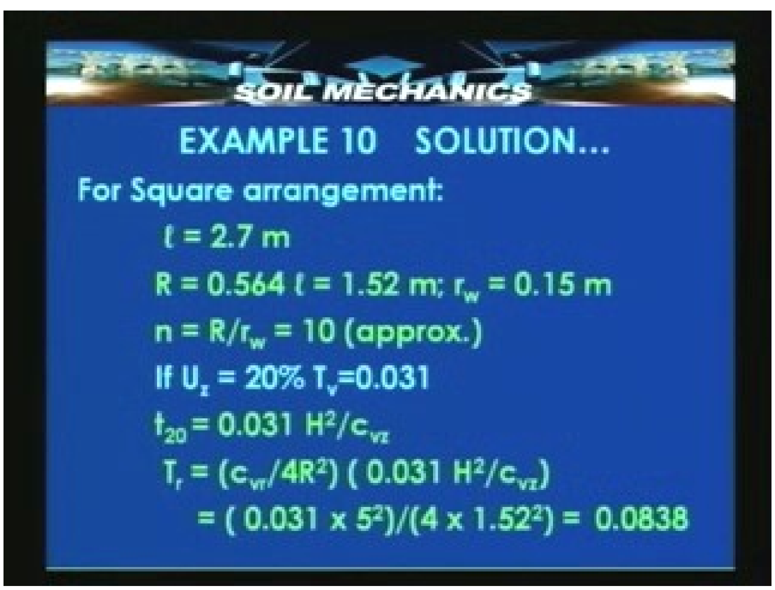

And at a spacing of 2.7 meters, let us consider both possible arrangements that is the square and the triangular arrangement. And then find out if U is 20% what's the corresponding U with the radial consolidation and therefore how much improvement is taking place in U? For a square arrangement we know that the parameter small l is 2.7 meters and capital R will be 0.564 l that is 1.52 meters and small r_w the radius of the well sand drain is 0.15 meters. That means the parameter n which is the ratio of capital R to r_w is approximately 10. We know that U is 20% without sand drains that means it is nothing but vertical consolidation that means U equal to 20% without sand drains is nothing but U_z with sand drains. So with sand drains if U_z is 20% the corresponding t can be calculated as 0.031 and small t_{20} that is the time take for the 20% consolidation will be capital T_{20} into H square by c_{vz}. That gives us the time taken for 20% consolidation as some value and the corresponding time factor as 0.0838.

Now what am I trying to do? I know that the vertical consolidation without sand drains is 20%. What I am trying to do is I am finding out for that vertical consolidation what is corresponding to t_v? For a U_v of 20% or U_z of 20% what is corresponding T_v and what is corresponding small t_{20}? Now at the same time if sand drains are provided what will be T_r? Therefore what will be U_r and therefore what will be U and then we will compare this U and U_z and see how much this U is more than U_z and that's what the intention of calculation is. What is the additional gain that we get because of the consolidation arising out of radial drainage? So for a square arrangement, a similar calculation will show that T_r is 0.0838 and U_r is 0.34 and this gives us 1- U equal to 1- U_z into 1- U_r as I mentioned just now, it gives capital U as 0.528 which means from 0.2 we have reached a value of 0.528 because of this radial consolidation arrangement and that means there is an increase of 136% over the no sand drain case.

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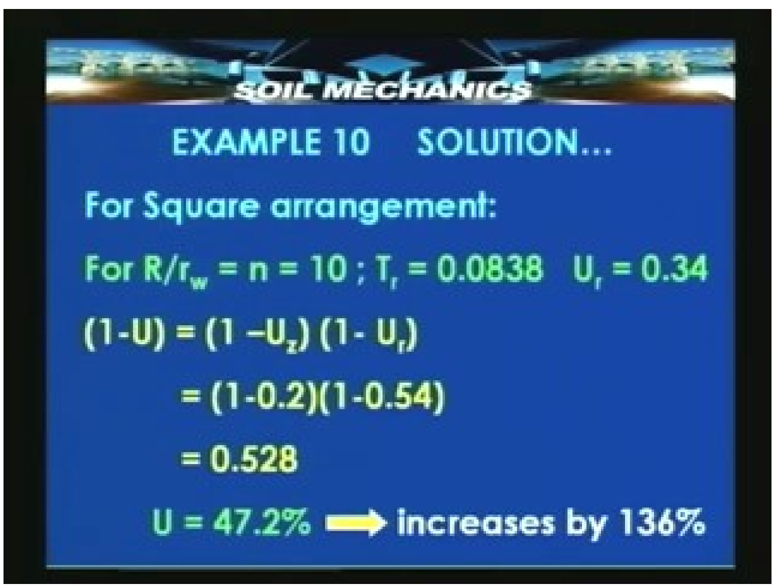

Now let us consider triangular arrangement in a identical manner corresponding to l and capital R and small n, we can find out U_z and T_v and small t_{20} and capital T_r that comes to 0.096. And given this value of T_r and corresponding U_r we get capital U is 50.4% that means over U_z of 20%, now we have got an increase of 152% in the degree of consolidation.

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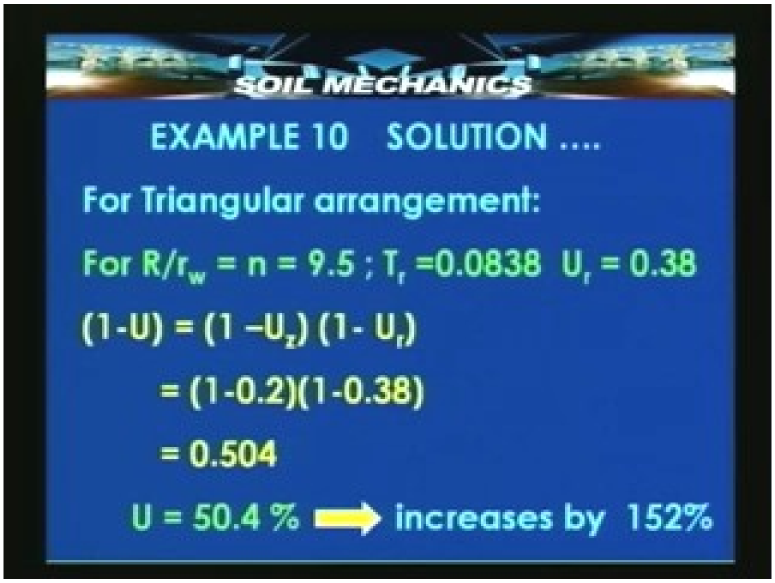

Just take a look at the previous slide once again, with square arrangement we were getting 136% improvement and with triangular arrangement we get 152% improvement. So that's the advantage of the pattern of arrangement of sand drains. Triangular arrangement makes the drains a little closer and the zone of improvement covered is more per sand drains and therefore we get a better improved consolidation performance with sand drains. We will take a look at example 11. Let's take a look at the next example that is example 11, it's an interesting case study from one my experiences.

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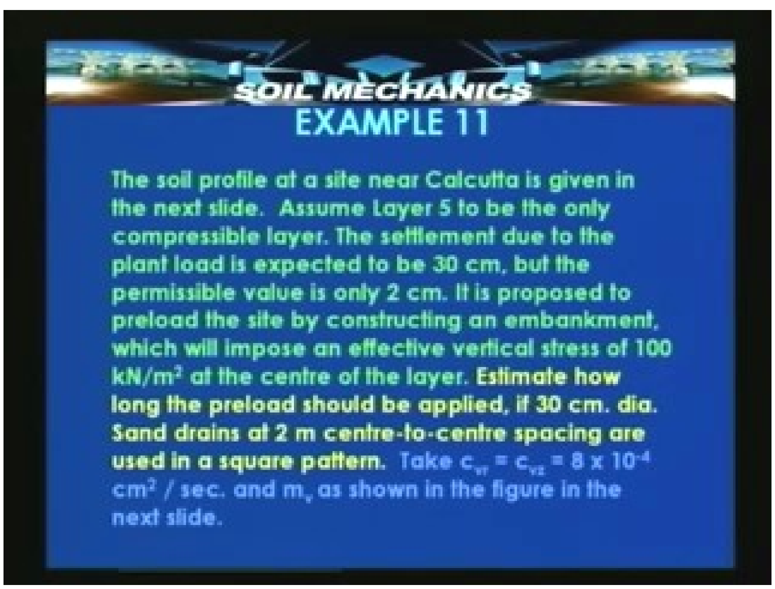

The example reads like this, the soil profile at a site near Calcutta is given in the next slide. Let us assume that the layer 5 in that profile is the only compressible layer. The settlement due to the load that is expected due to a structure there is 30 centimeters.

But the permissible value is only 2 centimeters, the structure is so critical that it weight causes 30 meters settlements but we can tolerate only 2 centimeters settlement. It is proposed to therefore preload this site by constructing an embankment which will impose an effective vertical stress of 100 kilo Newton per meter square at the center of the compressible clay layer. Now what this means is the size of the preload and embankment is decided, the stress that will induce is also pre decided, it is 100 kilo Newton per meters square. Now the question arises, how long this preload should be kept, so that it will take care of all the settlement except the 2 centimeters which is permissible.

The advantage is if out of a total expected settlement of 30 centimeters if 2 centimeters can only be permitted the remaining 28 have to be nullified by this preload. Preload should be kept long enough to cause 28 centimeter settlement and then once you remove the preload and replace it with the actual structure there will only be a settlement of 2 centimeters which is well within the permissible value and the capacity of the settlement the capacity of the structure to adjust to the settlement. Now the question asked is estimate how long the preload should be applied and the other conditions are sand drains are used, they are of 30 centimeters diameter and they are at 2 meters centre to centre and the pattern of arrangement is given as square, although in the previous example we saw that triangular is a better option, here in this case square option has been utilized.

Once again for convenience take c_{vr} and c_{vz} as equal and of magnitude 8 into 10 raised to minus 4 centimeter square per second and it's also given that the coefficient of compressibility m_v varies with stress as shown one of the figures that follows. So this is the sub-surface profile, there are 5 layers, first layer is a silty clay layer, second one is also a silty clay layer, the third one is a mixture of silty clay then fourth is sand, fifth is silty clay and once again the next layer below the silty clay layer is sand that means it is a doubly draining layer. This given 20 meter thick silty clay layer is the compressible layer, layer number 5 is the compressible layer and it is a doubly draining compressible layer.

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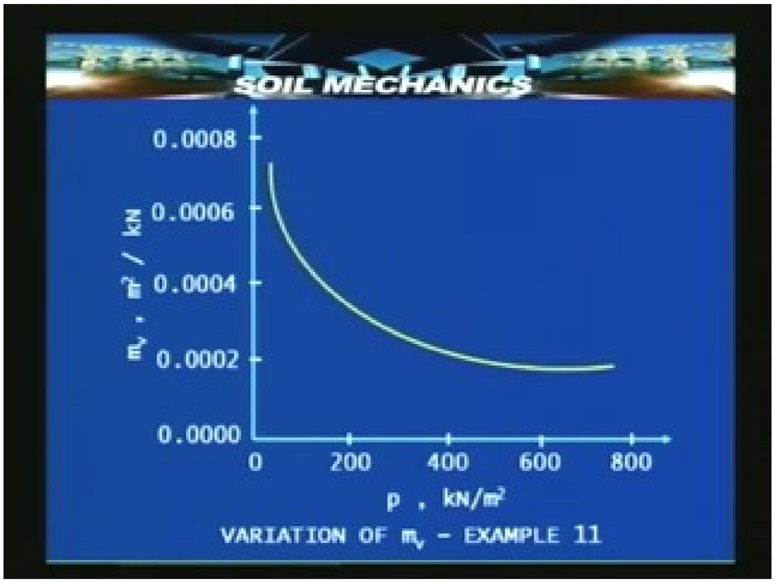

The value of m_v in meter square per kilo Newton is varying with pressure intensity as shown by this yellow line. So now what this means is we have to find out what is the increment in pressure that arises due to the preload over and above the overburden pressure that is already existing at the centre of the compressible layer. And then corresponding to that we should find out the value of m_v from this relationship which has been arrived at from an odometer test. Once we know m_v and once we know the increase in pressure that is coming due to the preload and once we know the thickness of the clay layer h, we can compute the settlement as m_v delta p H because m_v is nothing but a parameter which indicates the compressibility for a given intensity of pressure. So the solution of this example is take for convenience gamma to be same for all layers, take h to be 10 meters then at the center of the clay layer silty clay layer in this case.

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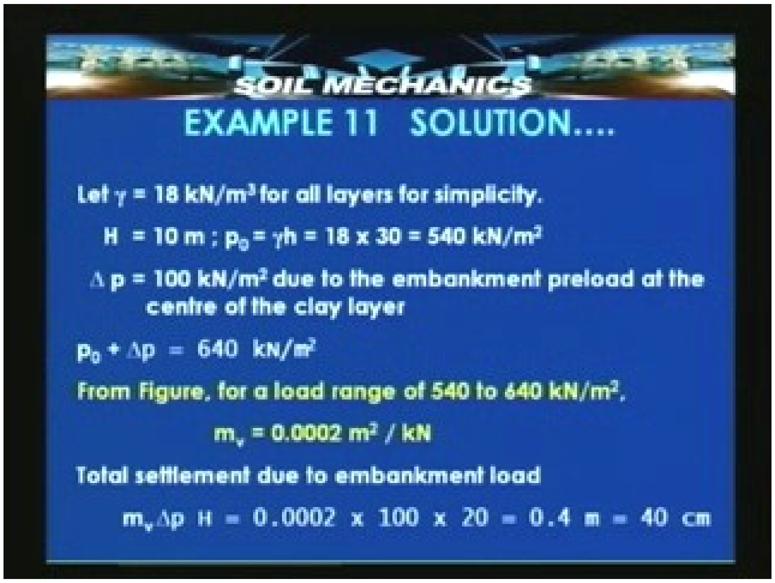

Then the initial pressure over burden pressure is gamma h which is 540 kilo newton per meter square then the increment in pressure is already given due to the preload is 100 kilo Newton per meter square at the centre of the clay layer. Now if this were not given then either we can take the intensity of pressure at the centre of the clay layer about the same as at the top surface or that is valid provided the preload is of very large size and it is usually of a very large aerial extent or alternatively if it is of a very small aerial extent we have to use boussinesq theory and compute the intensity of pressure at any given depth due to a given intensity of pressure at the surface.

Now m_v for this increase in pressure which is 640 kilo Newton per meter square that is over burden pressure is 540, additional pressure is coming is 100 that means 540+ 100or 640 kilo Newton per meter square is the net pressure. The load range is therefore 540 to 640. And the m_v value corresponding to this from the graph shown in the previous slide is 0.0002 meter square per kilo Newton and corresponding settlement therefore is m_v delta pH and that is 40 centimeters. Now this is the settlement that is arising due to application of a preload which produces an intensity of pressure of 100 kilo Newton per meter square at the centre of the compressible layer.

Now it is capable of producing 40 centimeter but the original structure itself is producing only 30 centimeter, it is expected, computation due to the structural load similar computation shows that 30 centimeter is all that the total settlement is going to be. So actually we do not need such a high preload which will produce a settlement of 40 centimeters, we could with a slightly lower intensity of pressure and a smaller preload. However let us say that for safety sake we will continue with this embankment which produces 40 centimeter settlement. Now the settlement due to the structure which is expected is only 30 centimeters but let us adopt 40 centimeters settlement and the corresponding preload. Now out of this 30, 28 must be caused by the preload, 2 can take place during the life time of the structure itself.

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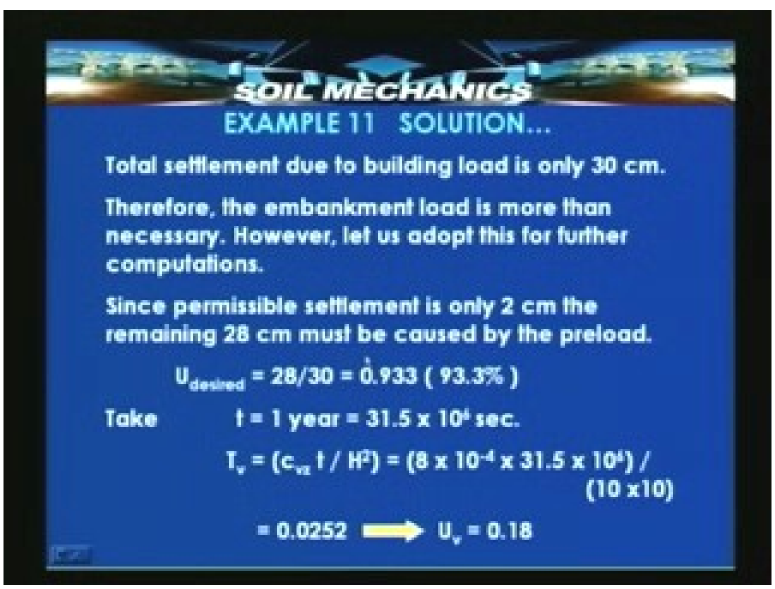

The degree of consolidation total that is required is 28 by 30 that is 93.3%. So 93.3% of the settlement should take place with the help of the preload. We need to determine what is the duration that is required for this, to achieve 93.3% consolidation. Now it is known that when t equal to one year or 31.5 into 10 raised to 6 second then for this given value of c_{vz} and t equal to one year we find that capital T_v is 0.0252 and U_v is 0.18. That means at the end of one year the vertical consolidation that takes place is 0.18. Now corresponding to this vertical consolidation U_v, we will find out what is the corresponding T_v and then T_r and then find out corresponding U_r. The procedure is the same as we adopted for the previous example. So given square pattern of consolidation layout of the sand drain we can calculate for a given value of capital R by small r_w we can get T_r is equal to 0.945.

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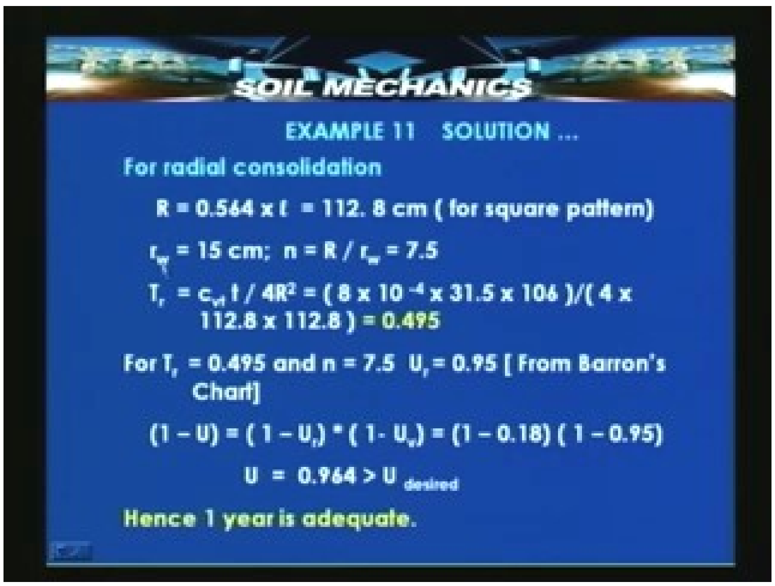

If T_r is 0.495 and n is 7.5 that gives us U_r is equal to 0.95 from Barron's chart. What it means is when U_v is 0.18, corresponding U_r is 0.95 that means the net U, total U is 1- this into 1-this is minus1that is 0.964. Whereas what we needed was only 93.3%. So this shows that if the freeload is kept for just one year duration we get 96.4% degree of consolidation. That means keeping the preload for one full year is sufficient to induce the 28 centimeters of settlement that we want. Now this is certainly on the over safe side, first of all the total settlement for the preload is 40 centimeter whereas that due to the structure only 30. We can therefore reduce the preload required.

Similarly the duration of one year produces 96.4% consolidation whereas we want to achieve only 93.3, so we can probably save in time instead of one year we may keep the preload for a slightly shorter duration which can be computed accurately. Now what this means is from a practical point of view we have to exercise a judgment now, as to really how much preload must be applied and for what duration. A more regression computation can be made rather than this approximate computation and we can arrive at probably some savings in terms of preload and in terms of the duration of the application of the preload. If required it can be attempted but very often in practice if the difference is not very significant we go with over safe considerations.

Now with sand drains and without sand drains if we want to compare, we have just now seen with sand drains we are getting 96%. Suppose sand drains were not there then U_v will be the only consolidation, we will not have any radial component added to it. So taking only the time corresponding to that, that is 90% of that, we find 90% of the consolidation takes place in 33.8 years. That means 90% of consolidation takes place in 33.8 years without sand drains and 96.4% takes place in just one year with help of sand drains and thats the degree of improvement, that's the degree of advantage that we gain.

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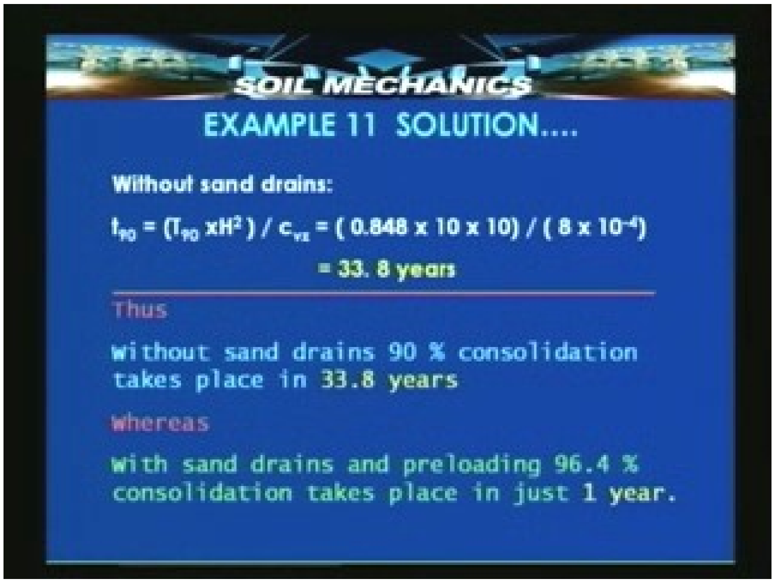

Now let us go back to one of the slides that we saw in the very early stages. I had listed as usual a set of questions which I sort to answer.

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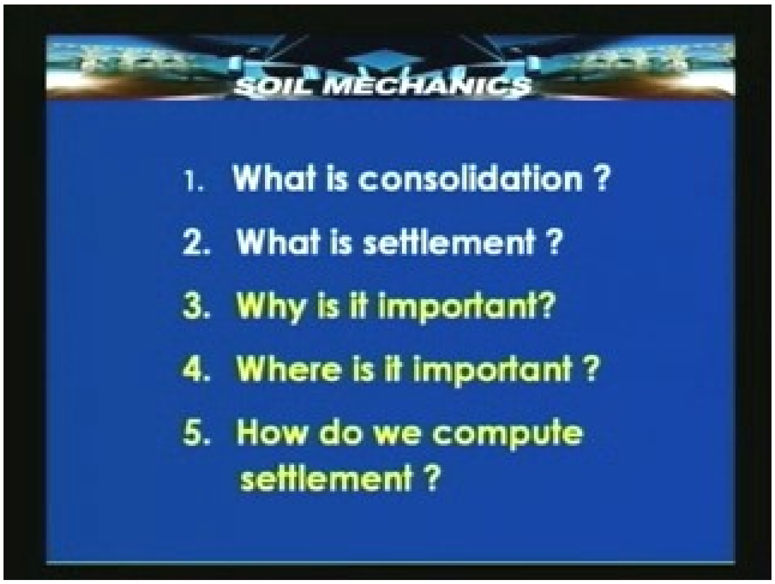

Now what is consolidation and what is settlement, we have answered in very great detail explicitly. But the remaining three question why is the consolidation important, where is it important and how do we compute have also been now answered during the course of the last few lectures. And therefore really there is nothing much to discuss, we now know the importance of the consolidation, we know why and where is it important. However let us see some examples and some idea about the importance of this.

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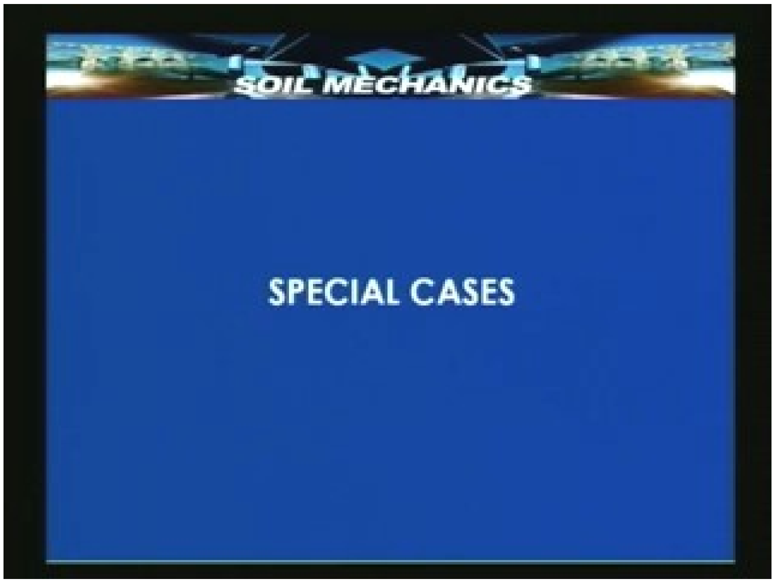

The importance of this can be highlighted with the help of two dramatic situations. Let us take the example of leaning tower of PISA. Almost every one of us know that this is a remarkable world tourist attraction.

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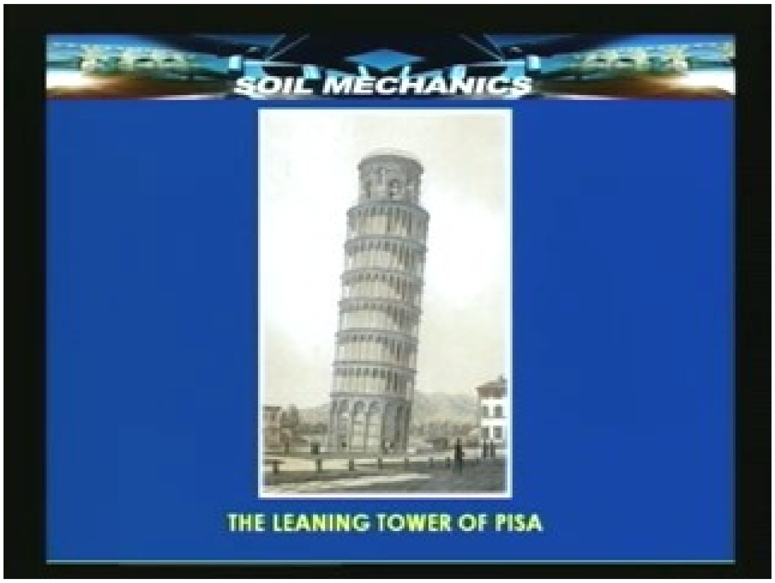

What is special about this is, one side of this PISA tower has undergone settlement due to a compressible soil layer below it and this has recently been rectified and it has been ensured that it will remain tilted and stable at a particular degree of rotation. Now why did it settled? Let us understand. In the first case some details the subsidence due to the clay layer below is 1.89 meters that means one side of the tower tilted by 1.89 meters.

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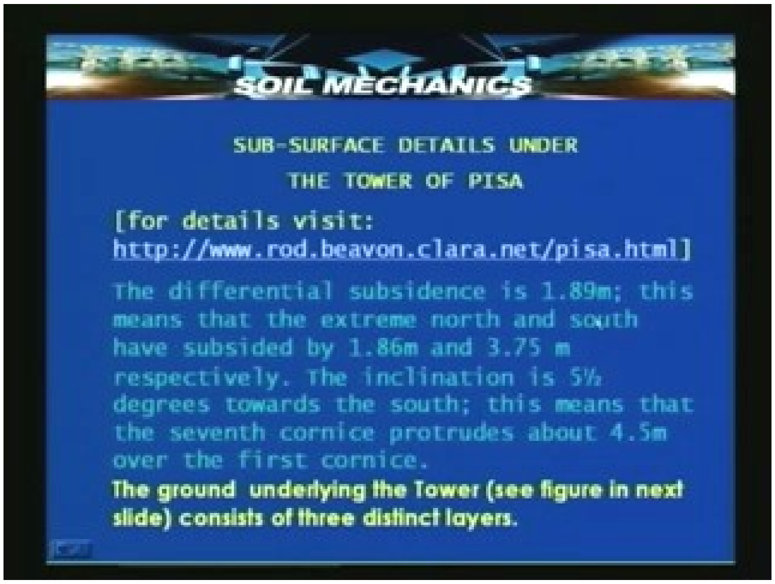

This means that the north and the south sides had a differential settlement amounting to the difference between 1.86 meters and 3.75 meters respectively. The tilt that took place because of this is 5 and a half degrees towards the north because the north as subsided more. This means that the seventh cornice, you know there are several levels, seventh cornice protrudes about 4.5 meters over the first cornice that is the amount of lateral movement that has arisen because of the settlement.

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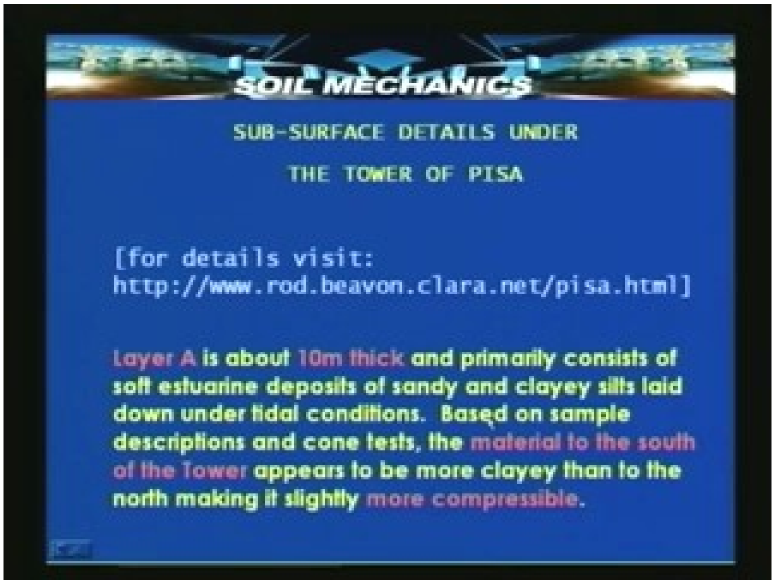

Now what is the reason for this settlement? You can see a lot of details about this including the details of the restoration of this in the website which I have listed here. The prime reason is there under sub surface condition there is a layer A which is 10 meters thick which is basically consisting of deposits of sandy and clayey silts.

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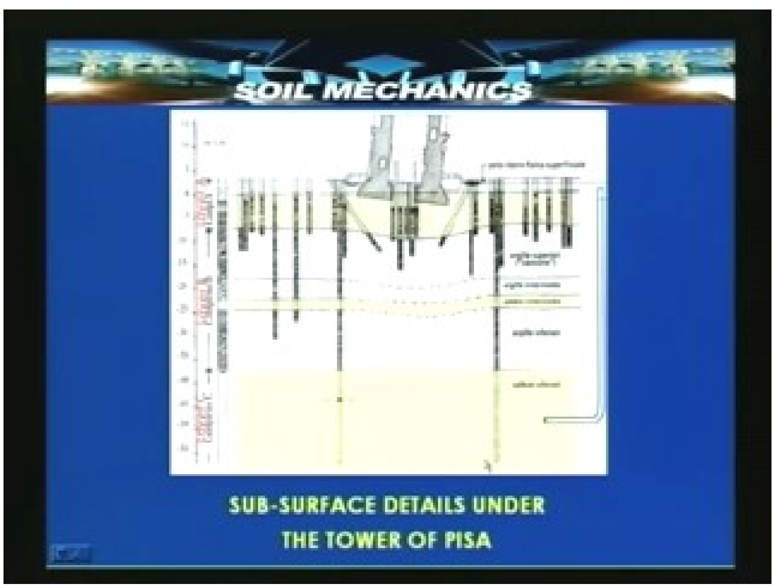

Then below that there is a layer B and below that a layer C. Layer B consists of sensitive normally consolidated marine clay, so this is the culprit. Below this layer C is a dense sand and there is a water table in horizon A that layer A.

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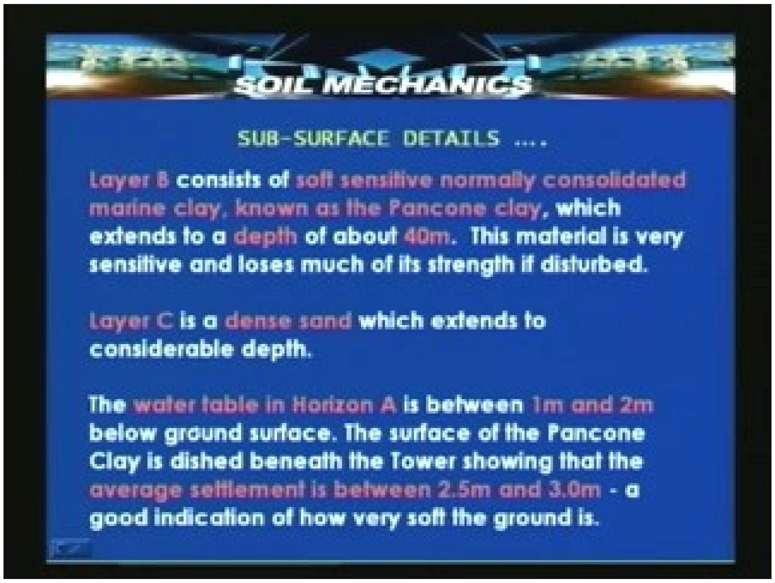

Now these are the culprits and you can see in this diagram that layer B has settled and that is the reason why the tower has tilted. If the tower had undergone uniform settlement perhaps it wouldn't have been a serious concern but this differential settlement leading to tilting had become a serious concern.

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Similar example, one can see in Mexico, for example this palace of fine arts in Mexico City had a staircase leading to the entrance from the ground level. Now today the staircase has gone below the ground level and you can directly access the building at this level. What was the first floor level earlier has now become ground floor level and there has been a total settlement of about 10 feet in this over a duration ranging from 1904 to 1972. The reason for this enormous settlement is the sub surface profile. The entire Mexico city is located in locostrain (Refer Slide Time:

49:21 min) deposits consisting of alternating layers of soft clays with igneous matters such volcanic, ash, some sand, some tuf pumice and some gravel.

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If this alternating layers of soft clay with all interspersed with other igneous matter and all under a lake, formed under a lake have given rise to the compressibility owing to which buildings in the Mexico city area settled by as much as 10 feet. Many building underwent lot of settlements and today of course because we are very well aware of what is consolidation and how it takes place and we also know how to take care of it, how to combat it (Refer Slide Time: 50:10 min). We are in a position to construct a building which do not settle. However in the past Mexico City was very famous for such instances of building settling by a large amount. Now there can be number of case like this, wherever there are marine clay there are structures, coastal structures such as refinery storage structures, container yards and even other buildings and structures. They are all highly compressible.

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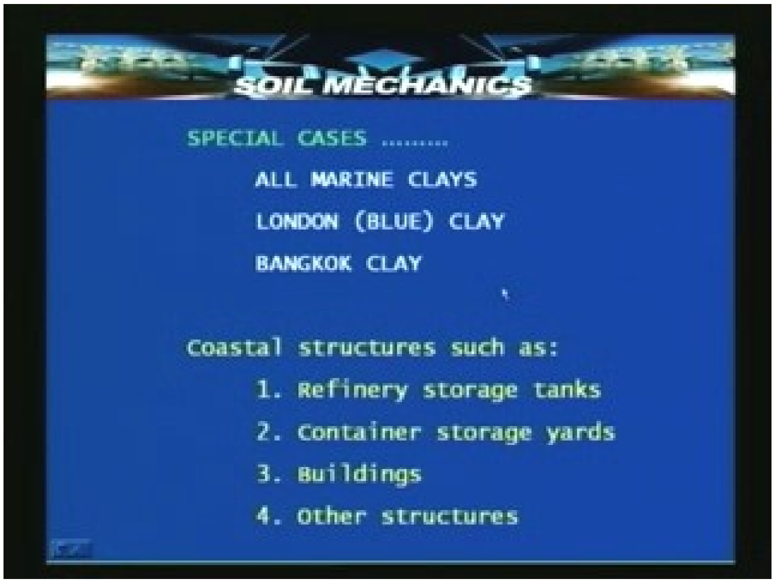

London blue clay is a very well-known example of compressible clay. Bangkok clay is again another example of famous compressible clay. Now these are all very special instances about which there is a lot of literature available today and I would very much advice you to go through that literature.

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Now what are the different types of settlement? Immediate, construction, consolidation and then total, we know what is total. We know what is differential, we have discussed. If you apply a load some settlement takes place immediately which is of elastic nature and it can be computed by elastic theory using this formula. And when you construct the building as the load gets applied also some settlement takes place and that is known as the construction settlement and all other terms are very well known to you.

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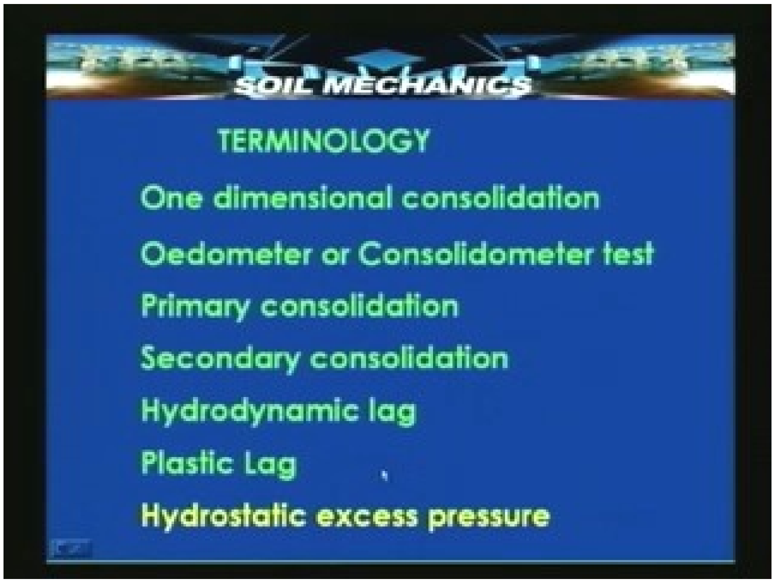

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Now there are a number of terminologies which I would advise you to go through. There is one list here, one dimensional consolidation, oedometer, primary, secondary consolidation, lags hydrodynamic and plastic, excess hydrostatic pressure. Then all the coefficients of compressibility then terminologies such as such as settlement and time factor.

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Then special terminologies like normally consolidated, over consolidated, preloading, radial consolidation and so on.

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And then with this background you should be able to solve a few exercises on your own. There is one self-assessment exercise; I would advise you to read this carefully. You were required to calculate the total settlement of footing; the answer is already given here 32.7 millimeters.

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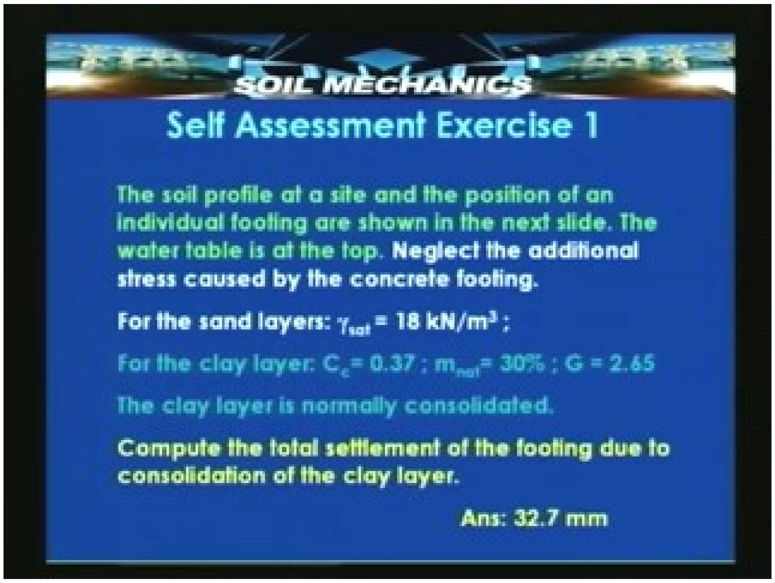

I would advise you to calculate this and confirm and satisfy yourself that you are aware of settlement computation.

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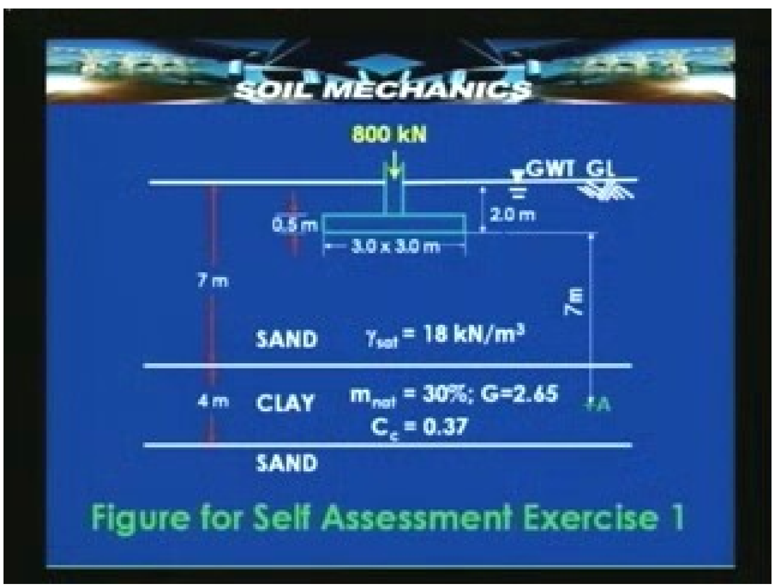

This is the illustration of fitting resting on a sand layer and a compressible clay layer followed again by a sand layer. So this is an instance of 2 way drainage.

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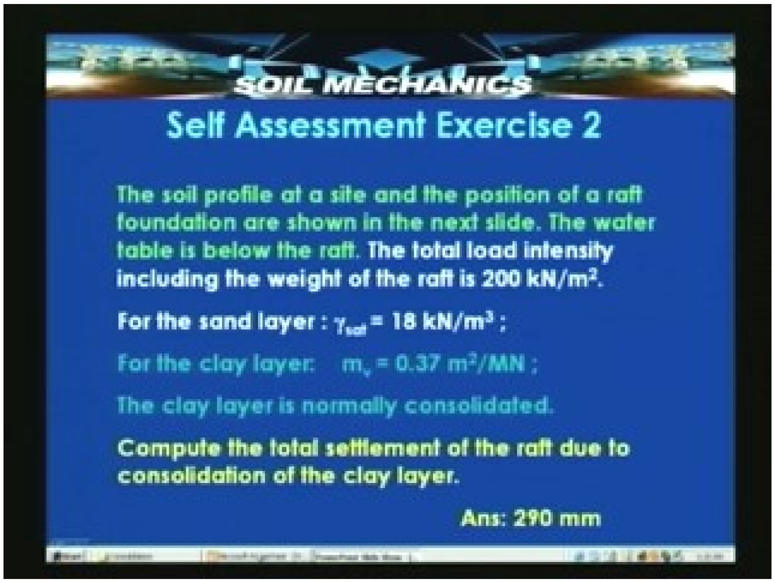

Another exercise is there; again calculate the total settlement below a raft. Answer is 290 millimeters.

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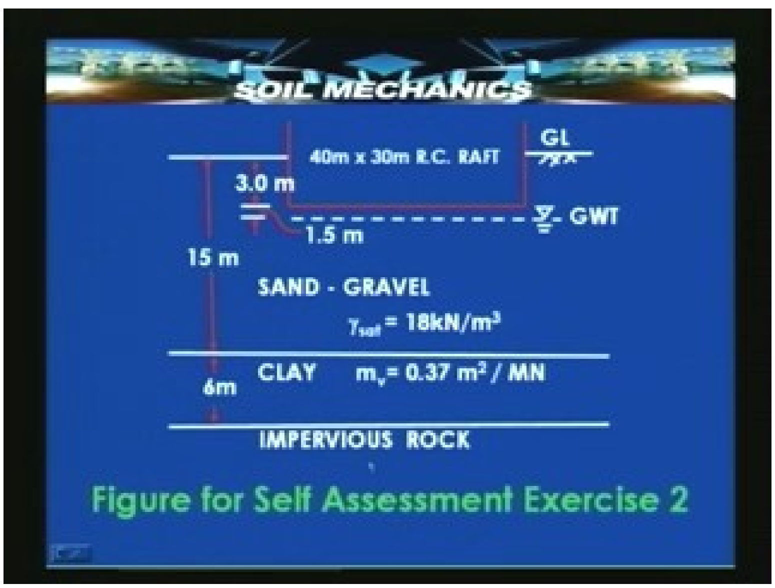

This is the illustration, again there is a clay layer above that is sand below that is impervious rock so this is an instances of single drainage. Then we have an exercise 3 in which we have to obtain this settlement at the end of several time periods 1, 5, 10 and 20 years. We can compute this as shown and the partial answers I have given already.

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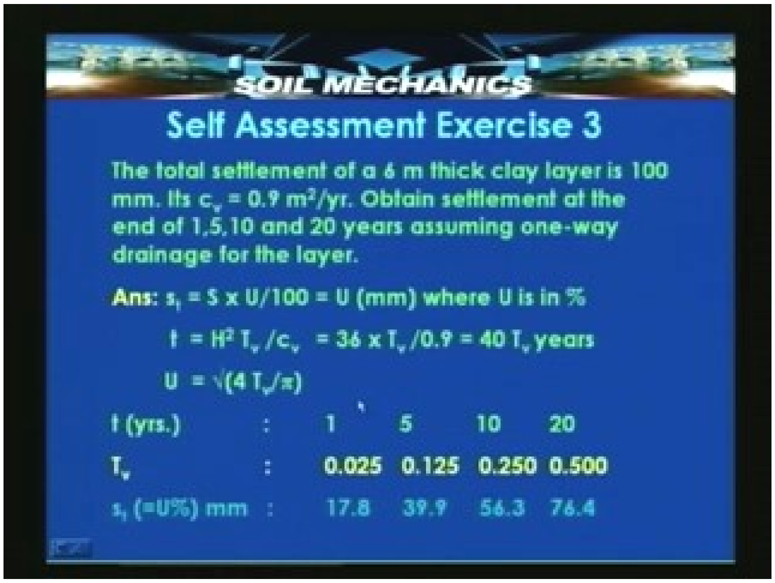

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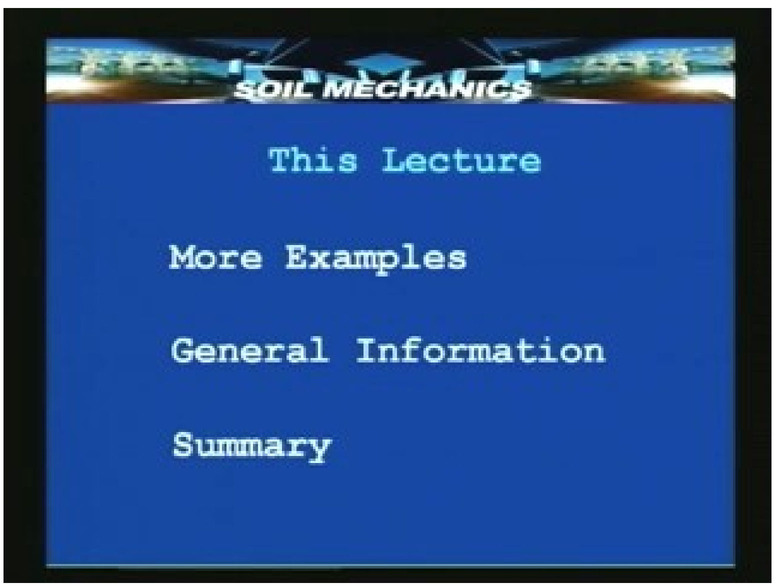

You can see that and convince yourself. So in this lecture today, we have seen a number of additional examples, we have seen some general information of special interest and I have summarized the entire phenomenon of consolidation and settlement. Thank you