Geosynthetics and Reinforced Soil Structures
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Lecture - 25
Accelerated Pre-consolidation of Soft Clay Soils Using Geosynthetics

Very good morning students, the previous lectures we have been discussing about the construction of embankments either on soft clay soils or very steep embankments on a hard foundation soil. In this lecture, let us look at on the topic of the use of geosynthetics for accelerating the pre consolidation of the soils.

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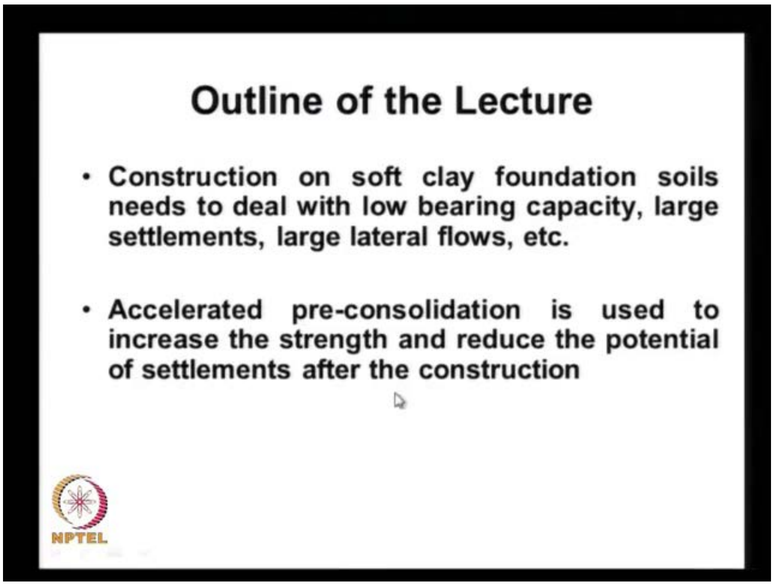

Brief outline of this lecture is, we have already seen that any construction on soft clays, we have to deal with very low bearing capacities and very large settlements and large lateral flows. Potentially, any engineering construction on the soft clays will have to deal with this before we take up any construction, and traditionally the accelerated pre consolidation is a conventional solution that is used for a addressing this problem. Then we use it not only to increase the strength of the foundation soil, but also to reduce the potential settlements, after the construction work is completed and the use of geosynthetics.

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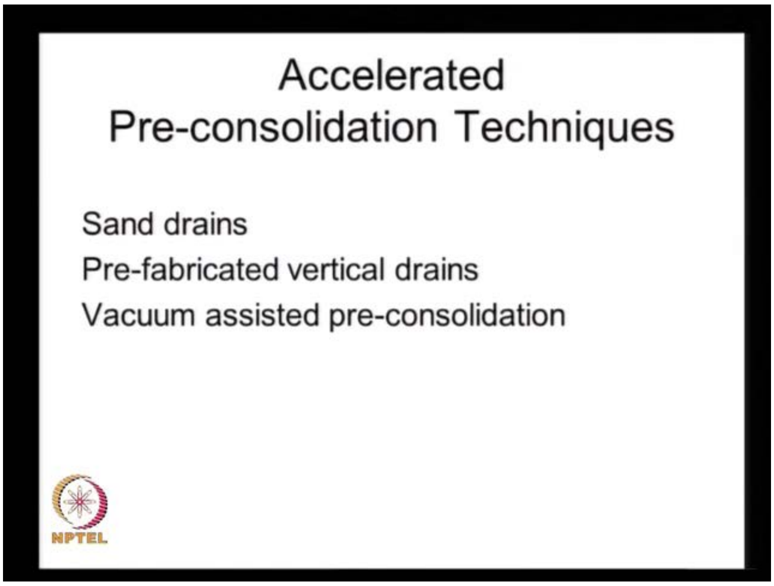

I have improved these techniques a lot and some of the techniques that we can use, for accelerating the pre consolidation of the clay soils or the sand drains. Historically, the sand drains have been used for a very long term, right from 1920 up to probably mid 1970s. After that we have the pre fabricated vertical drains made of geosynthetics and then more recently the vacuum assisted pre consolidation.

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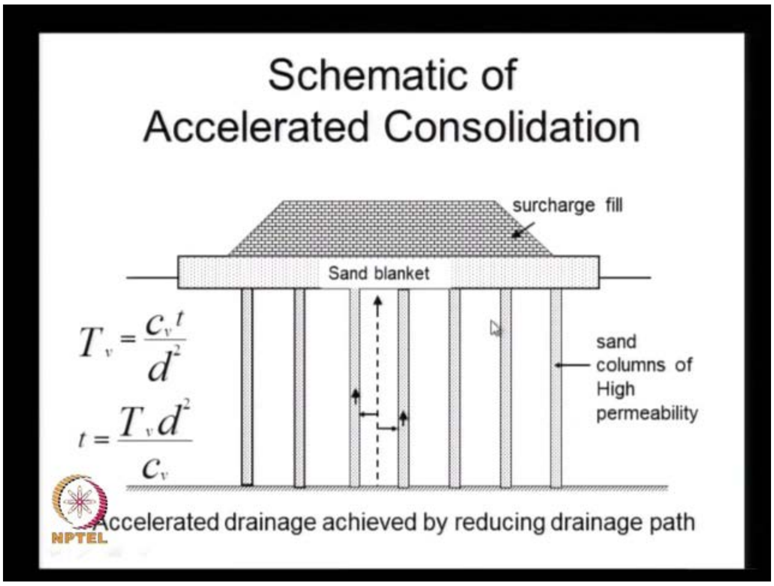

The approach that we take for accelerating the consolidation is, reducing the flow path. Here, we see an illustration of the construction of an embankment and soft clay of certain thickness and if it has to consolidate under the applied load, the water particle has to travel all the way from this depth up to the surface. If we install very large number of highly permeable sand columns which are known as sand drains, schematically they illustrated here. The maximum length a water particle has to travel to escape from the soft clays is only this much.

We already know that our time for consolidation is directly proportional to the square of the drainage path length is illustrated. Here, the T v is the time factor that is related to the to the coefficient of consolidation C v, the time t and d square, d is the drainage path length. If we did not have the sand columns, water particle has to travel this much distance, whereas if we install the sand columns, the water particle has to travel only this much, so you can imagine by how much the time for consolidation will reduce. In all these cases, when the water comes out, we need to have a mechanism for a leading the water away from the construction site and that we achieve a by providing a sand blanket like this.

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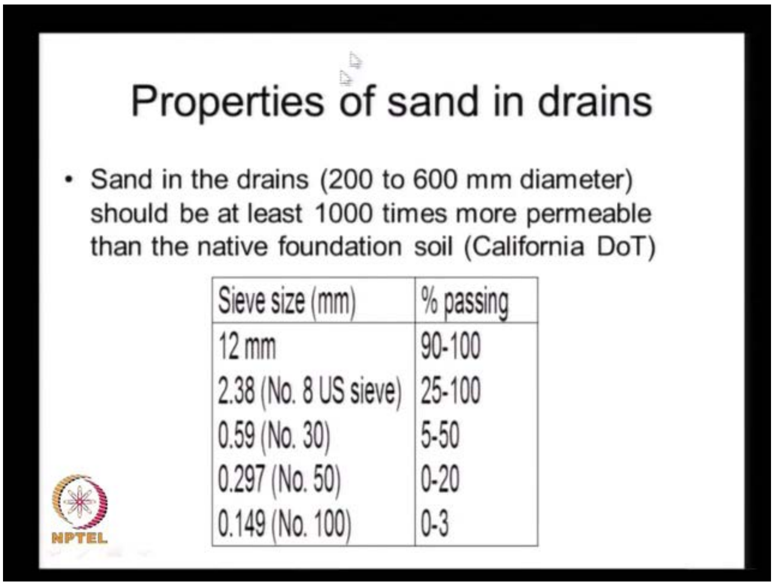

These sand drains or sand columns are typically 200 to 600 millimeters in diameter and the empirical experience shown that the sand in the sand drains should be at least 1,000 times more permeable than the native foundation soil. To achieve a very high permeability, we require the sand that is placed in the sand drains to meet a certain gradation requirements. One of the earliest to recommend this type of recommendations is the California department of transport, in fact that is where the first application of the sand drains is taken place, and these mostly are course grained soils. We see that more than 50 percent of the soil is coarser than number 30 ASU that is approximately 600 microns.

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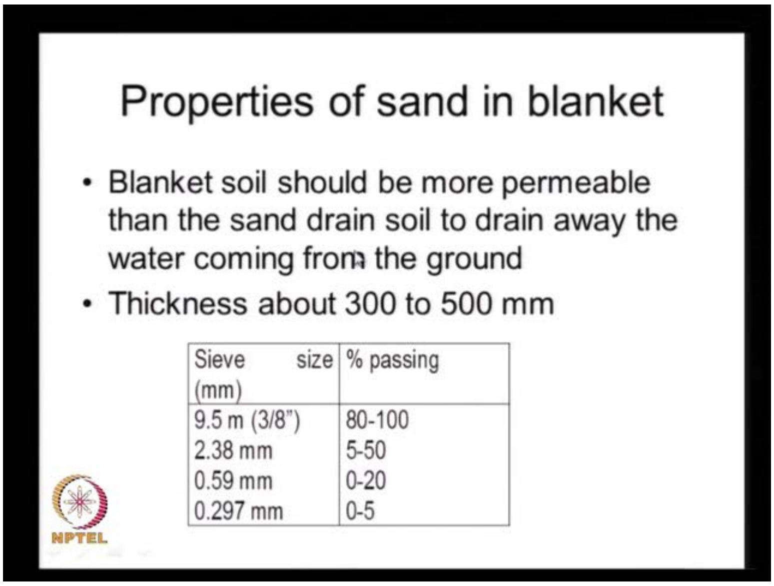

As the water is coming up through the sand drains, it should be able to flow away from the construction site, otherwise it is percolate down to the into the ground. The blanket soil, for that reason the blanket soil should be more permeable than the sand drain soil to drain away the water coming from the ground and the usual thickness. We need to design the thickness so that there is adequate slow path for the amount of water, that is coming out to drain out and as we can see more than 80 percent of the soil that is placed in the blanket should be coarser than 600 microns. In the previous case 50 percent was coarser than 600 microns, whereas here more than 80 percent should be should be coarser than 600 microns, because this soil should cater to the quantity of soil water that is coming out from the ground.

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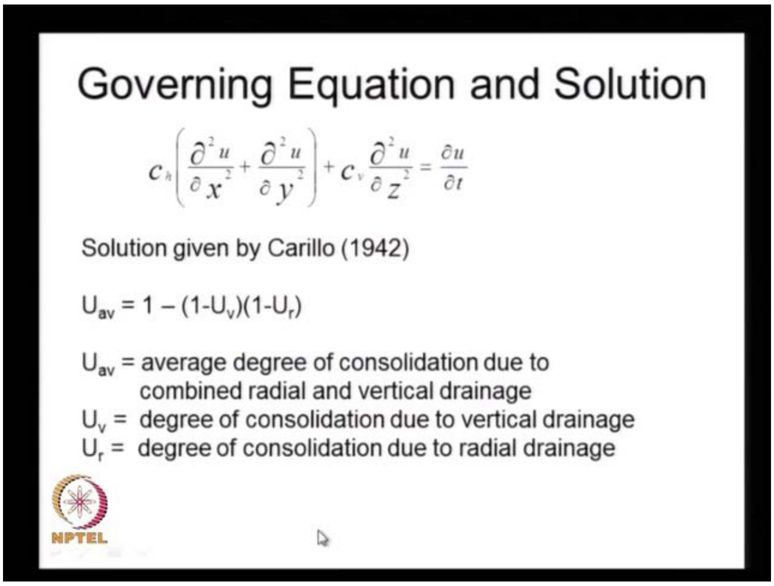

The design of the sand drains is based on certain principles and the governing equation is the three dimensional consolidation equations. Here U is the pore pressure, x and y they are the horizontal dimension, x and then z is the vertical dimension and the C h is the coefficient of consolidation in the horizontal direction. C v is the coefficient of consolidation in the vertical direction and t is the time and the solution for this is derived by several people notably Richard. Others are Carillo in 1942, he has proposed this solution that combines the effect of the vertical drainage and also the radial drainage in this form.

He proposed that the average degree of consolidation that we can achieve because of the combined radial and vertical drainage can be written as 1 minus 1 minus U v times 1 minus U r. Here, U is the degree of consolidation varying from 0 to 1 and the principle for designing is in a given time in a in a certain time we would like to achieve. Let us say 90 percent of the consolidation, so we need to design the spacing so that this, net sum total of the consolidation that we can achieve because of the combined the consolidation is so much.

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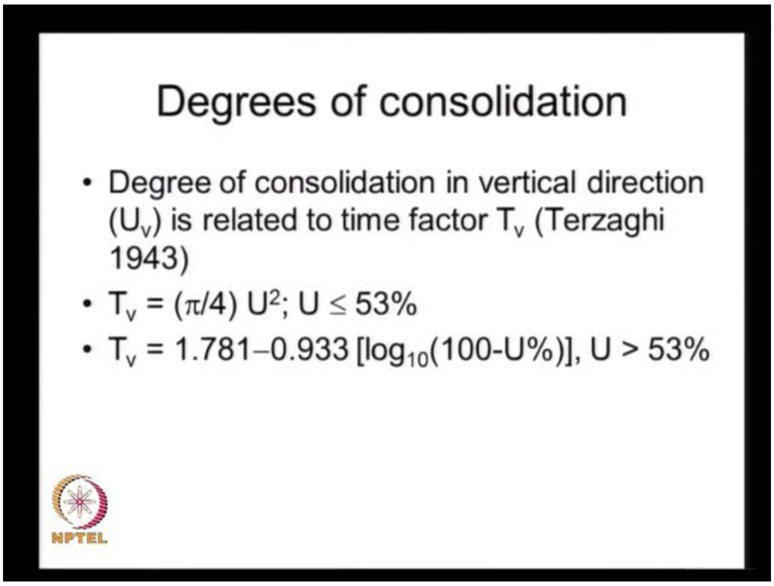

The solution for the consolidation due to vertical drainage is given way back in 1943 by Terzaghi and he has also proposed these empirical equations. There are several such equations and one set of equations that works out very well is this where in the time factor is related to the degree of consolidation as pi by 4 times U square. Here, U is less than 53 percent and if the of the degree of consolidation is more than 53 percent, the time factor is related to degree of consolidation through this equation. So, for any given time factor we can find the degree of consolidation.

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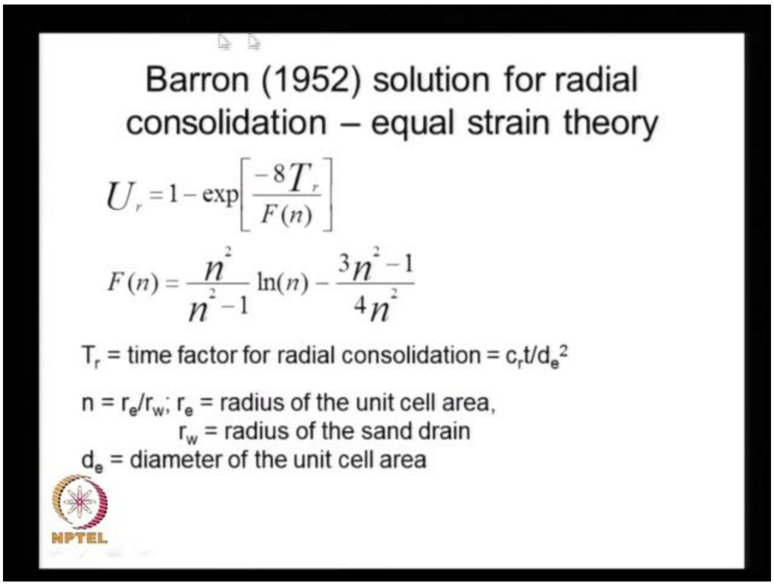

The radial consolidation theory has been solved by several researchers, Barron in 1952, he has proposed the solutions for two types of field analysis, one is the freed free strain case, where in we apply flexible loading and the settlement is non uniform. The other theory is equal strength area, the rigid loading where in our settlements are equal all through and in variably the equal strain theory is more applicable because our foundation structures.

They tend to be rigid and here, he has the final solution that was proposed by Barron is like this. The degree of consolidation in the radial direction is 1 minus exponent minus 8 t r by function which is written in terms of n where this function f of n is written as this n square by n square minus 1 l n of n minus 3 n square minus 1 by 4 n square. Our T r is the time factor for radial consolidation that is equal to c r t by d e square where c r is the degree the coefficient of consolidation in the horizontal direction. When the radial consolidation equation is solved in the radial coordinates instead of writing this coefficient of consolidation as c h, we write it as c r t by d e square.

Our n is r e by r w where r e is the radius of the unit cell area we assume in all these analysis, that each sand drain influences certain area of soil all around all around. That area is converted into an equivalent circle and this r e is the radius of that unit cell area influenced by each of the sand drains and that depends on the pattern of instillation. There are different patterns; one is square pattern where in along length and width, the sand columns are installed at equal spacing’s. The other is a triangular pattern, that we will see bit later on and r w is the radius of the sand drain and d e is the diameter of this unit cell area, it is influencing by each of these sand columns.

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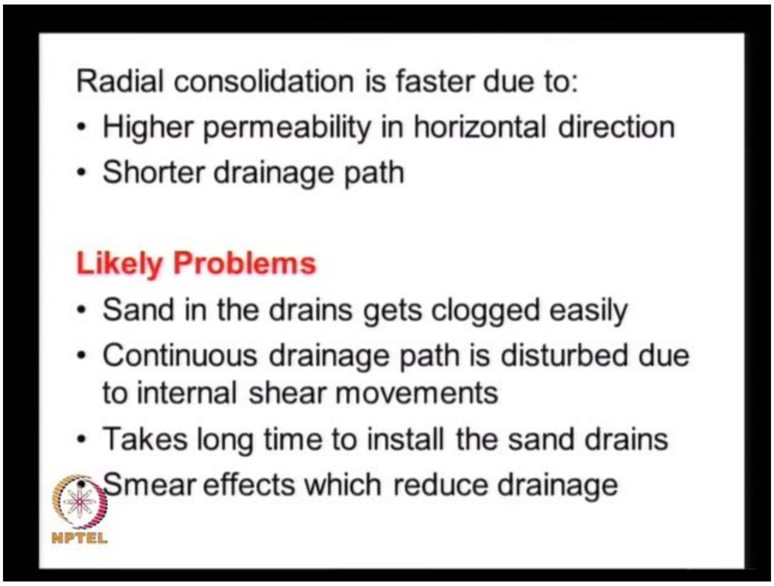

Then, our radial consolidation is very fast because of two reasons; one is because of higher permeability in the horizontal direction. We all know that most of the clay soils there highly an isotropic and they have different properties and different directions and because their direction of deposition is in the vertical direction, they have an easy flow path in the horizontal direction as compared to vertical direction.

So, they have higher permeability and relatively that gets reflected in higher coefficient of consolidation, and of course, the shorter drainage path. As a result of these two reasons, our radial consolidation is very fast because in a given time, if you are able to achieve about 10 percent degree of consolidation in the vertical direction. The degree of consolidation that is achieved in the radial direction could be of the order of 80 to 90 percent for a very long time. The sand drains been very popular for treating the soft clay soils, but then there were many instances, where the sand drain treatment did not help in accelerating the pre consolidation settlements.

Some of the problems that were encountered or as follows; the sand within the drains gets clogged easily because the soft clay may have very fine particles. In due course, the fine soil particles coming into the sand clogged the openings, thereby impairing the permeability of the sand. Then the continuous drainage path may be disturbed, because of internal shear deformations because all these pre consolidations are achieved by constructing a surcharge. If you are not careful enough in applying a uniform pressure and applying the surcharge load at a slow enough rates, there could be large lateral deformations.

As a result of the shear deformations, the sand columns may undergo some distortion and in that case, the flow path is disturbed. Once the flow path is disturbed, at that particular flow path, sand column becomes enough cannot transmit any water. It takes a very long time to install the sand drains, because we need to first drill out the bore hole of certain diameter like say 200 or some diameter as per our designs up to the bottom of the soft clay layer. Then we have to fill that with sand of certain gradation because of the complicated instillation process.

There are many cases, where the flow path is disturbed, because of this smearing of clay soil all around is basically remolding of the clay around that reduces the drainage capacity of the of the sand drains. As a result of all these reasons, there is a need to come out with better methods for accelerating the consolidation. The introduction of geosynthetics, has helped in completely transforming the way we look at this problem of the pre consolidation.

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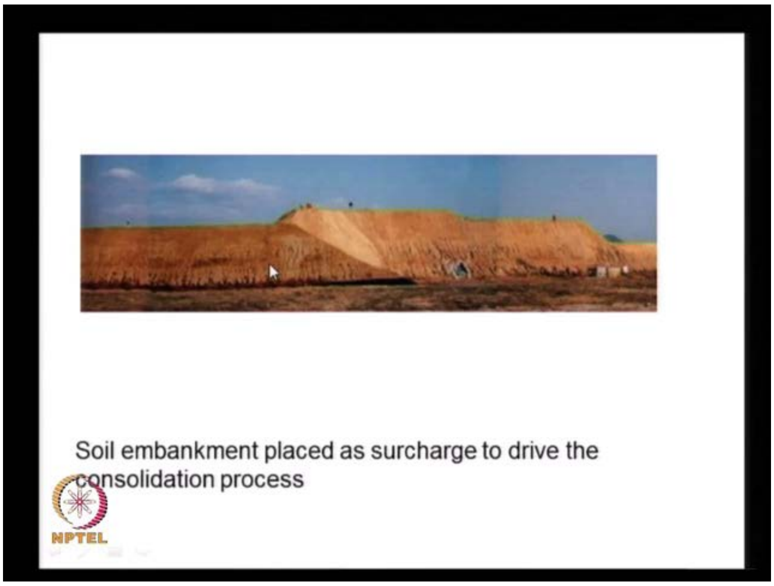

Here, we see an example of a soil embankment that is placed to drive the consolidation. We all know that unless there is an increase in the effective stress, the consolidation will not happen and the increase in the effective stress is achieved only by increasing the total stress. Initially, as per the Terzaghi's theory, we know that initially all the total stress is taken by pore water. So, the pore water pressure is equal to the total stress, but as the time passes by because of the drainage of the water. Gradually, the pore pressure reduces, that in turn increases the effective stresses. The increase in the effective stress is the one that causes compressions and once the soil compresses, the wide ratio reduces and the clay soil particles are tightly packed.

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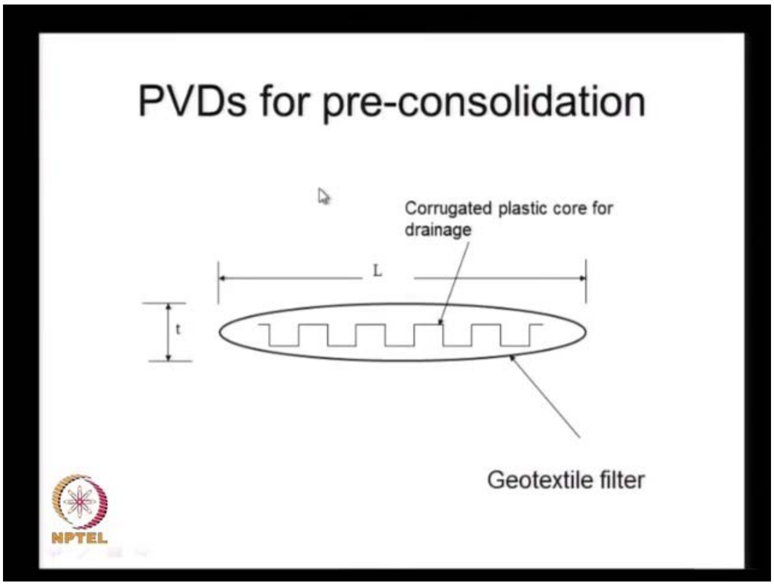

Other reasons are like the secondary Vander Waals forces and others, the strength of the soil increases. So, that is the basic principle of the of the pre consolidation that we have and because of all the problems that that we can potentially have with the sand drains, the geosynthetics coming to the market. A very large number of varieties of a geosynthetics have been manufactured just for the purpose of a pre consolidation and here we see the cross section of a typical PVD, this is the pre fabricated vertical drain. It is also called as width drain in the case of the sand drains, because of the pressure applied that drives and provides the gradient for the water to flow.

The water flows through this as opposed to the sand drains, this has two components, one is a drainage component and the other is the filter component, whereas in the in the case of sand drains there is only drainage component. There is nothing, there is no filter to stop the fine soil particles from migrating, Then clogging this and here we have the different types of drainage cores. The one simple thing is a corrugated plastic sheet and we can have a oven or non oven geotextile cover that acts like filter. The purpose of the filter is only to filter out the fine soil particles from escaping from the from the foundation soil.

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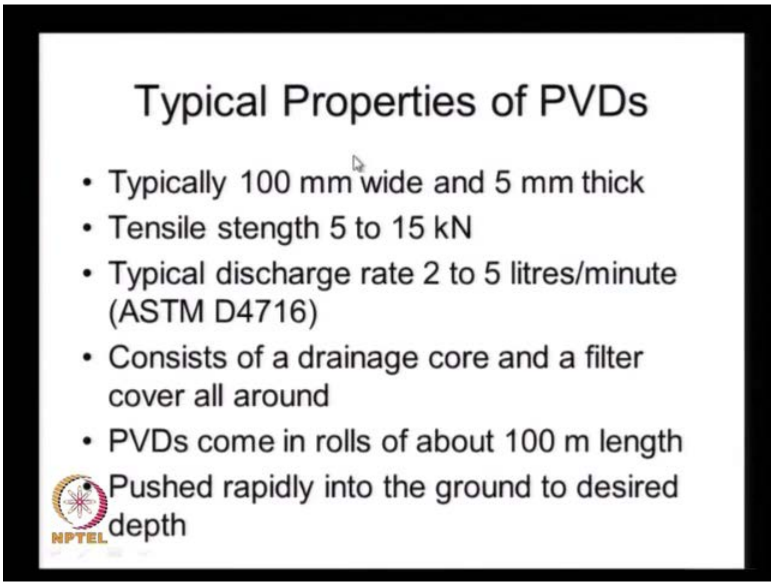

The typical property of the PVD's typically there about 100 millimeters wide and 5 millimeters thick. The inside core could be made of corrugated plastic sheet or we can make the inside core using geonets or some other materials like the crimped wire mesh and so on. The tensile strength of each of these PVD's is about 5 to 15 kilo Newtons because they are made of very good quality geotextile. As a result of that, they could have very good strength and typical discharge rate that is measured as per the ASTM D4716 is in where from 2 to 5 liters per minute, so this is quite substantial.

As I already mentioned, this PVD's consist of a drainage core and a filter cover all around and main advantage of this PVD's, they come in large roll lengths of about 100 meters or more. These can be pushed rapidly into the ground to desired depth because that is where the major difference between the sand drains and the PVD's come in for the installation of sand drains. We need to drill a bore hole and then fill it with a sand of required gradation and also when we fill the sand, it should be compacted so that the bore hole does not collapse. Here, in this case, we take a pre fabricated drain that already comes in rolls, it just simply pushes it into the ground and the type of soils that we deal with are extremely soft. It may have cohesion of about 5 to 10 kilo Pascal's or at the most about 25 kilo Pascal's and it is very easy to push them.

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Here, we see an example of the PVD, that is coming in a roll and this PVD is being connected to anchor plate, that gets that is connected to this rod. This simply pushes the anchor plate and along with the anchor plate the PVD enters the ground. Here, we can see some PVD’s that are already installed and the entire field is a soft clay soil.

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We see here another view of the same thing, we see number of these PVD rolls here.

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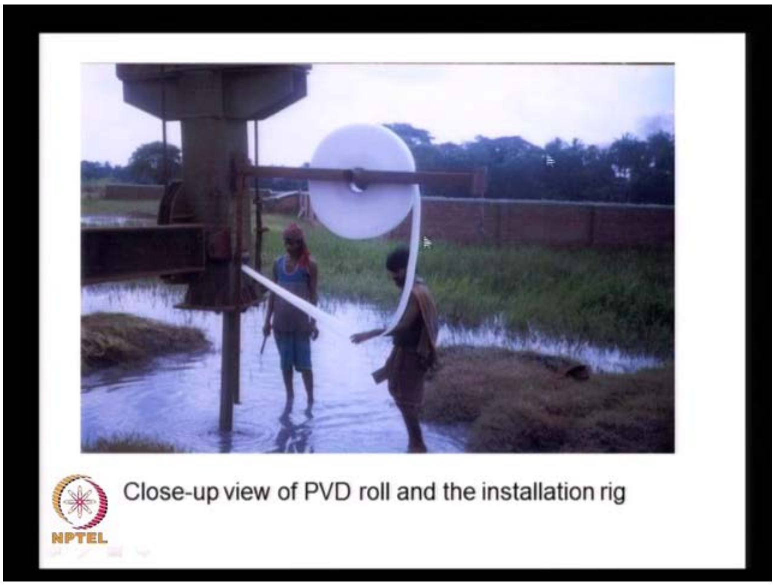

Another close up of this same thing is, actually we take the PVD's from this roll and feed it into this rig, and connected to the anchor plate.

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Here, another close up and we can see this crawler mounted like most of these PVD rigs, they are light weight compared to the other equipments. These come in on crawler and seize it to move them even on soft clays.

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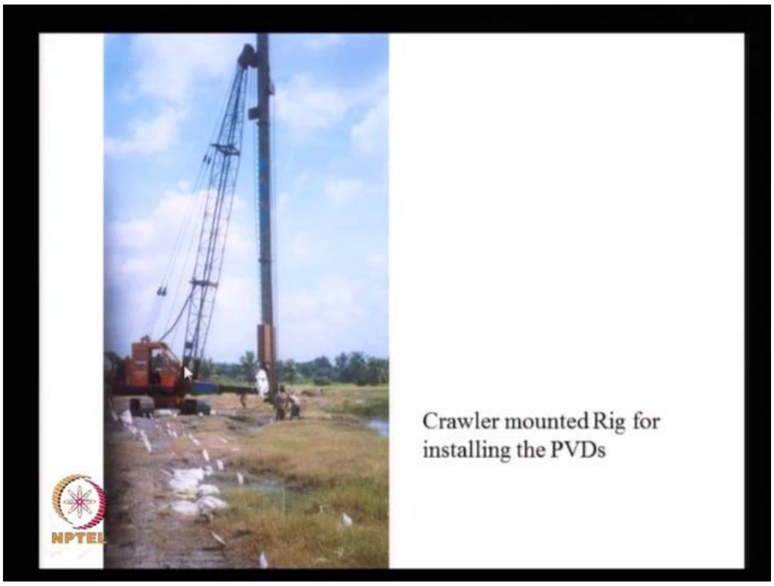

Here, we see the entire view and with the entire boom and the PVD’s installed by just simply pushing. In some cases, if we are not able to push, we also use the water jet to assist in the in the instillation. Typically, to install a PVD of about 10 to 15 meters, it takes hardly 3 to 4 minutes compared to that or the instillation of sand drains takes a long time because we need to position the in the drilling rig or the location. Then connect all the all the bore rods and then drill a hole and then stabilize it with the case in pipe or Bentonite then later fill that bore hole with sand.

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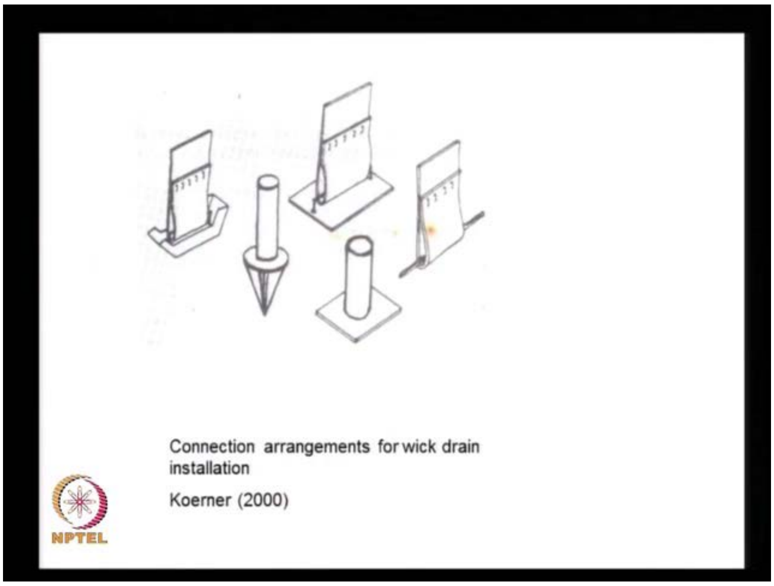

These are the different types of connector plates for connecting the PVD and these connector plates are the ones that are rigid. They can be pushed because the PVD's themselves are highly flexible and they cannot be directly pushed in to the soil. This particular picture is taken from Koerner text books on geosynthetics.

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Here, we see a picture of the PVD being manufactured; these are all the plastic cores that are put inside the PVD. They are all joined together by welding process, by heat bonding and then these plastic cores are covered with a geotextile, in this particular case it is a oven geotextile.

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Here, we can see the view of this site that is treated with a pre fabricated vertical drains. We have number of these and after the PVD's are installed, we need to lay the blanket soil that is highly permeable, so that all the water that comes out or can travel away from construction site.

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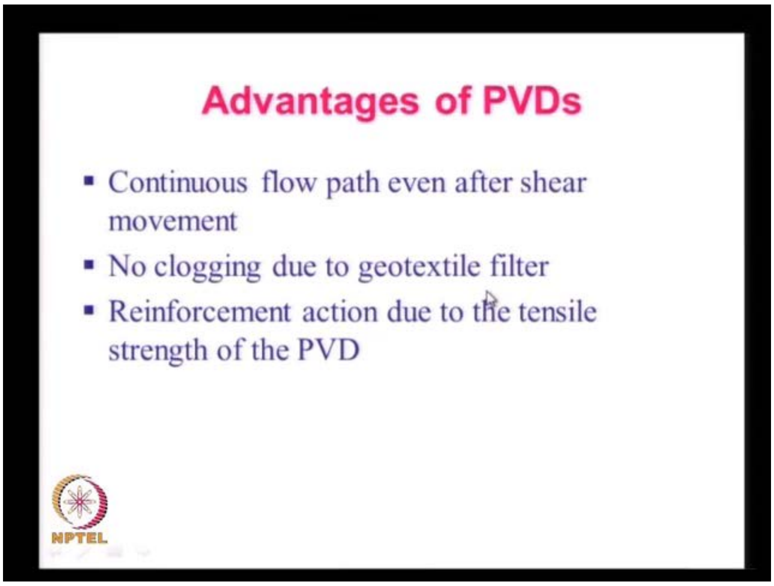

Some of the advantages that are claimed for a pre fabricated vertical drains are like this. The continuous flow path is ensured even after shear deformations because these PVD's are highly flexible. They can be bent or they can be twisted without rupturing because both the core and the cover that is filter are highly flexible and they can be strained up about 20 percent without rupturing.

So, because of that, even if there are some internal deformations or internal shear deformations, the PVD will only twist without rupturing. As a result of that, the continuous flow path is ensured and the ADTM D4716 code for testing of the PVD's also has a provision that these permeability test should be done at a very high pressure. Also, by assimilating the kinking, the kinking is bending of the PVD because of internal deformations and these discharge rates or the worst case discharge rates under very high pressure, and with some amount of kinking.

So, because of all these reasons, the flow through the PVD does not stop, even if there is some deformation in the ground and because we have a geotextile filter, there will not be clogging. This means that, we have to properly select the geotextile cover based on the soil properties, based on the on the drain size distribution and other things, that is all the principles that we have for the design of filters are applicable in this case. As a result, each of these PVD's, they have some tensile strength.

They also give some reinforcement action because of the tensile strength of individual PVD, because typically these are installed at a spacing of about 1 to 3 meters centre to centre. So, we can expect very large number of this PVD's within a unit area that can provide some tensile resistance either from lateral deformations or from horizontal deformations.

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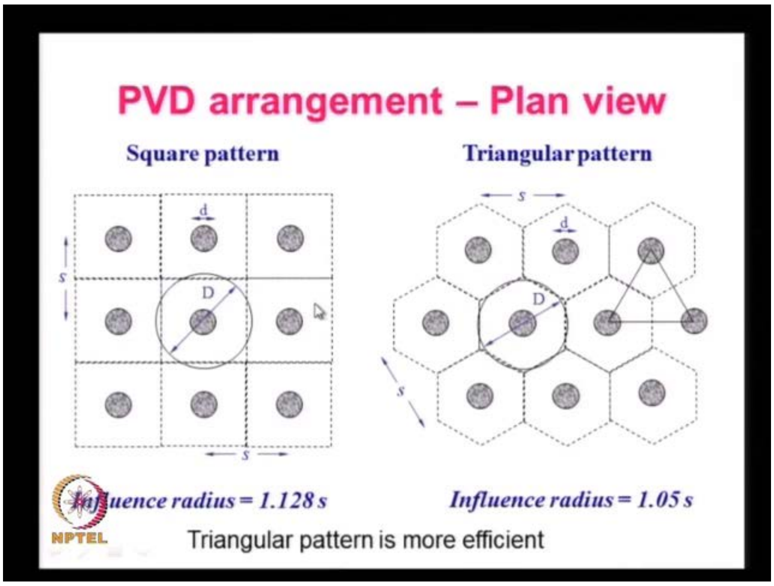

The typical arrangements, either PVD or sand columns are like this one arrangement is very simple square pattern where in along the length and width of the site, we place these PVD's at equal spacing s in this direction and also the same s in this direction. The area of the soil that is influenced by each of this each of these PVD's is assumed as a square. For the purpose of our mathematical analysis, we convert the square into a circular shape because then we can work with only polar coordinates and solve the equations easily.

We call this as the unit cell and if d is the diameter of the sand drain or the PVD and if D is the diameter of this unit cell, the factor n that we have seen earlier is, basically the D divided by the d. If s is the spacing, the influence radius that is radius of the influence zone in the square pattern is 1.1 to 8 times s. Another popular pattern is the triangular pattern, wherein there is equal spacing, but in a triangular manner like diagonally this spacing is equal, but not the other way. The triangular pattern has the advantage that the circle fits better within this hexagonal shape.

As a result of that, the influenced areas from one sand drain, does not influence the soil from the other sand drain. So, there is a better coverage and the influence radius in this case is 1.05 times the spacing s. It is found that the triangular pattern is more efficient because when we draw a number of the circles, the area of the soil that is not covered by any of the sand drain. For example, in this area in this square pattern, this area of soil is not covered and as the spacing is increasing, that uncovered area of the soil becomes substantial and that path of the soil may not consolidate where as the other rest of the soil may consolidate.

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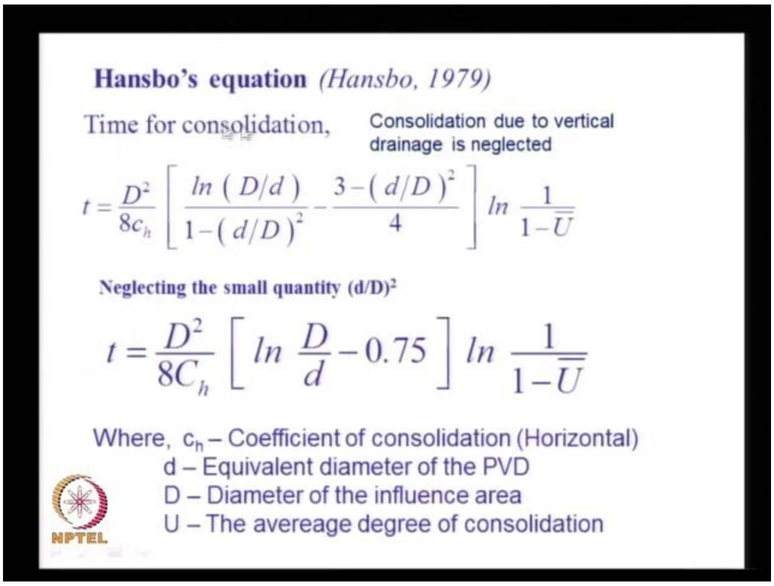

The design of PVD's can be done in the same manner as the sand drains, but in 1979, one Swedish engineer by name Hansbo has presented some data from large number of field thrust that was carried out. He related at the time for consolidation t in terms of the influenced D and c h that is the coefficient of consolidation. The horizontal or radial direction in this manner, the D square by 8 c h l n D by d divided by 1 minus d by D square minus 3 minus d by d square by 4 l n 1by 1 minus U bar. In this equation, we can neglect this d by D because invariably, this is very small.

The d is of the order of, let us say 0.1 or 0.05, whereas D is of the order of 1 to 2 and square of that is even smaller. So, by neglecting this term this d by D term, we can simplify this equation like this time. For consolidation, t is D square by 8 c h multiplied by ln D by d minus 0.75 multiplied by l n 1 by 1 minus u bar wherein our c h is the coefficient of consolidation in the horizontal direction. The d is equivalent diameter of the PVD and D is the diameter of the influence area of the soil and U bar is the average degree of consolidation that we desire within a time of small t.

It is very simple to solve this equation by trial and error and you can see that the contribution of the vertical drainage is neglected in this equation. Hansbo said that most of the consolidation is happening, because of the radial drainage. It is reasonable to neglect the contribution of the vertical drainage, because anyway it is very small.

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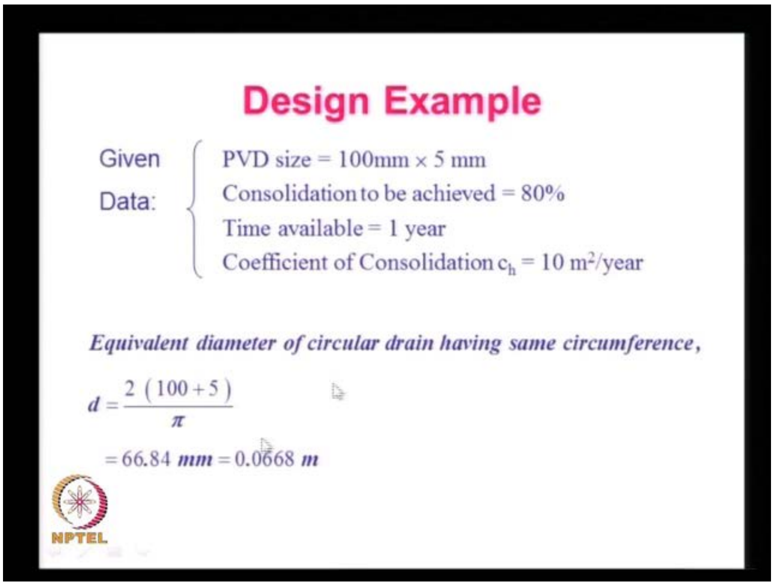

Let us look at a small numerical example on the design of the spacing of the PVD's for achieving pre consolidation. Let us say that we have a PVD having dimensions of 100 mm width and 5 mm thickness. We would like to achieve 80 percent consolidation in one year time. The coefficient of consolidation c h is given as 10 meters square per year. The first thing is because our PVD is rectangular in shape; we need to convert to equivalent circle because all our solutions are given only for radial geometry or polar coordinates. So, our PVD, if d is the equivalent diameter, pi d is the circumference of the of the PVD, that is 2 times 100 plus 5 that is the circumference. So, this equivalent diameter is 66.8 millimeters or 0.0668 meters.

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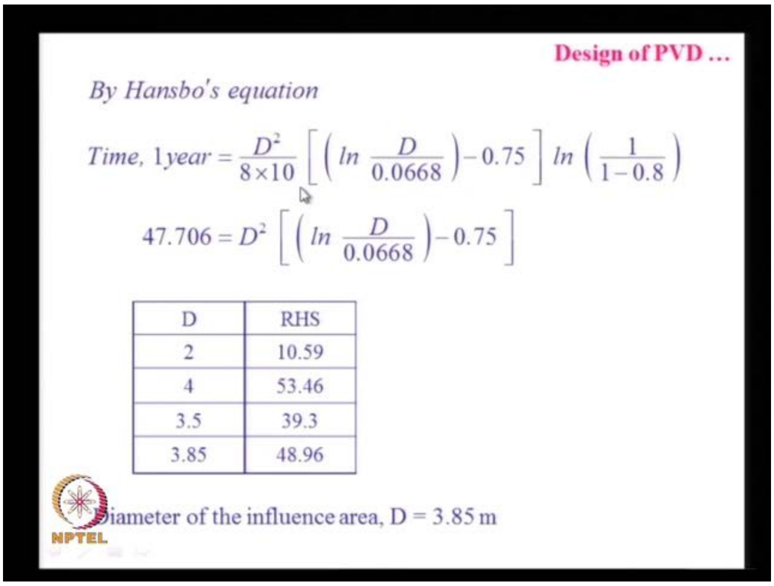

The equation that we have is the in terms of the time for consolidation t s; all these quantities D square by 8 c h and so on. So, time is one year and D is the one that we need to find and that 10 is the coefficient of consolidation in horizontal direction that is 10 meters square per year. The U bar that is the desired degree of consolidation that we want to achieve is 0.8. So, if you simplify and take this 8 times 10 and this l n of 1 by 1 minus 0.8 to the left hand side, this is 47.706 is D square multiplied by l n d by 0.0668 minus 0.775. We can solve it by trial and error by substituting different D's, we can find the right hand side quantity. When the right hand side quantities approximately equal to the left hand side quantity, we can stop the iterations. So, if we start with a D of 2 it comes out as 10.59, with 4 it comes to 53.46. So, that means that the D is in between 2 and 4 because at 2, the right hand side is less than 47 and at 4, the right hand side is greater than 47. So, let us try 3.5, it about 40 and let us increase it about 3.85.

Actually, there are several trials that were made, but all of them were not listed here and finally at a D of 3.85, the right hand side is 48.96 which is very close to 47.7. So, we can say that the diameter of the influence area, D should 3.85 to achieve 80 percent consolidation, within one year time using this particular PVD's.

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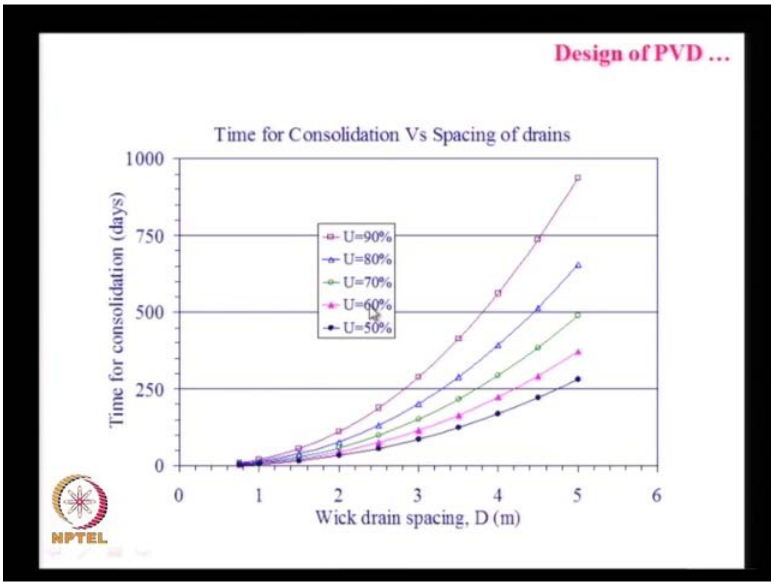

Actually, there is this equation is taken and for different potential with drain spacing's, what is the time that we can that we require achieving different degrees of consolidation. Let us say, this is our 80 percent consolidation is our interest, so this is the line that shows the degree of consolidation and we can say that within 1 year that is about 365 days about 3.85 is actually 10. If you do not want to solve it by trial and error, you can just go on substituting different D values, plot a graph and between horizontal, sorry the centre to centre spacing on the horizontal axis and on the vertical axis, the time for consolidation. We can read it out and in this case both of them they give 3.85 spacing and if you are if you want higher degree of consolidation 90 percent, the time, the spacing is lower, if you want within 1 year. If you want a lesser degree of consolidation, we can have a higher spacing as indicated here.

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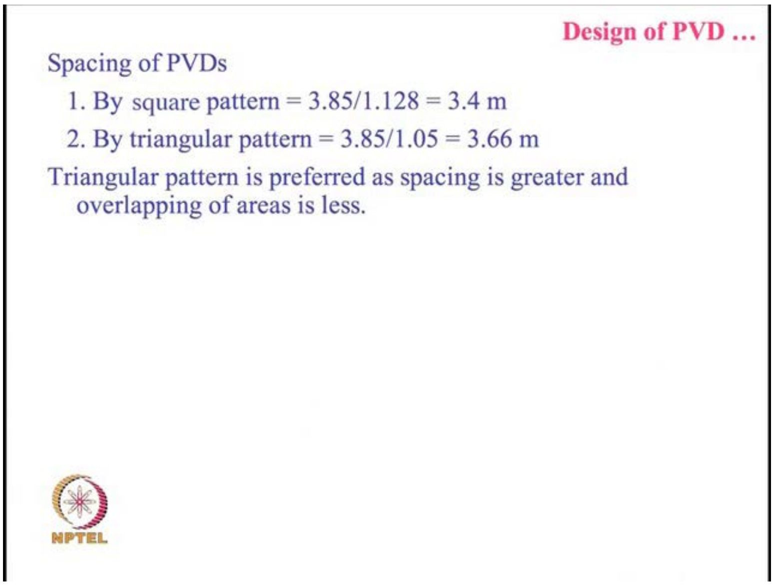

After we determine the diameter of the unit cell area, now we can determine the spacing in the square and triangular patterns, in the square pattern this spacing is 3.4 meters. In the triangular pattern this spacing comes out as 3.66 meters between these two, we prefer triangular pattern because the spacing is larger and also the coverage much is much better. So, we get better efficiency by using triangular pattern and is there a way of achieving even faster consolidation than PVD's and not using surcharge.

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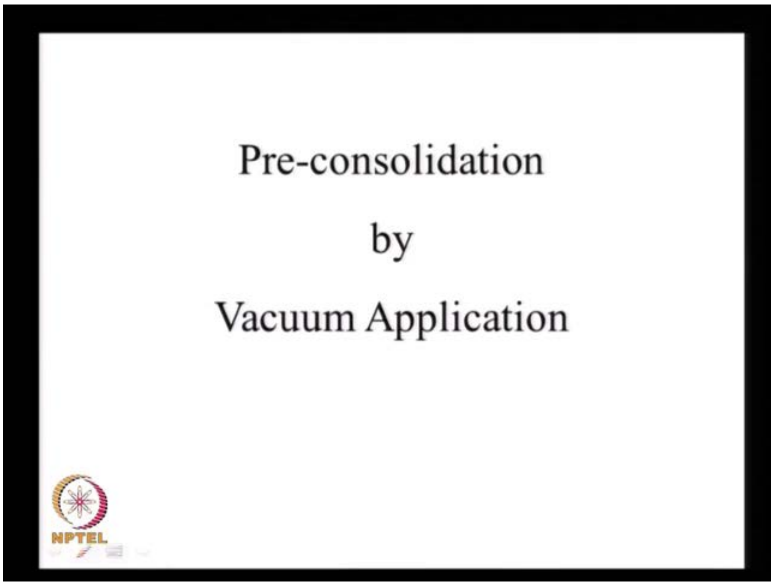

That is possible by using our vacuum for driving our consolidation.

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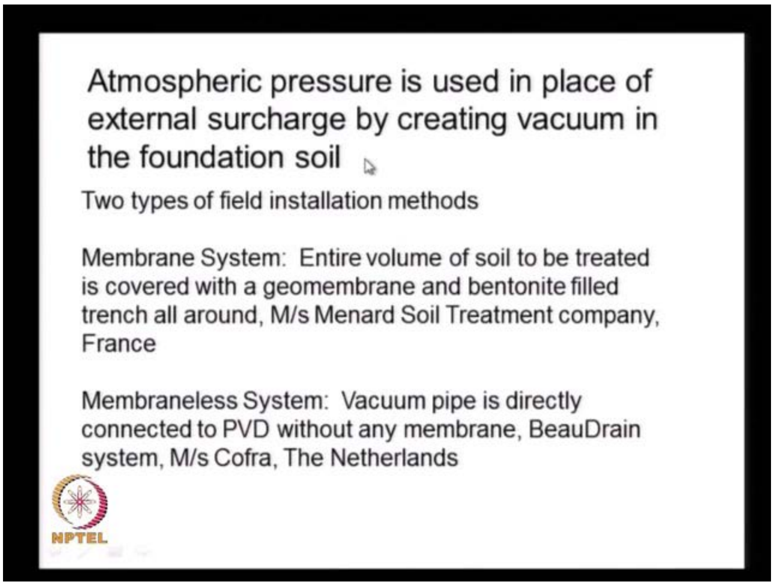

The principle is very simple, we remove the atmospheric pressure from the volume of clay that needs to be consolidated and then the atmospheric pressure itself acts like the surcharge. Then it drives the consolidation and as you know the vacuum is an isotropic stress or an isotropic pressure. So, we get much better consolidation with vacuum treatment and typically, there are two types of field installation methods. One is membrane system that is that was developed first, this is when the vacuum techniques of coming to the market here, we cover the entire volume of soil, we treated by using a geo membrane.

We use a bentonite filled trench all around the treated area to isolate the volume of soil that is treated from the rest of the soil medium, so that our vacuum is preserved. This method was developed by Menard Soil Company in France and there is another system called membraneless where in the vacuum pipes is directly connected to the PVD's without any membrane. This is called as a BeauDrain method that is developed in the Netherlands. The membraneless system is suitable for sites, where we have a thin layer of hard clay that is relatively impermeable and it will not allow the vacuum to be leaked.

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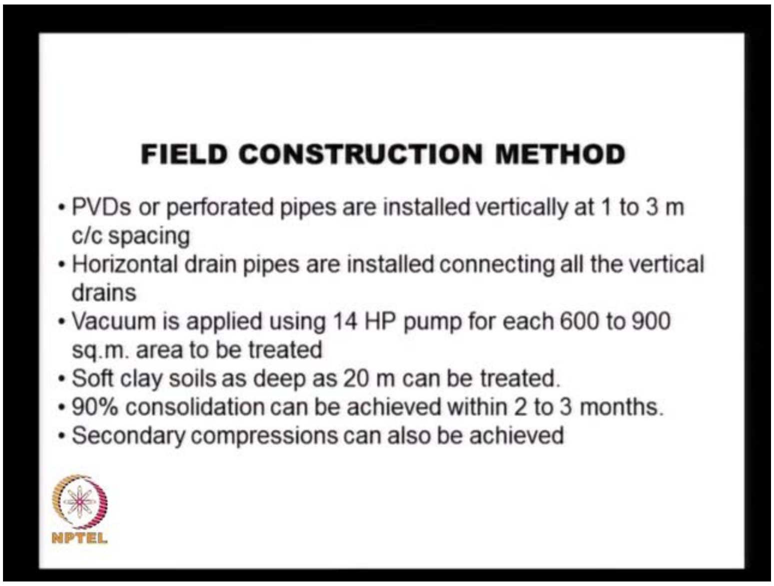

Both of them can be illustrated, I will show you the pictures later, some of the pre consolidation by vacuum or like this the PVD’s or the perforated pipes installed vertically at 1 to 3 meters centre to centre spacing. Initially, when the technique came in, the companies have used perforated vertical pipes to suck the water or to apply the vacuum distribute the vacuum into the soil. Later on, once the PVD’s coming to the market PVD’s are used to distribute the vacuum.

These are installed at spacing’s of 1 to 3 meters centre to centre spacing and these vertical pipes are connected to the horizontal drain pipes at the ground level. Typically, we use we need about 14 horse power vacuum pump for treating in area of soil equivalent about 600 to 900 square meters plan area. We can treat the soft clay soil area as deep as 20 meters and typically 90 percent consolidation can be achieved within 2 to 3 months. One main advantage of the vacuum treatment is, we can get it of even the secondary compressions that is not possible with ordinary surcharge method.

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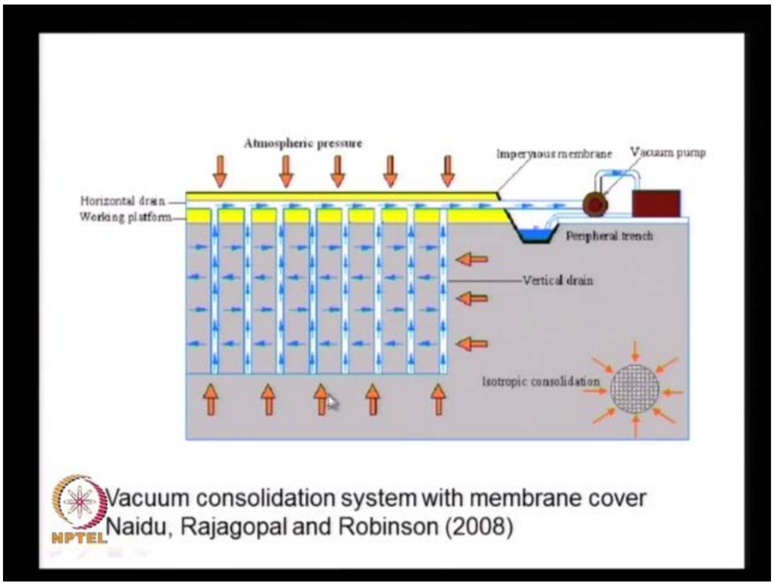

Schematically, the system that employs geo membrane cover is shown here. We have number of these PVD's or perforated drain pipes that are connected to horizontal pipe line that is connected to vacuum pump. We cover the entire area by a membrane and once we create a vacuum here, the atmospheric pressure directly acts on it and drives the consolidation. So, here the main principle that we have is, we increase the effective stress without increasing the total stress. That is the main principle that we will see later on and the vacuum pressure is isotropic, it is equal in all the directions, in all the radial directions and all in the vertical direction.

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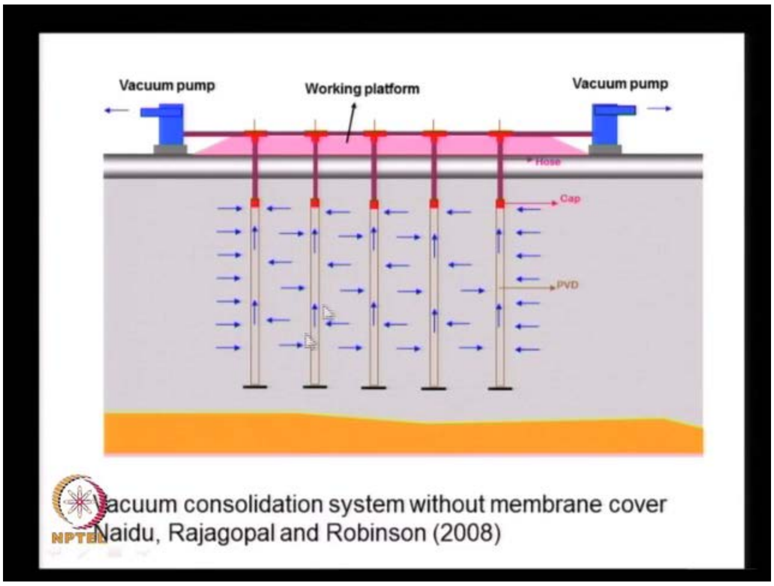

The system without any membrane is shown here, if we have a natural thin clay crust, we can take advantage of it, otherwise we can we can place a place a mat of clay soil to isolate the area of treatment from the rest of the soil medium. Once again, we connect these vertical PVD’s into the drain pipes or the horizontal pipes, through which the vacuum is applied.

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Here, in this photograph, you can see these horizontal pipelines that are laid on the ground surface.

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Here, we can see the bentonite filled trench around the treated area.

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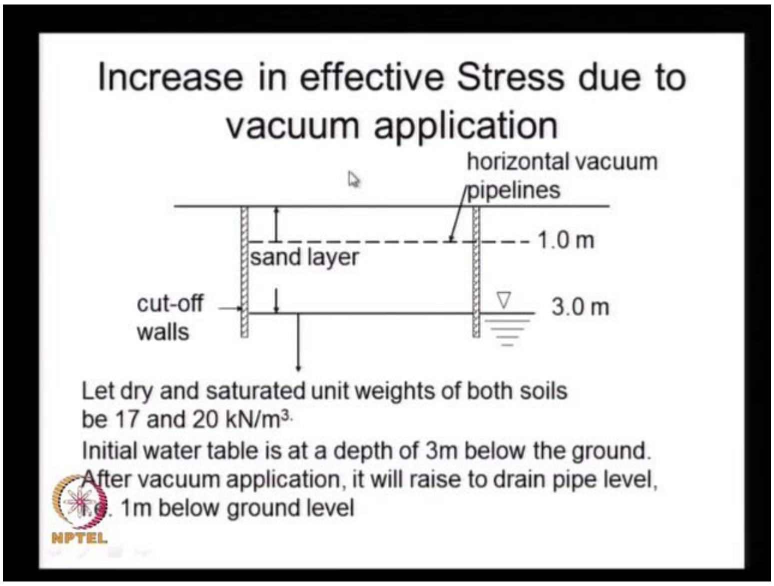

Now, let us let me illustrate how the removal of the atmospheric pressure from the soil increases the effective stresses. Let us take a case where we have the top 3 meters is a sand layer and then below this we have a clay layer. Let us say that initially the water table is at the depth of 3 meters and we have installed our vacuum pipelines at a depth of 1 meter below the ground level.

Let us assume for the purpose of calculation, the dry and saturated unit weights are 17 and 20. I think it should be 18 and then initially the water table at depth of 3 meters. After the application of vacuum pressure because the atmospheric pressure is removed, here the water table raises up to 1 meter.

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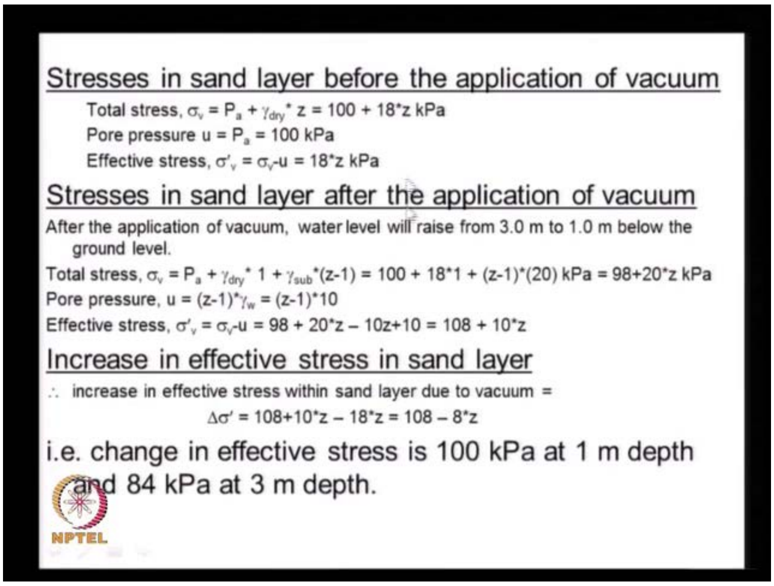

So, let us calculate the Stresses in the soil before and after the application of the vacuum and the let us calculate the stresses within the sand layer before the application of vacuum. It is total stress P that is the atmospheric pressure that is acting on the soil and then plus gamma dry times z and gamma dry is taken as 18, so it is 100 plus 18 times z. The pore pressure is just simply the P because that is the neutral pressure that is acting and the effective stress is sigma v minus u that is 18 times z.

Actually, we do not normally consider the atmospheric pressure as the pore pressure, but in this case because we are dealing with the removal atmospheric pressure. It helps us in separately considering the atmospheric pressure. In fact, this is what we write normally, if you have dry sand, the effective strength is just simply the unit weight multiplied by z. Let us look at the stresses in the sand layer after the application of vacuum. So, after the vacuum application, the water level will raise from 3 meters to 1 meter below the ground level.

Now, the total stress is P a plus gamma dry times 1 plus gamma submerged times z minus 1, that is the z is measured from the ground level and 1 meter is the depth up to which the water level raises. So, it is 98 plus 20 times z and the pore pressure is z minus 1 times gamma w. After the removal of the atmospheric pressure, there is no P a, so it is z minus 1 times 10, that is the gamma of water. So, the effective stress is 108 plus 10 times z.

So, the increase in the effective stress in the sand layer is the difference between the two pressures 108 plus 10 z minus 18times z, so it is 108 minus 8 times z. So, that means at a depth of 1 meter, the change in the effective stress is 100 kilo Pascal, that is our atmospheric pressure and then it is 84 kilo Pascal at 3 meters depth. Just for illustration purpose, I have taken the P as 100, but to be very precise P a is 101.6.

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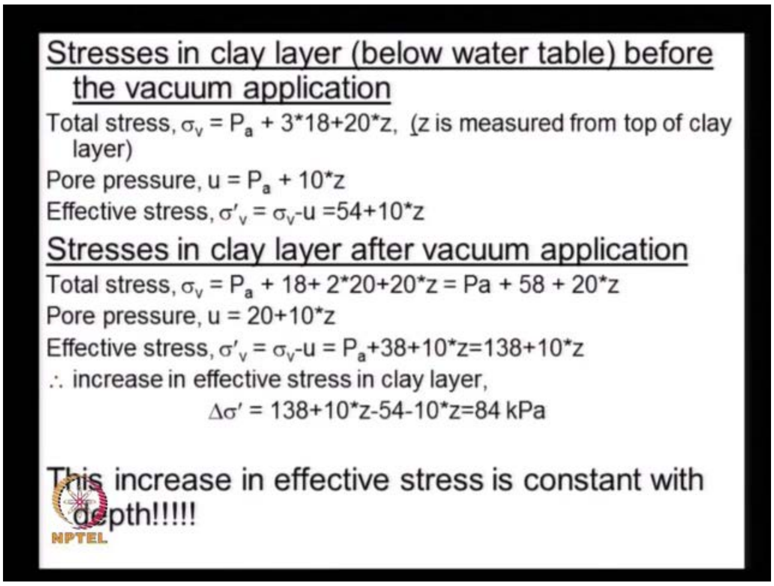

Let us look at the stresses within the clay layer below the water table and before the vacuum application, the total stress is P a plus 3 times 18 times z. Here, the z is measured from the top of the clay surface and the pore pressure is P a plus 10 z. So, our effective stress is sigma v minus u, this minus this, so it is 54 plus 10 times z and the stresses the clay layer after vacuum application. The total stress is P a plus 18 plus 2 times 20 because 18 is the top 1 meter of sand is unsaturated or without water and 2 times 20 plus 20 times z. That is the unit weight of 2 meters of sand and this is the unit weight of clay soil times z that is p a plus 58 times plus 20 z.

So, the increase in the effective stress is the effective stress after the vacuum application minus the effective stress before the vacuum application. It comes out as 84 kilo Pascal and this is independent of the independent of the z. So, that is the main advantage that we have with vacuum consolidation, because if you apply surcharge gradually because of the stress dispersion the effect of surcharge is maximum at the ground surface. As you go down below it reduces, whereas here we see that the effect of vacuum is constant with depth.

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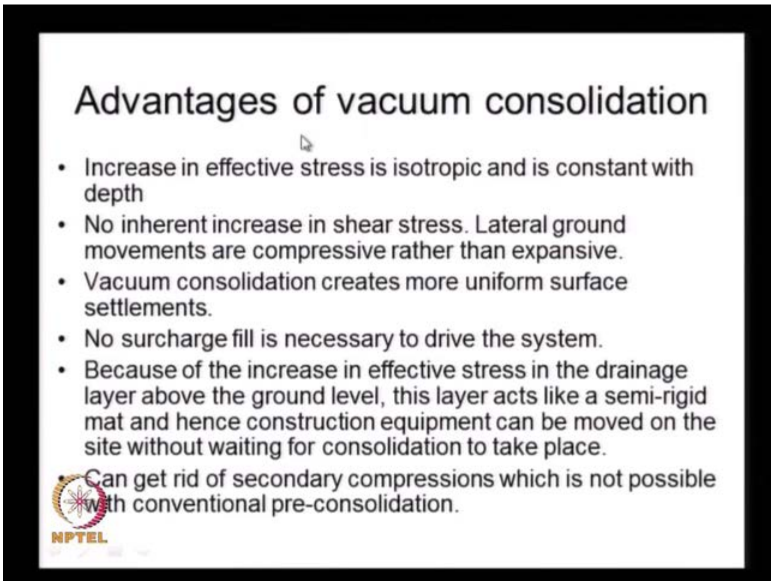

And I will briefly outline some of the advantages that we have seen, the increase in the effective stress is isotropic and its constant with depth, and the type of lateral strains that induced are compressive with vacuum. With normal surcharge there is an outward movement and there is no increase in the shear stress. So, that means that the lateral ground movements will not take place and the consolidation vacuum is known to a result in more uniform surface settlements. We do not have to apply any external surcharge pressure to drive the consolidation. The increase in the effective stress, immediate increase in the effective stress within the blanket acts like a rigid mat for our construction purposes. The vacuum consolidation is known to get rid of even the secondary consolidation settlements.

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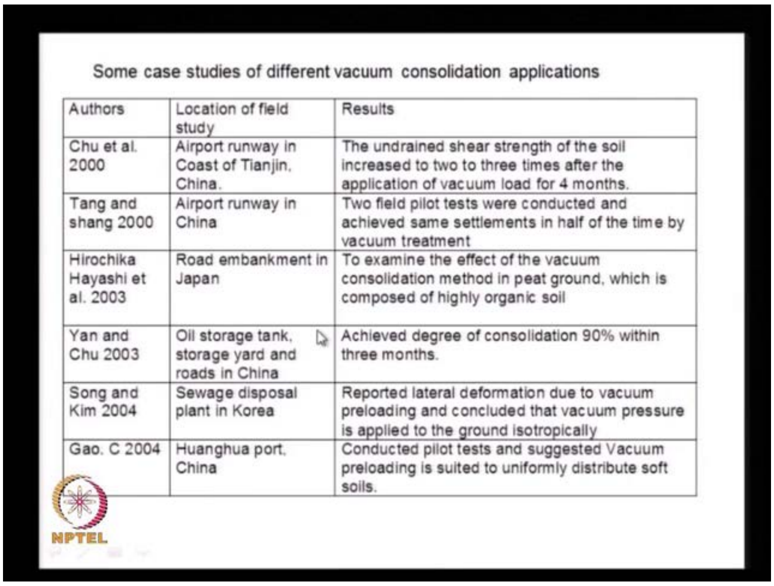
Some case studies of different vacuum consolidation applications

Authors	Location of field study	Results
Chu et al. 2000	Airport runway in Coast of Tianjin, China.	The undrained shear strength of the soil increased to two to three times after the application of vacuum load for 4 months.
Tang and shang 2000	Airport runway in China	Two field pilot tests were conducted and achieved same settlements in half of the time by vacuum treatment
Hirochika Hayashi et al. 2003	Road embankment in Japan	To examine the effect of the vacuum consolidation method in peat ground, which is composed of highly organic soil
Yan and Chu 2003	Oil storage tank, storage yard and roads in China	Achieved degree of consolidation 90% within three months.
Song and Kim 2004	Sewage disposal plant in Korea	Reported lateral deformation due to vacuum preloading and concluded that vacuum pressure is applied to the ground isotropically
Gao. C 2004	Huanghua port, China	Conducted pilot tests and suggested Vacuum preloading is suited to uniformly distribute soft soils.

Some of the field applications of vacuum methods are listed here, most of the applications are in south east Asia and in Netherlands. They have extremely soft clays, you see here this is in china this is in China, this is in Japan, China, Korea, China. The vacuum consolidation is applied for a different field cases for construction of roadways and airport runways and then embankments and so on oil storage tanks.

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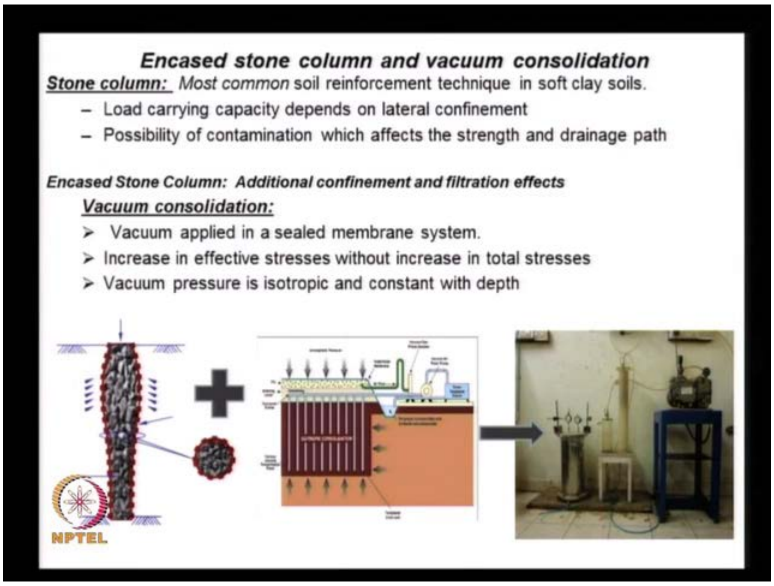

I will just briefly present some of the results that we have obtained at IIT Madras from studies on vacuum treatment and just to summarize, I will show you some results.

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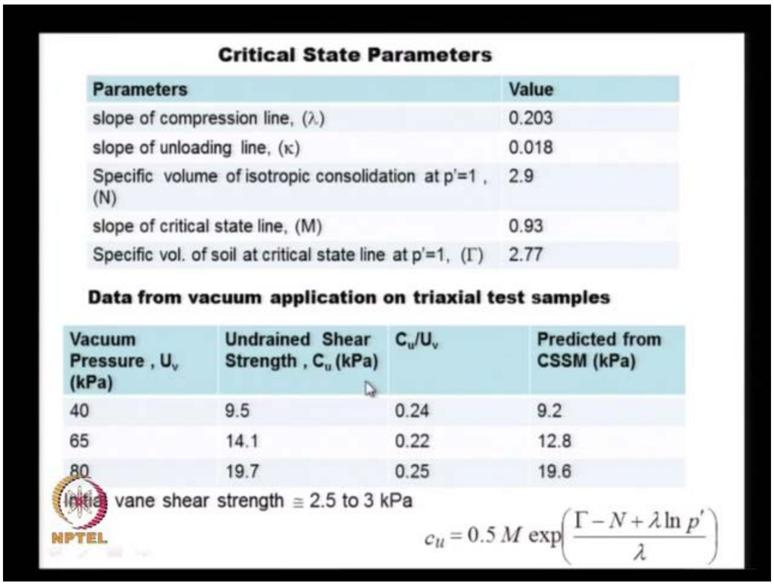

Critical State Parameters

Parameters	Value
slope of compression line, (λ)	0.203
slope of unloading line, (κ)	0.018
Specific volume of isotropic consolidation at p'=1 , (N)	2.9
slope of critical state line, (M)	0.93
Specific vol. of soil at critical state line at p'=1, (Γ)	2.77

Data from vacuum application on triaxial test samples

Vacuum Pressure , U_v (kPa)	Undrained Shear Strength , C_u (kPa)	C_u/U_v	Predicted from CSSM (kPa)
40	9.5	0.24	9.2
65	14.1	0.22	12.8
80	19.7	0.25	19.6

Initial vane shear strength ≅ 2.5 to 3 kPa

$$c_u = 0.5\,M \exp\left(\frac{\Gamma - N + \lambda \ln p'}{\lambda}\right)$$

The gain in the shear strength, because of the vacuum treatment can be explained easily using critical state soil mechanics theories that are given here. The experimentally measured undrained shear strength after vacuum applications is given in this column and those predicted from a critical state theory or given in this column. So, that means that we can theoretically estimate the effect of vacuum consolidation.

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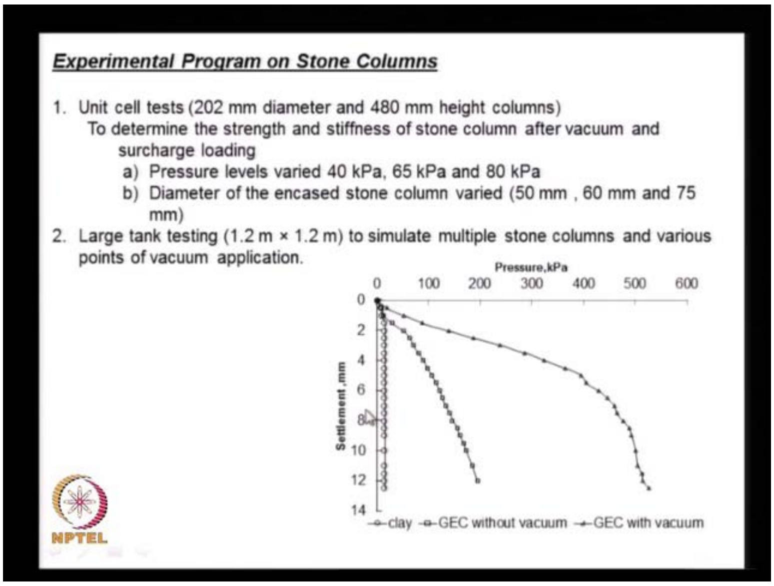

Here, we see the application of vacuum, the result of that vacuum and stone column if we draw the pressure settlement graph, this is the response of the soft clay soil and this is the response of the stone column, which is not treated with a vacuum. The same stone column after the vacuum treatment behaves very stiff and also much stronger, that is the main advantage of the vacuum treatment because it can increase the strength.

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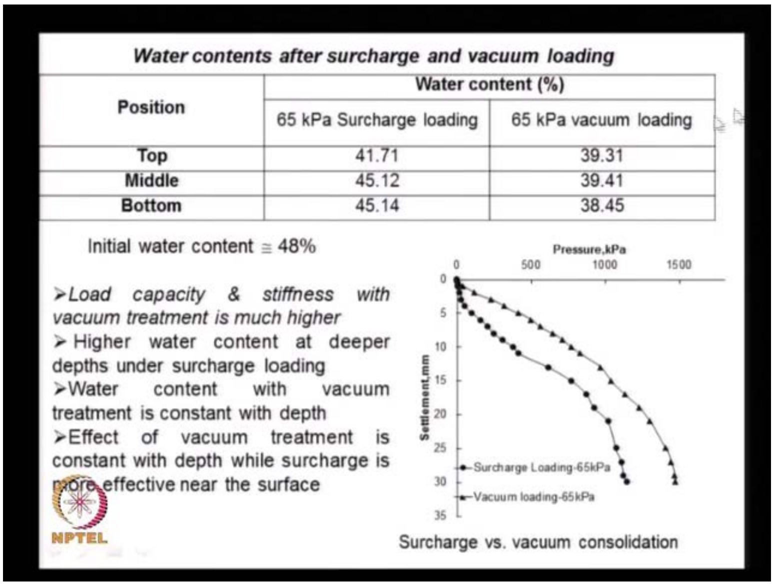

Here is actually, this is some test data comparing the vacuum treatment with surcharge loading and in both cases tank was treated by surcharge loading or vacuum treatment and with vacuum treatment. The water content was found to be constant with depth, whereas with surcharge loading, the top the water content is reduced from initial water content of 48 percent to about 42. At the middle and bottom, the water content is relatively high of 45 percent, whereas with vacuum treatment the water content is a constant with depth about a 39 percent.

So, that means that the effect of vacuum is relatively constant with depth whereas the effect of surcharge is a more at the ground surface and as we go down, the depth is reducing. Here, we see the effect of surcharge treatment and vacuum treatment on the response of a stone column. It is the surcharge treated stone column is relatively soft and it has a lower bearing pressure as compared to treated with vacuum.

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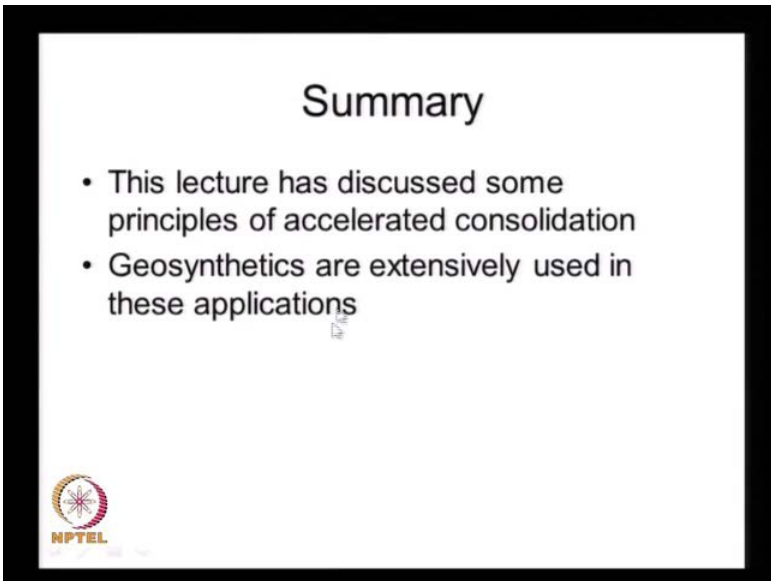

So, just summarize the introduction of the geosynthetics into the civil engineering field as complete to change the way we do the accelerated consolidation. This particular lecture has highlighted some of these techniques.

Thank you very much.