Geo synthetics and Reinforced Soil Structures
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Lecture - 27
Geo synthetic Encasement for Stronger and Stiffer Stone Columns

Good morning students, and in this lecture let us look at how to construct on extremely soft clays, using encased stone columns. Especially with the introduction of geo synthetics, we have very large varieties of solutions that we can adopt for a construction on soft clays.

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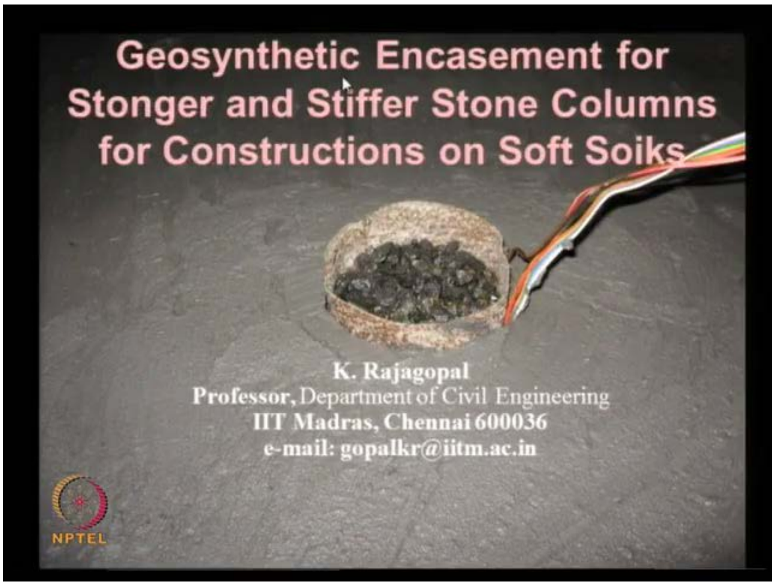

And this particular construction method called as the geo synthetic encasement as coming to the civil engineering field more recently. And I will briefly give you a background on this construction procedure.

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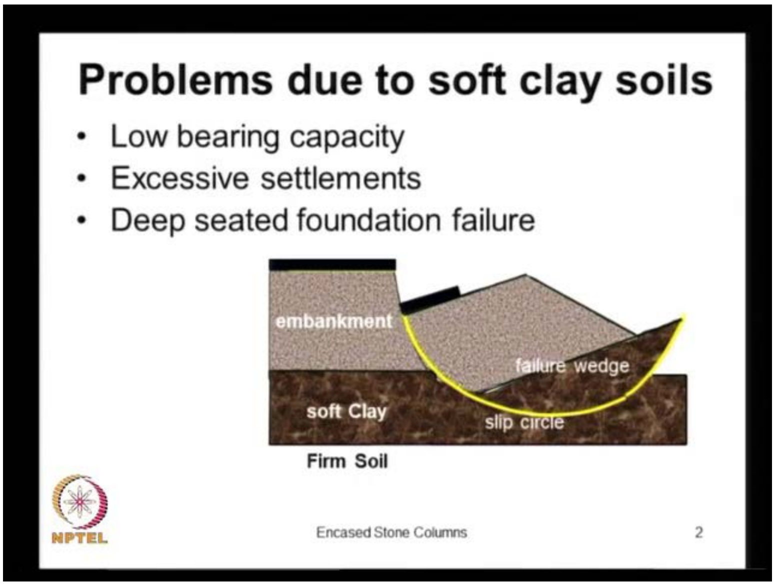

And before we do that, let us look at what are the problems with constructions on extremely soft clays, will have very low bearing capacities. So that means that we cannot design any foundation with very large bearing pressures, and then excessive settlements, associated with a very low bearing capacity, the settlements of soft clays or very, very large. And then we also need to design, against lateral spreading or deep seated failure.

And this is what happens? Even if you construct a very low height embankment, because of the lateral spread of the soil. We have a deep seated failure and part of the embankment and just simply slides of from the rest of the embankment like this. And so we need to overcome all this problems when we want to construct any engineering structure on the soft clays.

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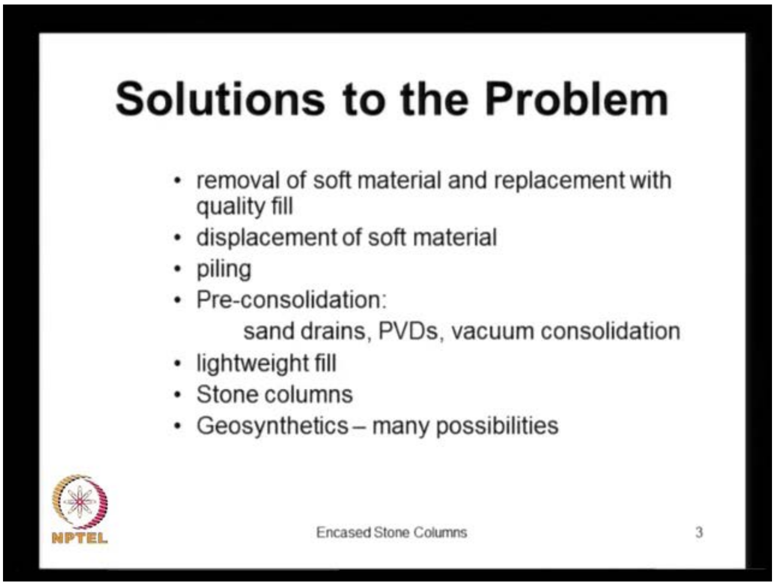

And one of the methods is the stone column.

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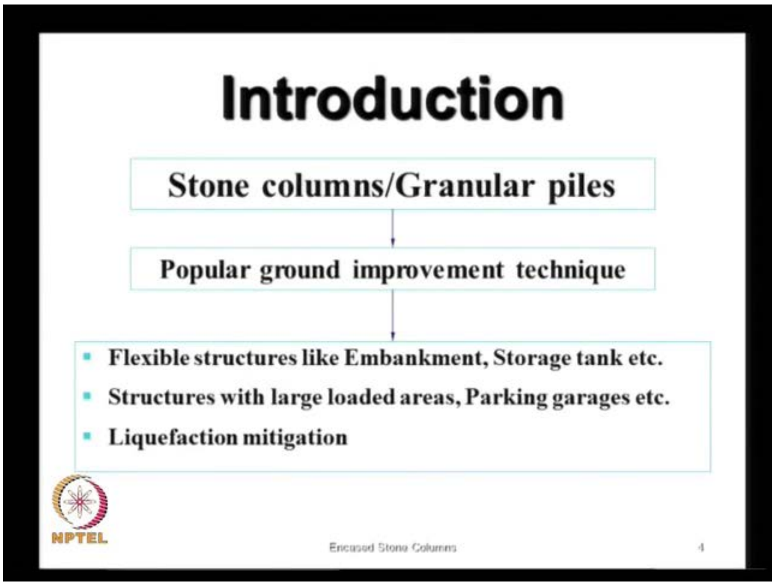

The stone column method it is a very I would say, it is been there for a very long time and it is very similar to pile foundations, reinforced concrete piles all of us are aware; what they are, they are basically to carry the loads to very deep stratum. And the purpose of the stone columns are also similar, except that the stone columns are made of granular materials and there is no cement or there is no reinforcement used the steel reinforcement. So, because of that they are more economical.

And then in terms of the diameters, stone columns are very huge, the piles usually they are about 4 to 500 millimeters diameter for a normal load whereas, the stone columns are usually 800 to 1000 millimeters are even larger. And it is a very popular ground improvement technique, in geotechnical engineering because it is reasonably well understood and the success rate is not bad. And we employ these stone columns, to support especially the flexible structures like embankments or oil storage tanks, made of steel and so on.

And especially, when we have a very large area to support, like for example, if you have an approach road leading to a bridge and we will have almost 600 to 700 meters length and then, about say 25 meters wide area to treat and it is not easy to design a rigid concrete pile foundation because they become very expensive. In such cases we going for stone columns and these stone columns because they are made of highly granular materials, they can also be used to mitigate the liquefaction potential.

Because, they can drain the water very fast and if we place, these stone columns close enough they can help in dissipating the pore pressures very rapidly.

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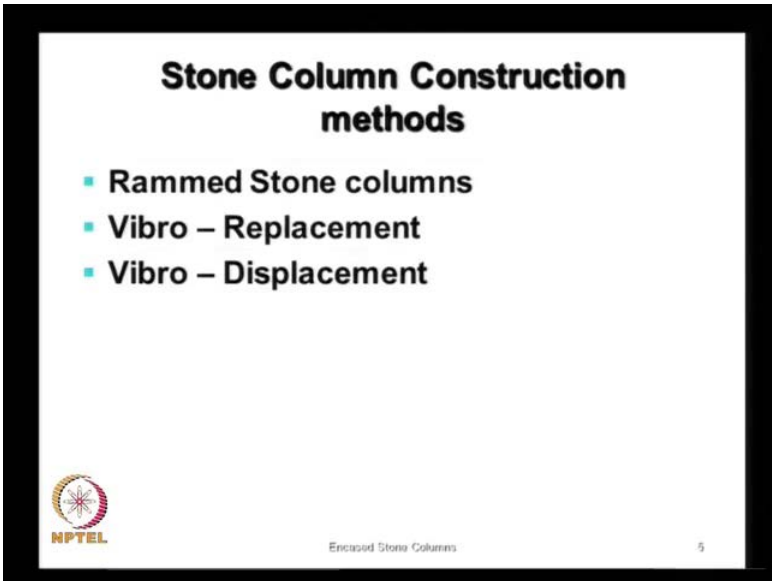

And there are different methods of construction, the very old one is the rammed stone column you create a hole and then you pore in the stones and then the just simply ram them. And then vibro replacement, we use vibration together with water jet to replace the existing soil with a better quality, either granular material or stone aggregate. And then virbo-displacement, like we just basically displace the soil by using some vibration and then replace that volume with some other material.

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And here, we see a bore hole being drilled using an auger. And we drill in the case of rammed stone columns, we create a hole of the required height and then ram the stones, so that we can form this stone column.

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And here, we see the stone being poured and actually, this is the stone column that is formed. And then this is the rammer that is repeatedly lifted up and then dropped to compact the stones, within the stone columns.

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And here, we see a vibro-float is actually, it depends on the principle of vibration and then water jetting to compact the soil, is actually it creates some vibration because of the movement of an eccentric marks, within this probe. And then we see this a water jet that is coming out, at very high speed we pumped the water to remove the soil, then at the same time we create some vibrations, so that the particle structure collapses.

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And the close-up of the stone column.

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And another view of the same stone column.

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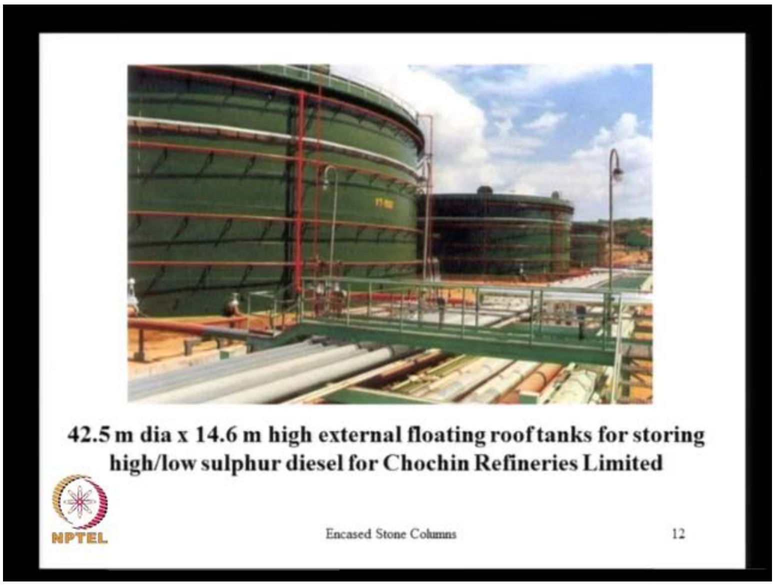

And here, we see a very large, oil storage tank made of steel. Typically the preferred support for these structures is or the stone columns because they are flexible structures because they have a thin steel plate of the order of about 10 millimeters to 12 millimeters. And the diameter is, so large that is better to it is easy to provide a flexible foundation.

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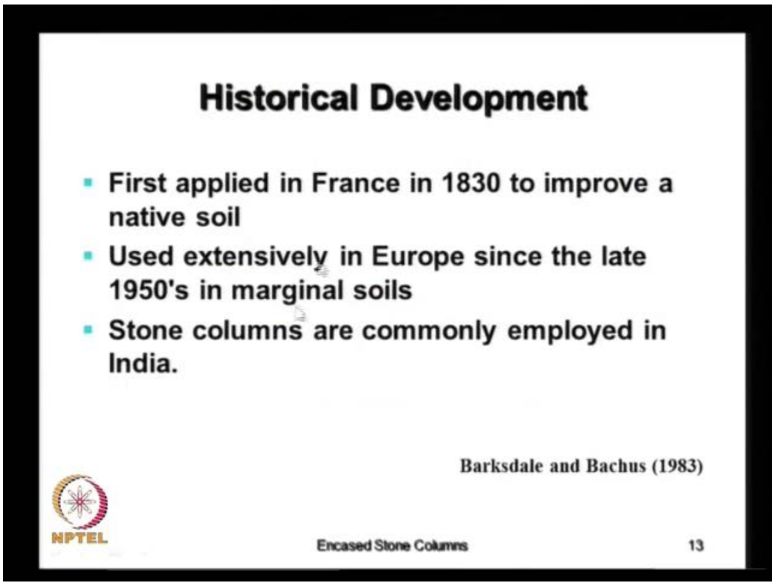

And historically, the stone columns were first applied in France, at about 1830 to improve a native soil. And then used extensively in Europe since then. And they are very popular in India, most of the I think the current stone column conceptions are in India, the it is not used very much in other countries.

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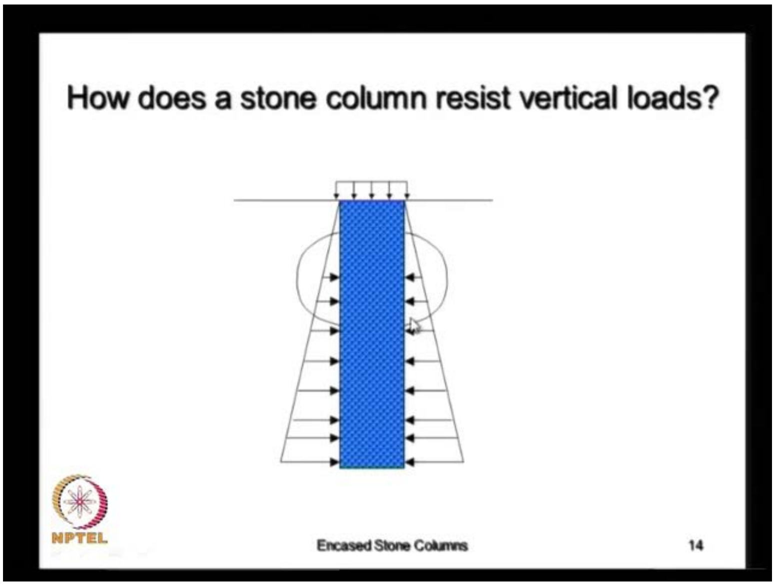

Then how does this stone column resist the vertical load, just imagine that, we have a column basically it is a granular material; that means, it does not have any cohesion. So, if you apply any load it should just simply collapse, but because of the lateral pressure that is applied on this column from the native soil, we can apply some vertical pressure. And; that means, that the vertical load capacity is very much of function of the strength, and the pressure that is applied by the native soil.

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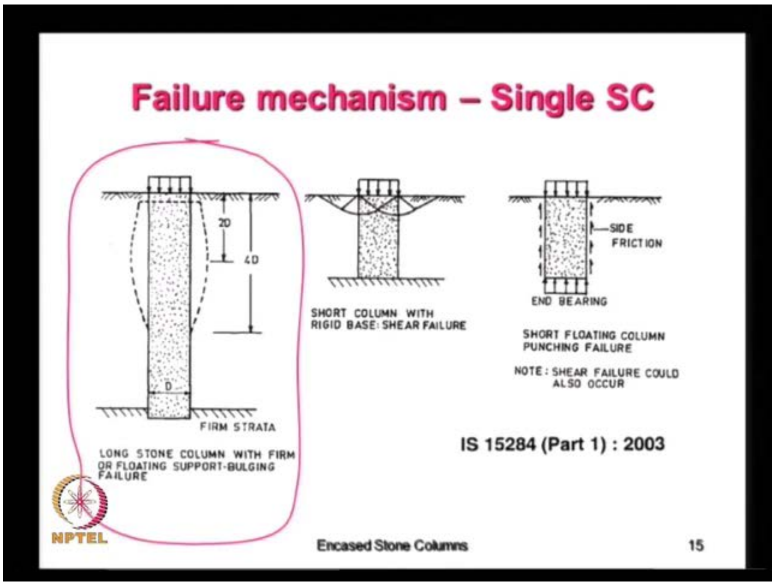

And these are some of the failure mechanisms of the stone column, if you have very long stone column within about the four times the diameter in the top portion, the column bulges. And then in the process it develops some passive pressures in the surrounding soil. Then if you have a very short column, the failure is more similar to the general bearing capacity mode of failure, then if you have a very short column placed in extremely soft clay, we could have a punching type failure where in the entire column gets punched into the soil.

And the most probable failure mechanism is this a long stone column, where in the length of stone column is at least four times the diameter of the stone column. And this case the second case usually does not arise because; this failure case is for a short column with a rigid base. And if this is the case, we would rather prefer replacing the soil with a better quality fill rather than trying to treat and this thin layer of soil the soft soil.

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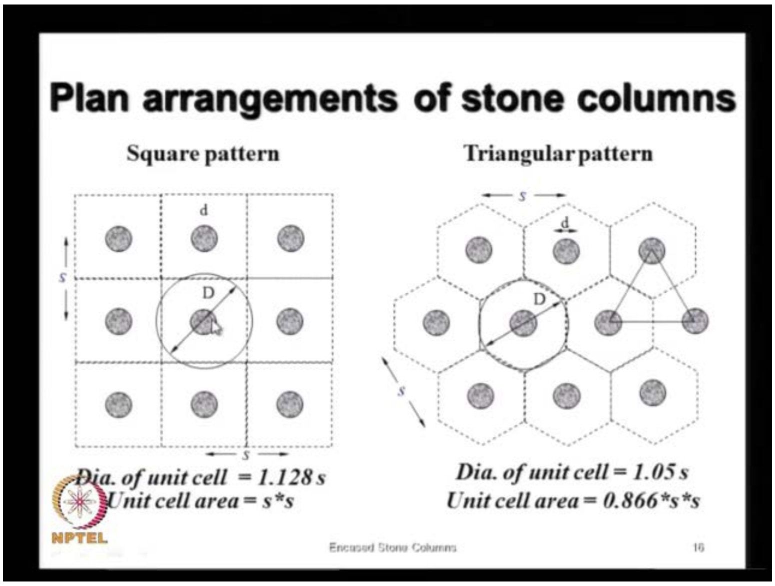

And the way these stone columns are arranged there are two different patterns the one is the square pattern and then the other is the triangular pattern is actually you can see the in the square pattern they are all aligned in the length and the width wise. And whereas, in the triangular pattern there alignment is more similar to, front to, equilateral to triangles.

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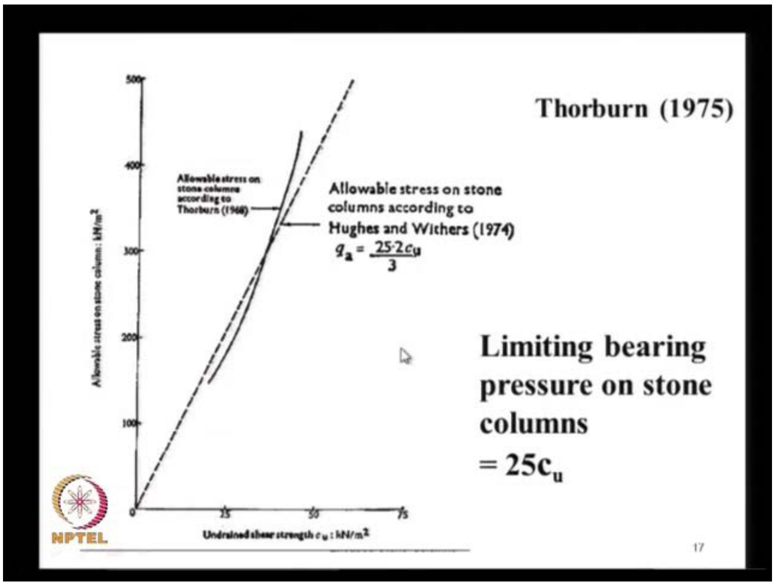

And theoretically we can prove that, the maximum bearing pressure that we can apply on the stone column, is about 25 times C u that was published by professor thorburn in

1975. And he has collected lot of field data and then he has also analyzed theoretically and shown that, the limiting pressure is approximately 25 times the C u. And if your C u is the undrained cohesive strength if that is small; that means, that we cannot really apply too much pressure on the stone column. Then it that case what do we do.

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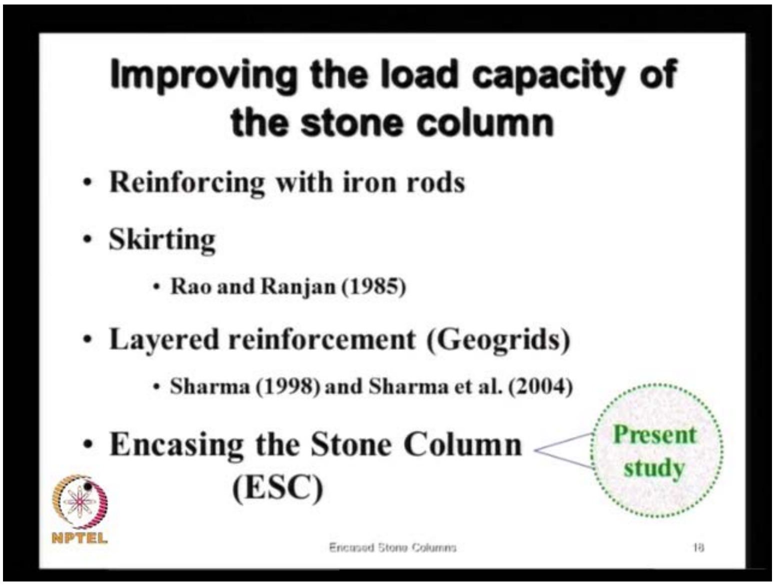

Lot of people have worked on how to improve the load carrying capacity of the stone columns, some people tried reinforcing with the iron rods, the steel rods just like in the reinforcement concrete. And then the skirted foundation similar to this skirt that we have below the shallow foundations we can also have a, some confinement of the top. And then a the layered reinforcements that is providing horizontal layers of reinforcement. And then the more recent one is the encase in the stone column, inside a tube of geo synthetic, either a geo grid or a geo textile tube.

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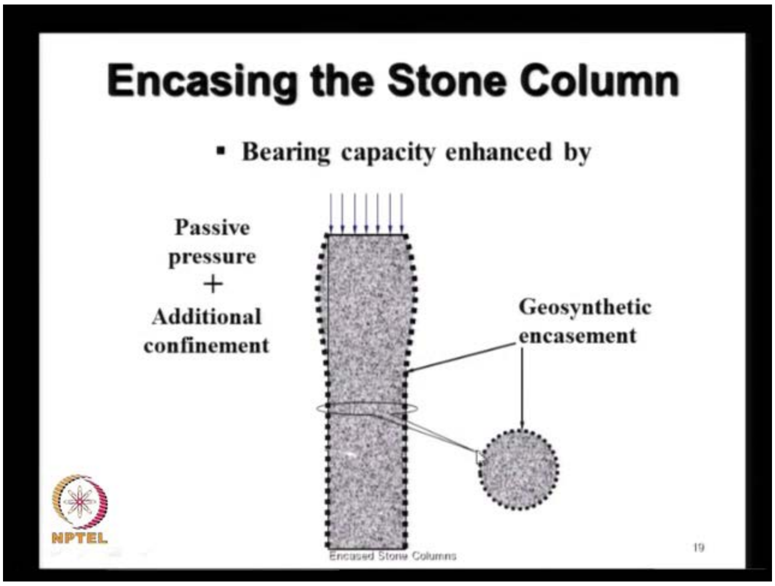

And this is how it looks like, we have a column is actually in plan, we have a column like this and it is encased within a geo synthetic and the cross section it look something like this. And the bearing capacity of the stone column is increased by an order of magnitude because of the additional confinement that is given by this by the geo synthetic to the granular material, depending on the amount of stiffness that you required, we can always choose a geo synthetic that is stiffer. So, that our stiffness is more similar to that of reinforced concrete pile.

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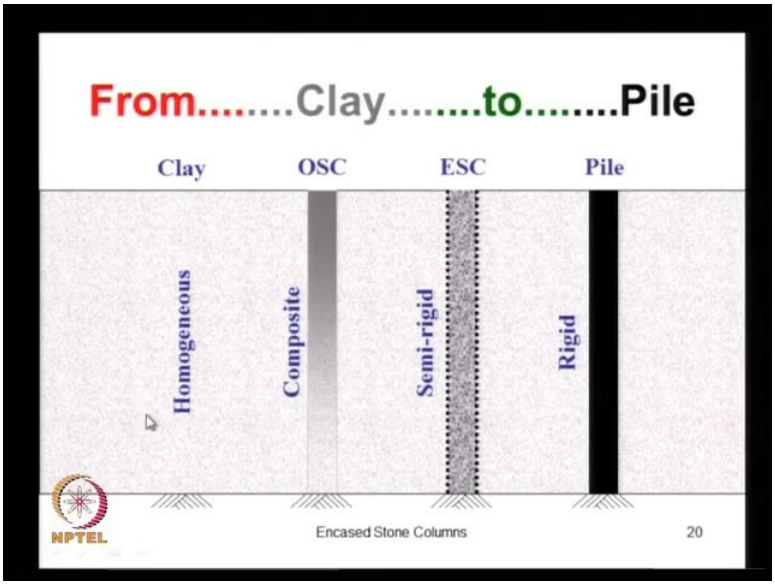

The actually this slide shows that, when you have a homogeneous clay the these not much stiffness and when if you have rigid concrete pile stiffness is very high. And if you have a ordinary stone column that is without any reinforcement, stiffness is slightly more than that of the clay and by using encasement the geo synthetic encasement. We, can make the column as a semi-rigid and by design it by proper designing it, we can have as much stiffness as we could achieve, even with a reinforced concrete pile.

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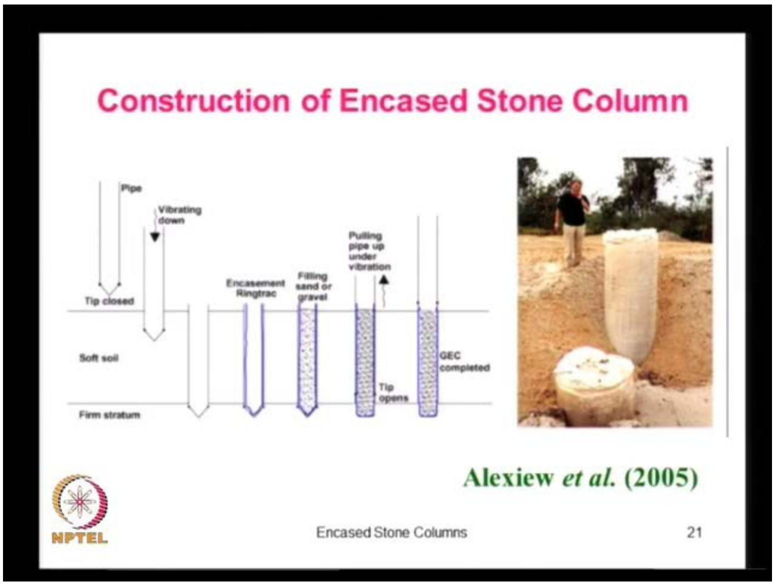

And the construction methodology is something like this, we can load a hallow pipe by either vibration or by water jetting. And then we can introduce, geo synthetic tube in this particular case is actually it is a geo textile tube, and then we can fill it with sand or gravel, and then pull up the hallow tube by vibration. And then, we would have the formed a column of granular material that is encased by geo synthetic tube, something like this. And is actually this was employed at several places.

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Most notably at Hamburg for the construction of the A 380 air bus factory that slide I will show. And this is the theoretically, the illustration of the displacement method.

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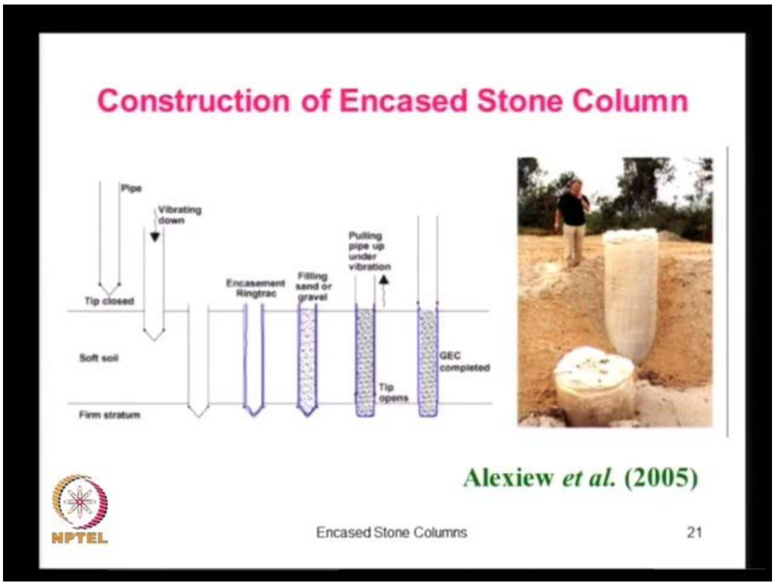

And this particular construction method is called as the displacement method because I driving a steel tube and then displacing the soil.

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And this is another illustration, we drive a tube and then introduce the geo synthetic tube and then fill it with soil.

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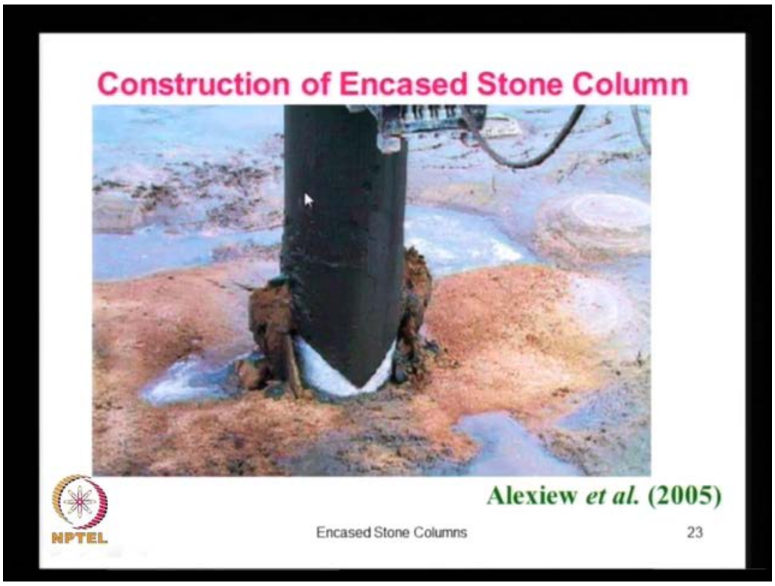

And this is how the process looks like.

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And this another close-up of the geo textile encased sand column.

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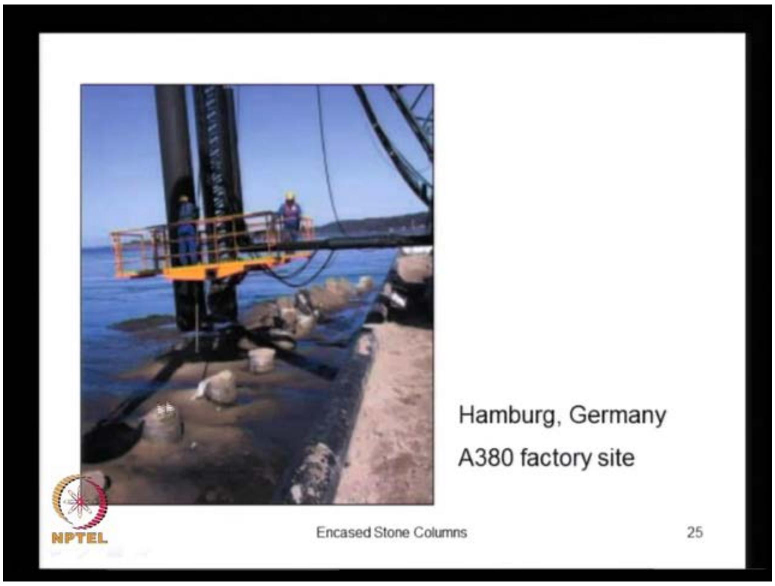

And this is the, picture of the air bus A 380 factory in Hamburg. They have treated extremely soft clay by using geo textile encased and sand columns.

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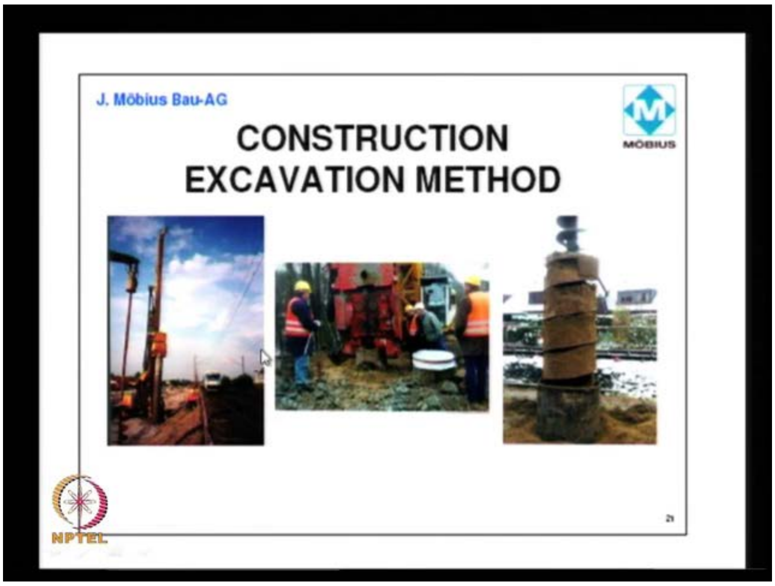

And this is drilled method, we can drill a hole and then replace that volume with granular material.

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And this is how it looks like, we drill a hole and then we can introduce a column of granular material that is encased, inside a geo textile or a geo grid. In this case, this entire thing is encased by a geo grid.

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And this is another type of geo grid, depending on the size of aggregate, you can chose the material that we want either a geo textile or a geo grid. And geo grids usually they can offer highest stiffness.

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And this is a picture of the geo grid encased stone column.

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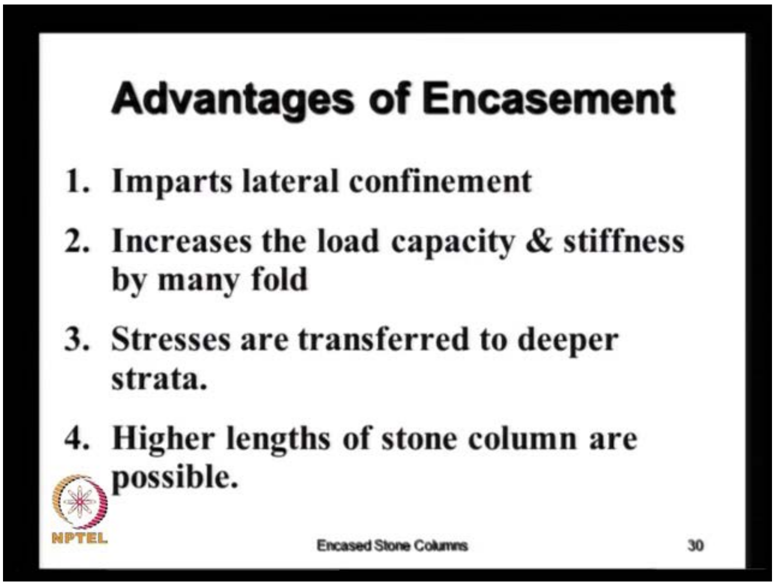

Some of the advantages that we have are, the encasement imparts lateral confinement; that means, that we can form this column even in extremely soft clays and we get increased load capacity and stiffness by many fold. And in this case, we can theoretically prove that, the increase in the stiffness and the load carrying capacity is not a function of the, strength of the surrounding clay it could be just a function of the encasement that we provide.

And we can transfer the stresses to deeper strata because normally the stone columns they cannot be used to for transferring the loads to very deep strata because of their flexibility. And, so by because we are important some additional confinement and increase in the stiffness, there can be used to transfer the loads to deeper depths; that means, that we can use a higher length of the stone columns.

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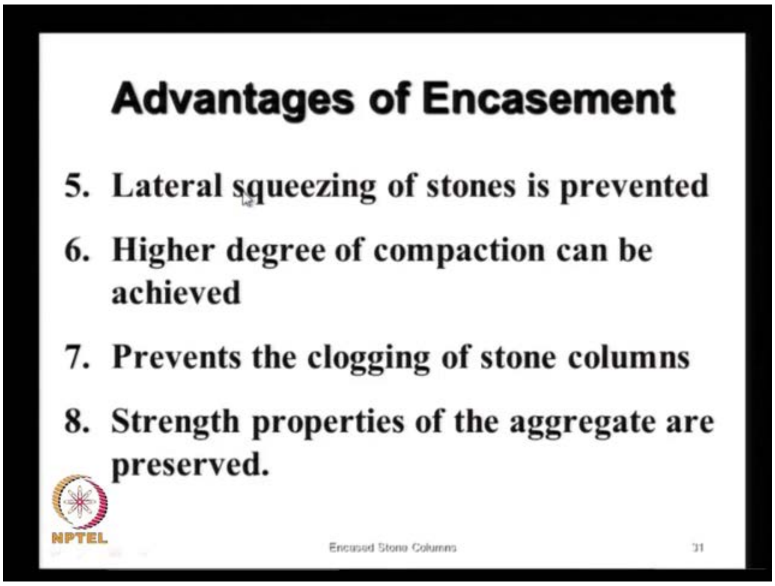

And the lateral squeezing of the stones is prevented because sometimes if the surrounding clay is very, very soft even while forming the stone column the stones, they disappear by lateral spreading. And when that happens we cannot get a good compaction and here because of the geo synthetic encasement, we can get a very good compaction. And once you are able to achieve good compaction; that means, that our stiffness could be very high.

And it prevents this the geo synthetic that we provide around, it can also act like a filter and it prevents the clogging of the stone column. In two ways it will help, first is in faster dispersion of the pore pressures, once there is no clogging the water can flow freely and then the strength of this aggregate is preserved to a large extent because they are mired with soft clay in the during the service life. And because of that the strength properties of the aggregate are preserved for a very long time.

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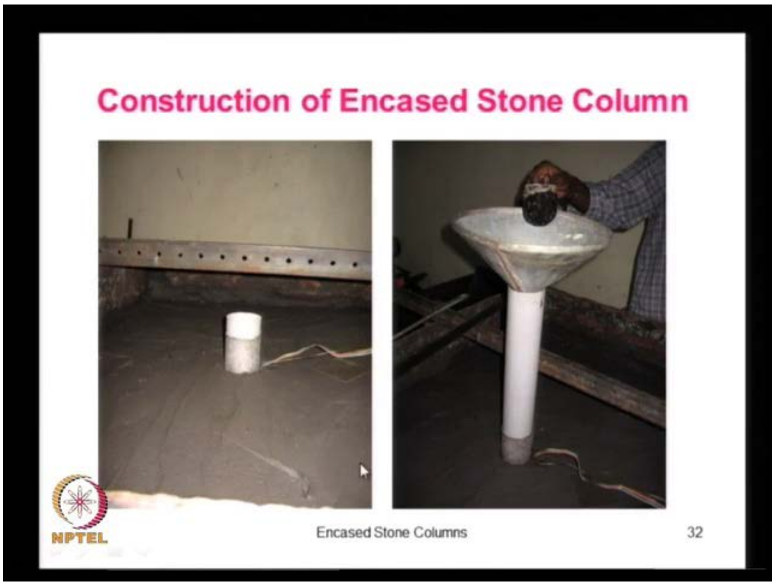

And now, I will show you some experimental data that we have done at IIT madras on the strength and stiffness of a encased stone columns. Here, we see an example of extremely soft clay that was formed inside a large steel tank and the soft clay, so soft that if you stand on it you will sink up to your waist that was the type of clay. And here, we have the geo synthetic encased stone column and that is charged with stone aggregate. And these wires that you see, they are connected to the strain gauges that are fixed on the on this geo synthetic.

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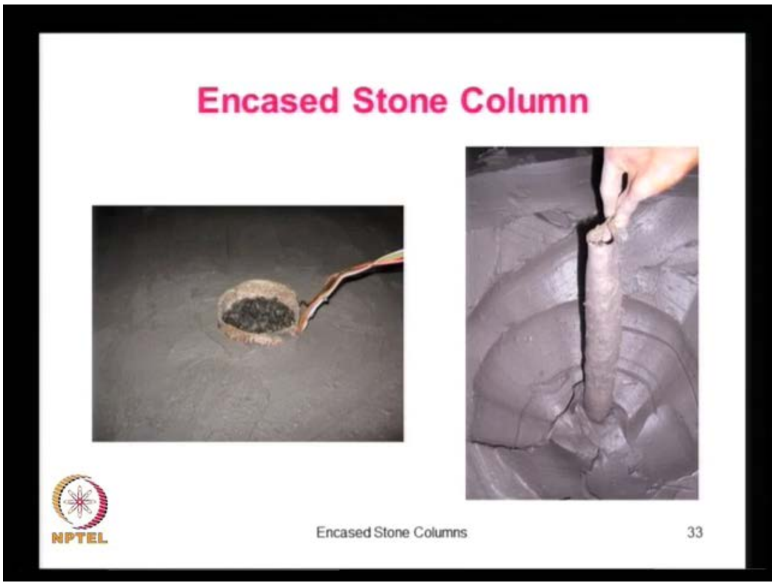

And here, you can see the close-up of the same stone column. And this is actually after the test was over, we exhumed the stone columns to look at the diameter and other response features.

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Well, now let us study how the aggregates behave under compression.

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And the aggregates because they are granular material they do not have any cohesion, unless they are confined they cannot have any strength. And in this case, we have made columns of this aggregate by confining them inside a geo textile tube.

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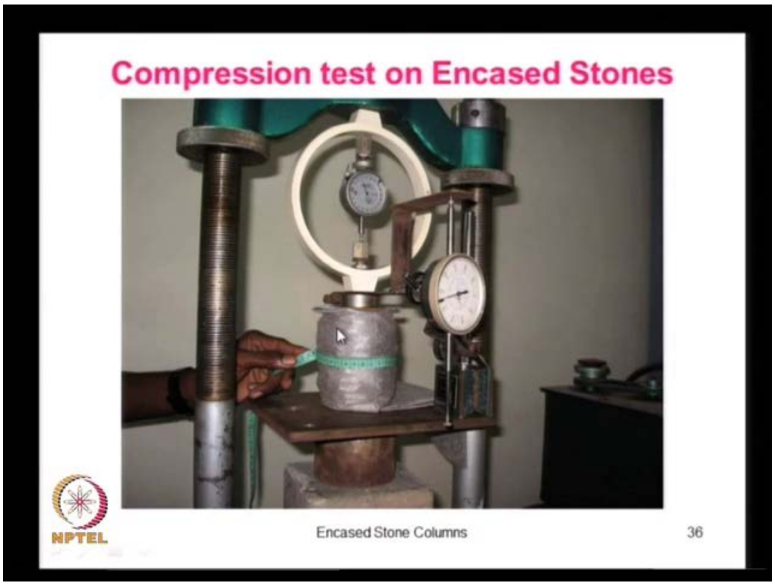

And they were subjected to compression load like this. And because of the geo synthetic encasement, this aggregate has developed some compressive strength.

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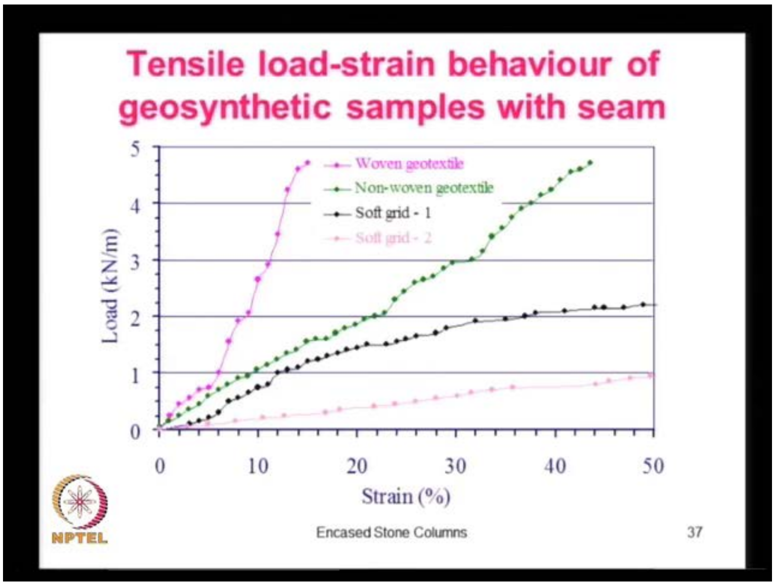

And this is how the responses look like, the strain and then the load on this is the, we have used three types of a geo synthetics, one is a very, very reasonably stiff woven geo textile and non-woven geo textile, and then a very soft geo grid and then extremely soft geo grid.

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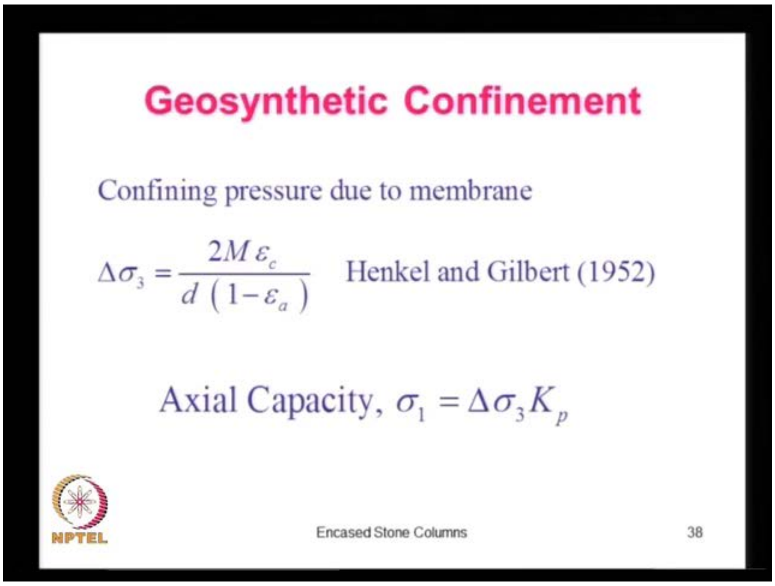

And the way to explain the confinement given by the geo synthetic is through this equation proposed by Henkel and Gilbert way back in 1952. He said that, the confinement given by the rubber membrane on the triaxial samples is related to the modulus M. And then the diameter d diameter of the column and then epsilon c is the circumferential strain and epsilon a is the axial strain and the change in the confining pressure is related to all this parameters. And the circumferential strain is related to the axial strain, by we can derive simple equation to relate them. And we know that, once the confining pressure increases the axial capacity increases, by a factor of K p, where K p is the is the passive pressure coefficient.

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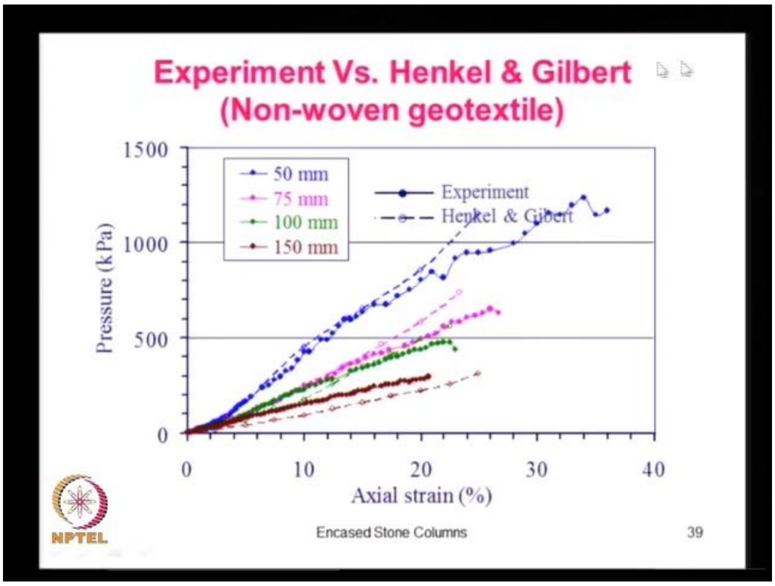

And this is the data between the predicted and the experimental data, for different terms for the non-woven geo textile for four different diameters the 50 mm diameter, 75 mm 100 mm. And 150 mm, is actually in terms of the pressure loading, the pressure capacity.

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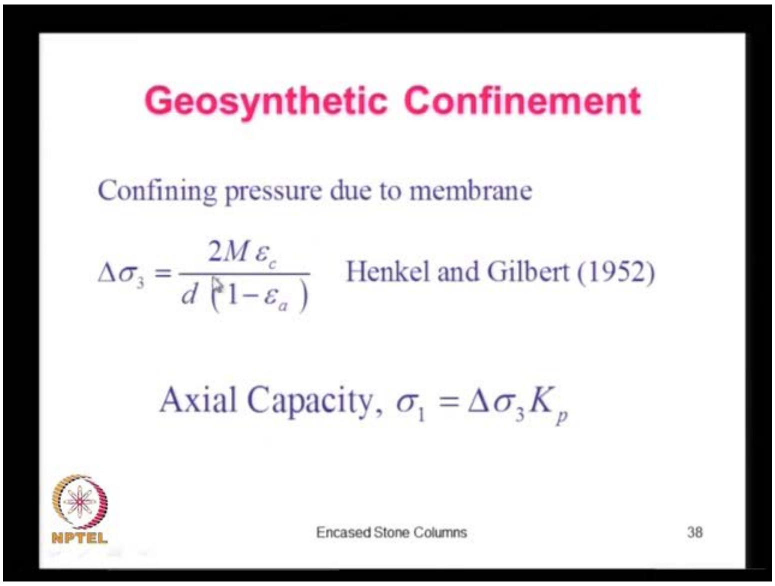

The capacity is inversely proportional to the diameter because you see the diameter in the denominator of this equation. So, as the diameter is increasing for the same properties of the geo textile, the effect of confinement reduces.

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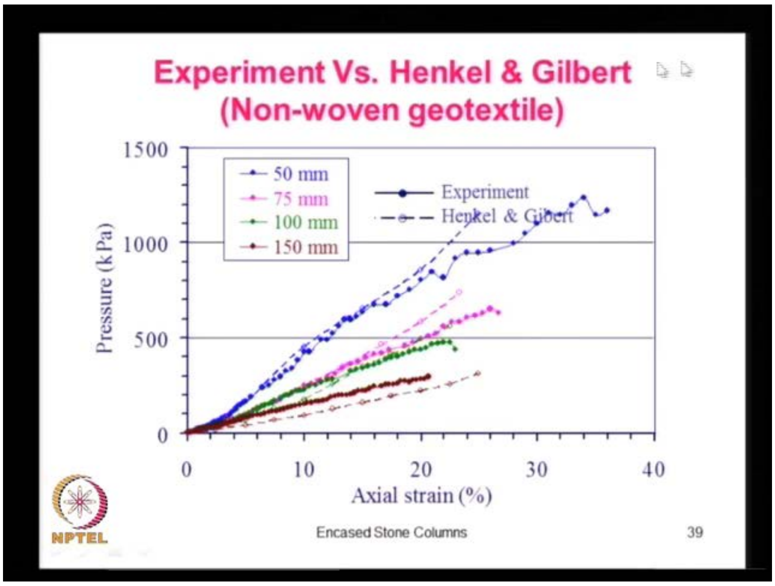

And this is with woven geo textiles is actually the comparison between the experimental and the theoretically predicted once, they are very good.

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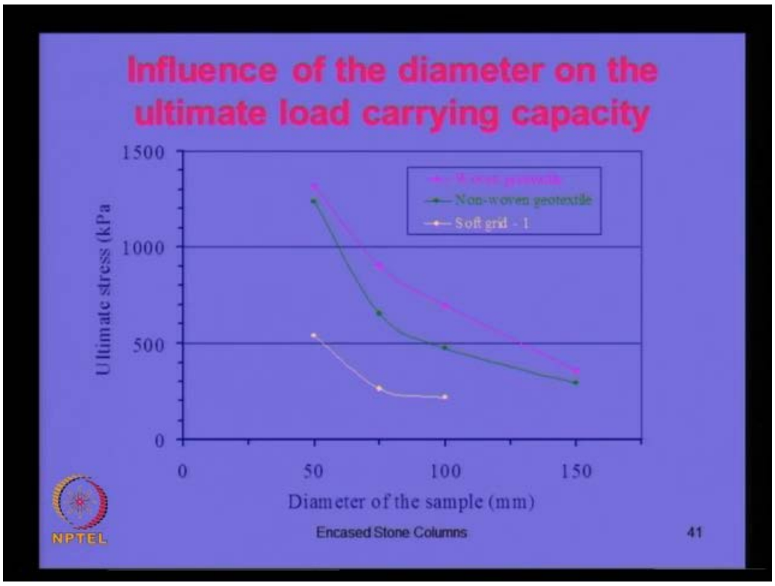

And this particular picture, shows the effect of diameter on the load carrying capacity as the diameter is increasing, the load capacity is decreasing, because as we have seen earlier, the additional confinement that we give is inversely proportional to the diameter of the column.

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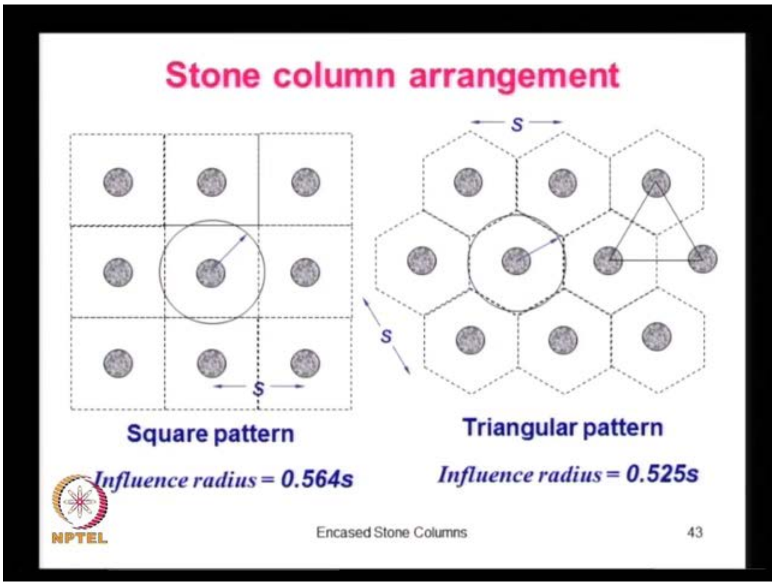

So, as I mentioned earlier we can introduce the stone columns, in different patterns the square pattern and the triangular pattern. And cells that we call as unit cell that contains one single stone column and some soil surrounding it is normally tested in the laboratories, we do not test the entire thing because it is not possible. We can only do field test on this type of arrangements.

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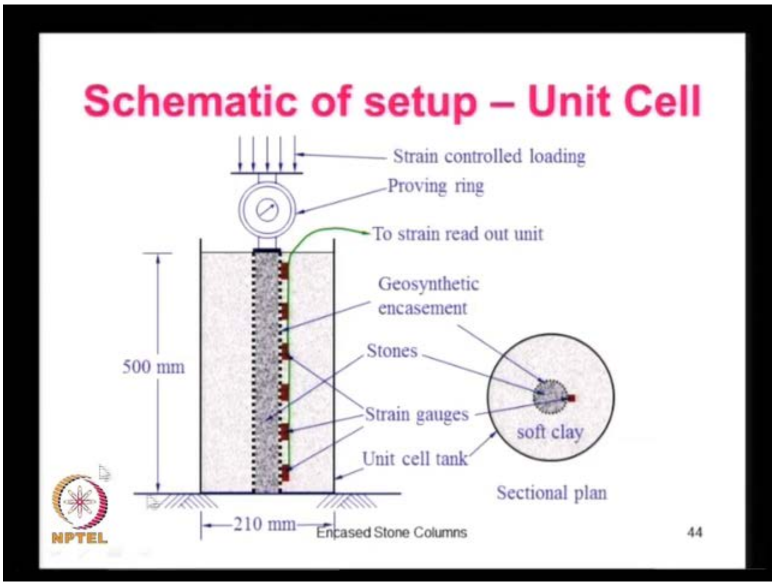

And once such arrangement is shown here, we have unit cell of diameter 210 millimeters and the height is 500 millimeters and we have a stone column that is formed by displacement procedure. And then it is heavily instrumented with strain gauges and then the pore pressure cells and, so on.

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And before we do anything, we need to have a clay of known properties and known consistency. And that we achieve by pre-consolidation and here, we see a large tank 1.5 meters by 1.5 meters and that is surcharge to a known pressure. And once you consolidate the clay, for long enough time it would have gain some strength and that type of clay soil having known properties are is used in this test and procedure.

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Properties of Clay

Sl.No	Properties	Value
1	Liquid limit	49 %
2	Plastic limit	17 %
3	Specific Gravity	2.59
4	Moisture content after consolidation	47±1%
5	In-situ vane shear strength	2.5 kPa
6	Consistency Index	0.06
7	Dry unit weight	11.56 kN/m^3
8	CBR value	0.11 %
9	IS Classification System	CI (Silty clay of medium plasticity)
10	Degree of Saturation	96 %
11	In-situ void ratio	1.25

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And the most notable property that we need to see is, the in-situ vane shear strength is very, very low 2.5 k P a. So; that means, that it is more like water and if you stand on it you just simply sink, that is the type of consistency the clay soil is prepared at.

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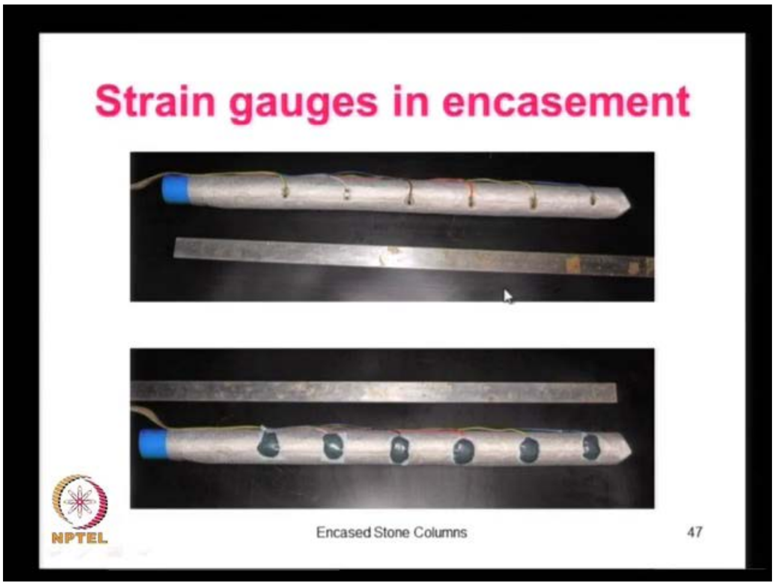

And this pictures, they show the stone column or the columns or the geo textile tubes, with number of strain gauges fixed on them.

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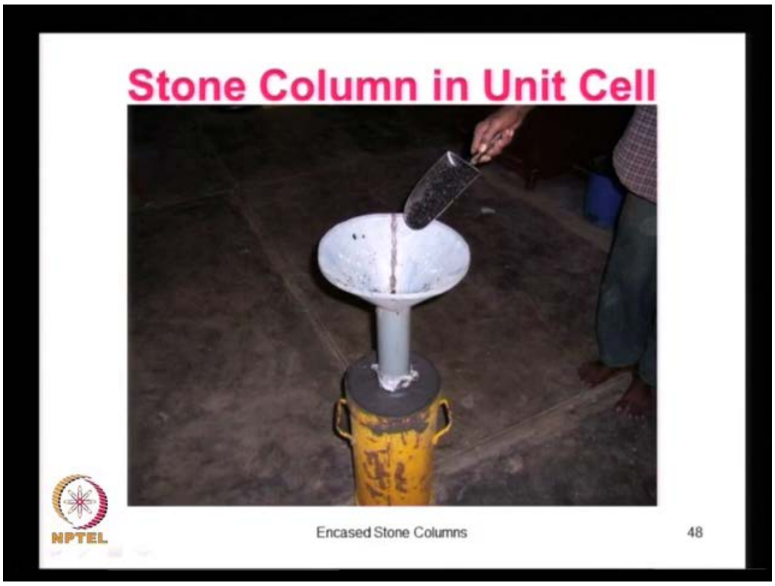

And this is you see, the unit cell and then we have the, soft clay then it is charged with stones.

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And this is the prepared stone column ready for testing.

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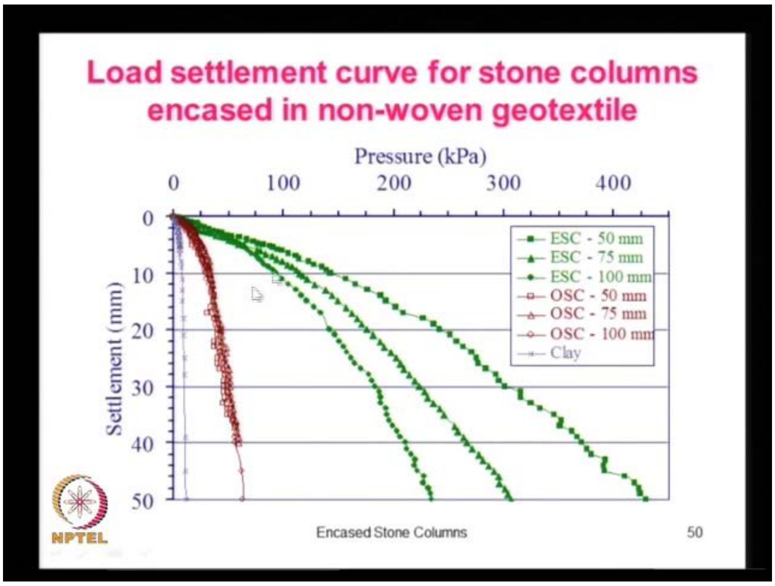

And here is the pressure settlement data, for the stone columns with different diameters. And the first graph, the one with the lowest pressure that shows the pressure settlement data for the soft clay, it hardly develops about 10 to 15 k P a pressure and with different types of ordinary stone columns. All of them whatever may be the diameter of the ordinary stone column, the load capacity is similar it is increased to, this is actually this is 20. The bearing capacity or the pressure capacity of clay soil is about 10 to 15.

And if it is treated with ordinary stone column, the pressure is increased to about 40 k P a sorry 50 k P a and by different types of encasements see, when we encase it with 50 mm diameter stone column, the pressure can be increased to almost 400 k P a for the settlement 50 k P a 50 mm. But, let say if you are interested in more reasonable settlements say 10 millimeters, even at 10 millimeter settlement the pressure that we can apply on 50 mm diameter encased stone column is about 150.

And on this encased stone column is with 100 mm diameter it is about 100 k P a which is substantially larger than, what we have with ordinary clay or with ordinary stone columns. And then more importantly the stiffness, the slope of this pressure settlement graph is much steeper for encased stone columns. And depending on the type of the encasement that we give, we can increase the stiffness by an order of magnitude.

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And this is how, the stone columns have behaved actually after the test is over, we pumped in some plaster of Paris of liquid to freeze the stone column and then, we excluded the stone column. And the ordinary stone column, this is how it looked like is actually at the top they some bulging. Whereas, the geo textile in case stone column they were more or less uniform they are not too much of bulging because the lateral confinement.

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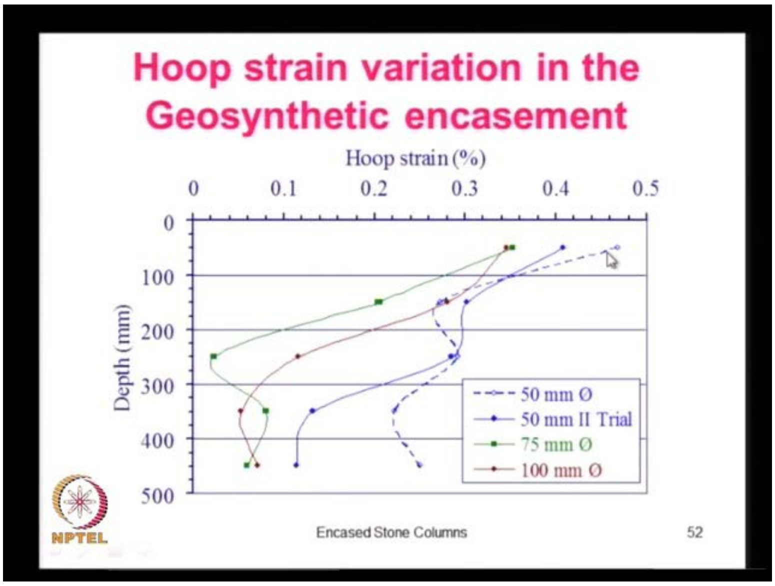

And these are all the different hoop strains that are developed. And the hoop strains, they are is actually this green line is for 75 millimeter diameter and this line is for 50 mm diameter and as I said earlier, because the confining pressure is inversely proportional to the diameter or the strain that is developed is directly proportional to the size of the diameter. And 50 mm column it is developed a higher strain as compared to larger diameter columns.

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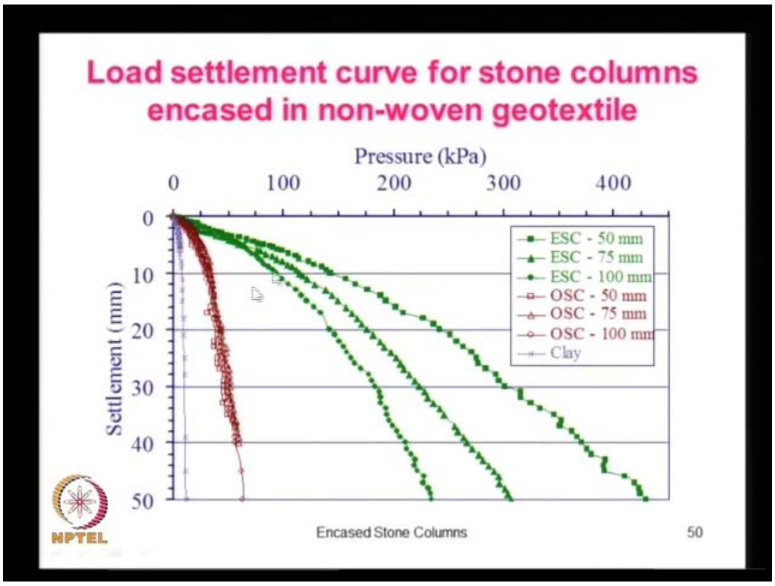

And this is the data, with different type of encasements is actually the woven geo textile which is by far the stiffest one, with higher modulus and nonwoven geo textile the green colored one it has lower modulus. And there are two soft very, very soft geo grids which develop tensile strength of hardly 2 or 3 kilo Newton's per meter, at a strain of 40 percent. They were also able to increase the, strength of the stone column by an order of magnitude.

And this is the response of ordinary stone column. And these are all the responses with different types of encasements. And here, we can see that even if we use very soft geo grid or a geo textile, we can still increase the stiffness because of the development of the hoop strains and the hoop forces, they tend to confine the soil or the confine the aggregate mode and that results in higher load carrying capacity and higher stiffness.

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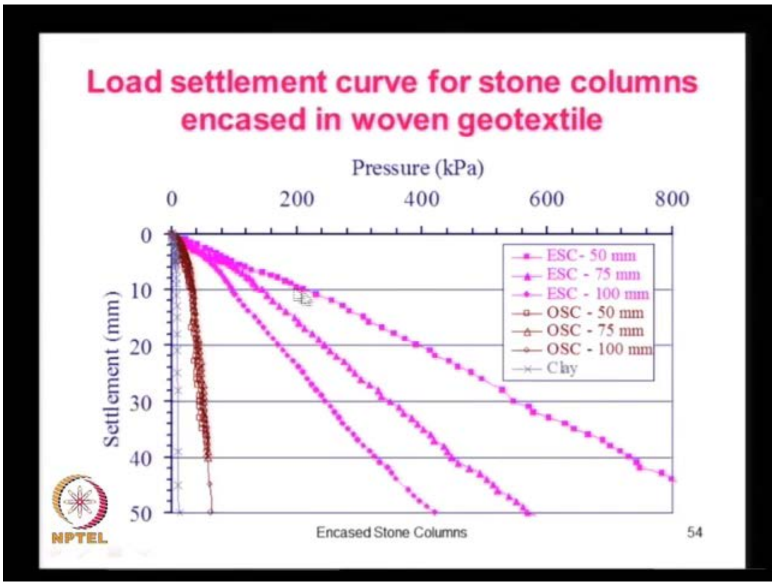

This is the data for woven geo textiles, is actually we see that the pressure increase to almost 800 k P a without any sign of failure, this curve is more or less like a straight line. Whereas, the ordinary stone column they have all failed, at low pressures whereas, the encased stone columns they have not shown any failure, the higher pressure that we have applied they develop higher settlements, but there is no failure. In these the pressure settlement data is more or less like a straight line without any sign of failure.

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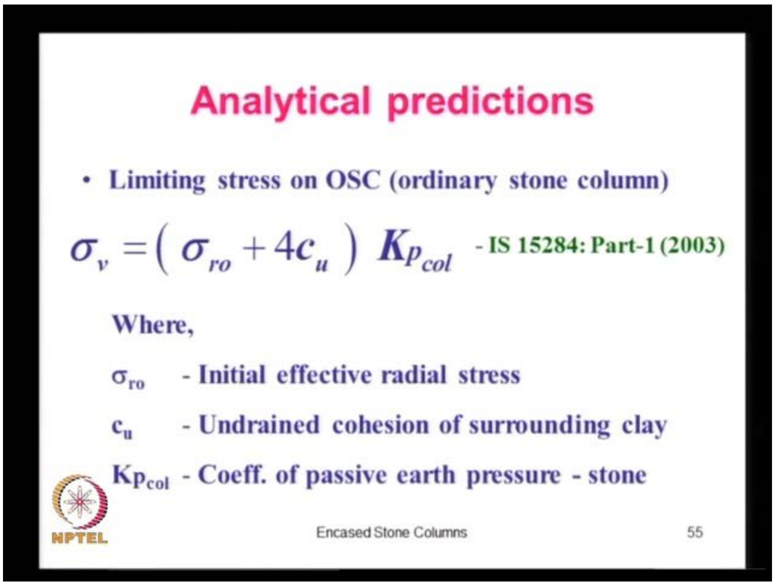

How do we analyze the stresses that are developed in the stone column, is actually here I am reproducing the vertical stress. That is developed in the ordinary stone column that is given in the in the IS code for stone columns IS 1.5284 basically it is a function of the passive earth pressure constant of the column material the granular material, sigma r naught is the effective initial radial stress. Then the c u is the undrained cohesion of the surrounding clay four times of that, and that is the limiting vertical pressure that we can apply.

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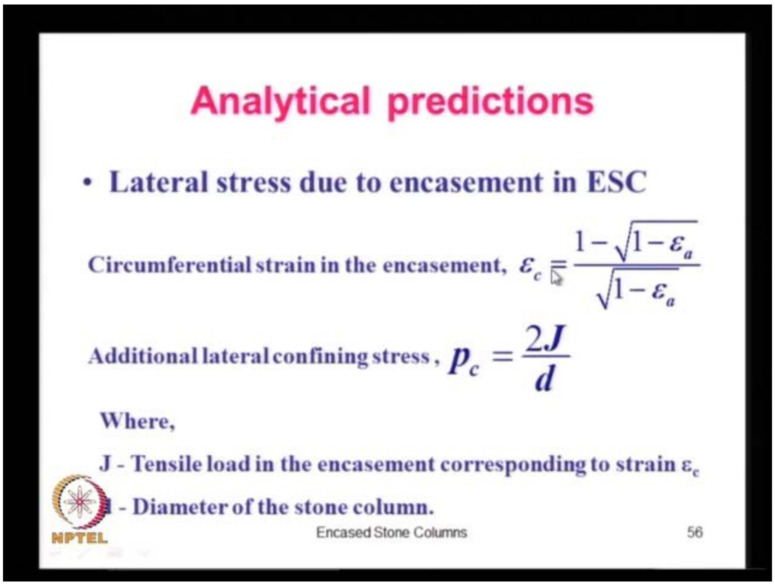

And this is how, we calculate the hoop strain or the circumferential strain, in terms of the axial strain epsilon c is 1 minus square root of 1 minus epsilon a by square root 1 minus epsilon a, Is actually this equation is derived on the assumption that, the volume of the deformed soil is equal to the volume of the undeformed soil and by using the simple equations we can derive this. And then the additional lateral confining pressure, is related to the J is the tensile modulus and the d is the diameter like this.

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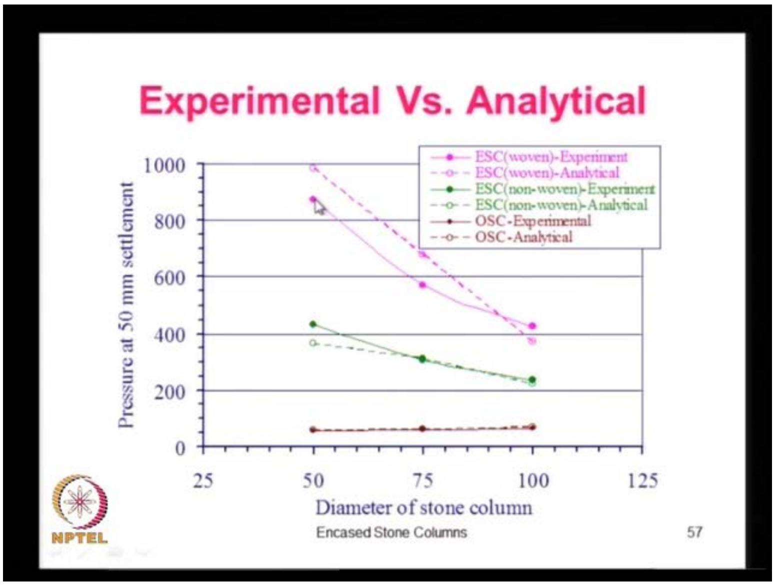

And these are the different comparisons between, the predicted and the experimentally measured pressures at 50 mm settlement, for three different diameters 50, 75 and 100. Here, we see that at 50 mm column diameter, the woven geo textile helps in increasing the pressure to nearly 800 50 or 900 k P a for the ordinary stone column it is hardly about may be this is about 20 or something. And for all the 3 diameters of the ordinary stone column, the pressure is more or less the same. Whereas, for the encased stone column as the diameter increases the pressure decreases. But, even this the lowest pressure that we can get, with nonwoven geo textile which is very soft, it is about 200 50 or something which is more than that we can get with ordinary stone column.

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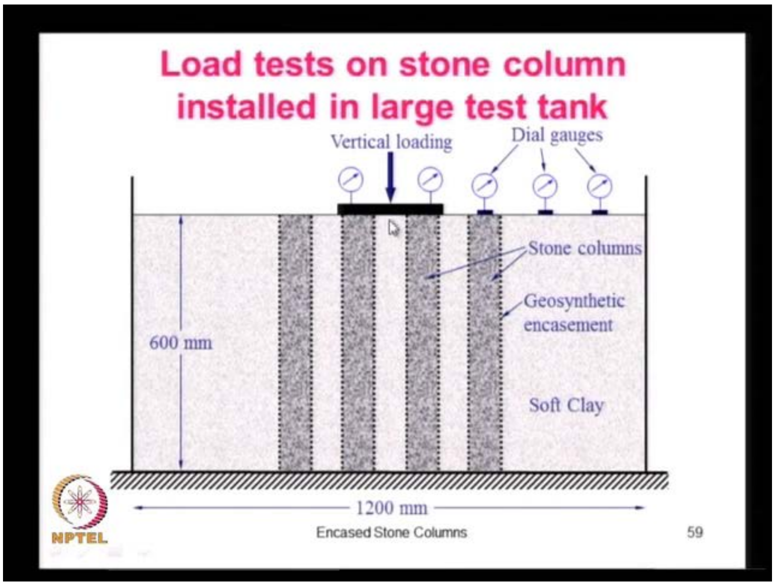

And I will show you some data, from tests on multiple stone columns. Because, we are interested in knowing how much pressure is transferred into the stone columns and how much pressure is transferred into the soil in between because our settlements are related to the pressure the amount of pressure that we can transfer into the columns and into the clay into the soft clay. If we are able to transfer higher load into the columns and lesser load into the soft clay our settlements will be lower.

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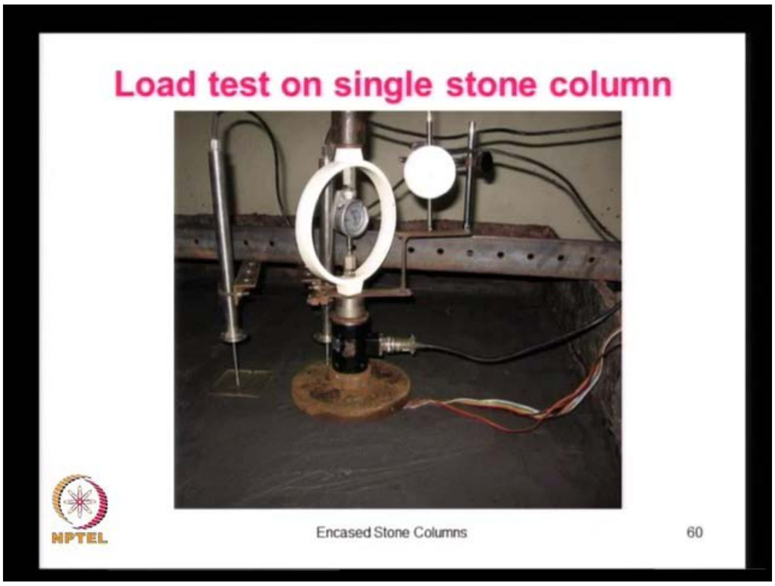

And for this, what we have done is we have taken a large steel plate and instrumented it with different types of pressure cells.

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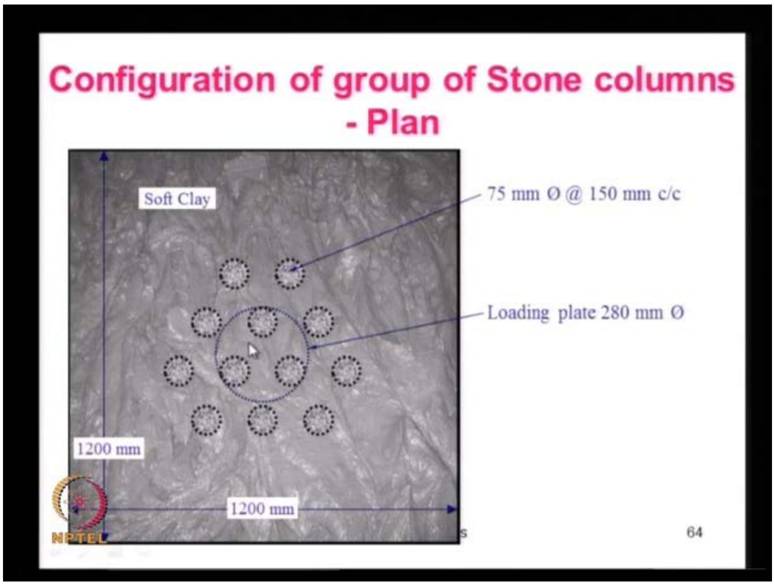

And then we what we have done is, we have taken a stone columns that are arranged in a triangular manner. And we had put in the pressure cells to measure the pressure that is developed on the soft clay and then on top of these columns.

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And this is how, the stone columns are formed, they are all placed in a triangular manner.

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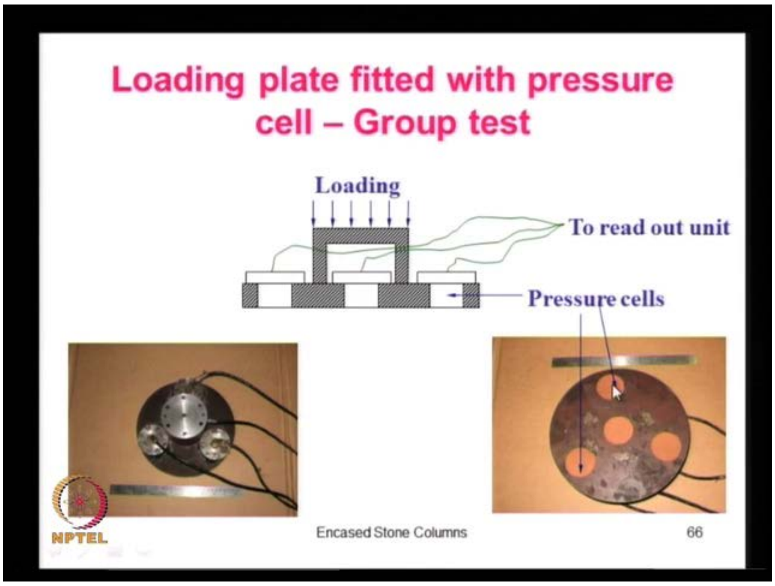

And these are the different pressure cells, there are four of them, three of them will be sitting directly on top of the on the on stone columns. And the middle one, it sits directly on the soft clay and to measure and, so that we can measure the pressures in different columns and the soil.

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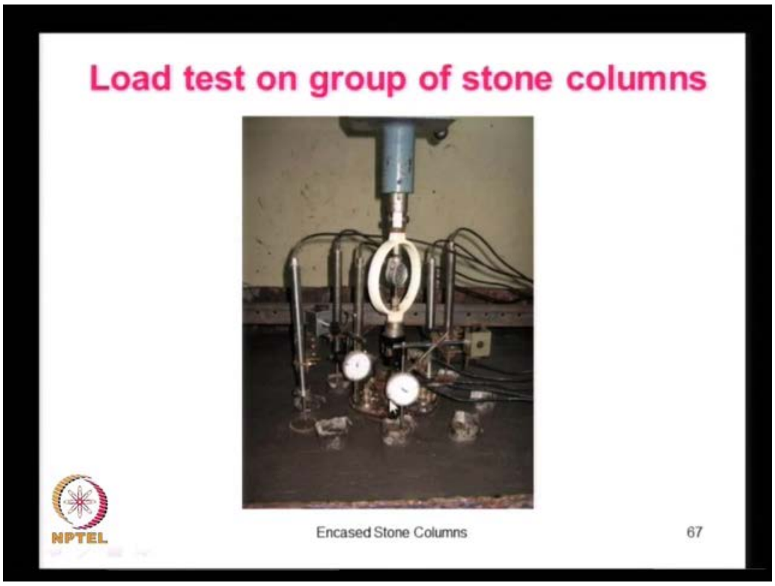

And this is the entire instrumentation, these are the dial gauge and then the LVDT's and then of course, the pressure cells.

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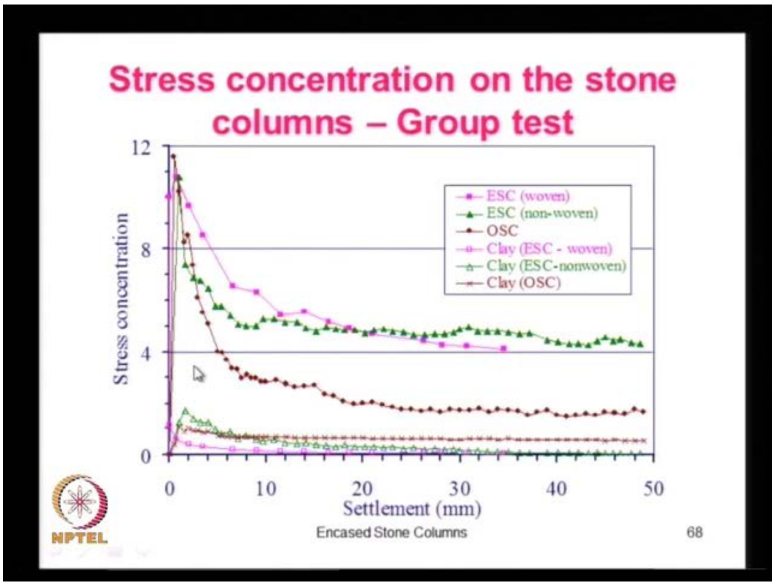

And this is the data that shows the plot between the settlement on the x axis and the stress concentration. Stress concentration is basically, the measured pressure divided by the applied pressure and if it one; that means, that there is no stress concentration and if it is more than one; that means, that at some places we are able to apply higher pressures. And, so this is how it is actually these are all the, lets look at the pink one the woven encased geo textile reinforcement, is actually initially the pressure is increased.

And then as the settlement is increasing there is some load redistribution and then the pressure falls down. And then this is how it looks like even at very large settlement, this stress concentration for both woven and nonwoven geo textiles, it is nearly equal to 4. Whereas, for an ordinary stone column, this stress concentration initially it was of the similar magnitude, but very rapidly it is fell down and it has fallen down to about 2; that means, that the reinforced stone columns they are able to take higher load compared to the ordinary stone column.

And is very interesting to look at, the pressure that is transferred to the clay soil. And this particular line shows the pressure that is transferred into the soft clay, it is nearly equal to 1; that means, that whatever pressure is applied on the system, that is directly transferred into the clay. Whereas, if you look at the pressure that is transferred into the clay for this system with woven geo textile that provides very stiff confinement, the pressure is very, very low the stress concentration is very, very small.

And even the nonwoven geo textile it shows that there is not much of pressure that is transferred into the clay soil. And in a way it is good because if you are able to transfer lesser load into the clay, is not going to undergo any compression that leads to settlements. So, here this particular data is very clearly showing that, the ordinary stone columns they are not able to reduce the pressures that we transfer into the soft clay. Whereas, the encased stone columns because they are, so rigid that they are able to take the load applied pressure and transfer only very small tiny fraction into the soft clay.

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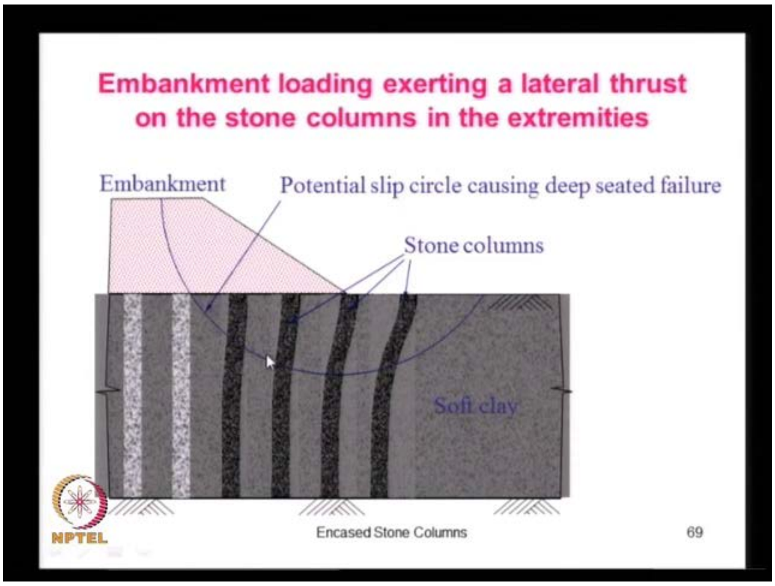

The advantage of these encased stone columns, they are it can be seen in the case of lateral loading for example, here when we have a high embankment on constructed on a soft clay, we typically end up with a slip surface failure. And if you provide a stone column, the columns they just simply get sheared because there is no confinement on the stones, whereas in the encased stone columns they develop much higher lateral resistance because of this encasement and unless we shear off the geo grid or the geo textile failure of the column will not happen. So, that is by that much the stone columns can help in increasing the lateral load capacity.

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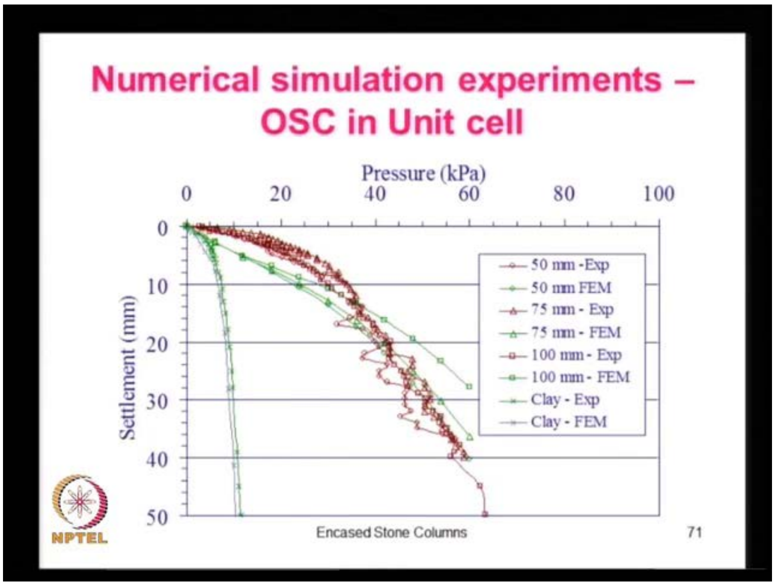

Well for the purpose of generating more data for more realistic dimensions, we have used finite element analysis to predict the response of the stone columns. And then the stone columns encased within the geo synthetics. And this is the data from numerical simulations, these are all the data for ordinary stone column is actually here, we can sorry that is these two data they correspond to the pressure settlement data the clays whereas, this data corresponds to different diameters of the stone column 50 mm, 75 and 100 mm and then, so on.

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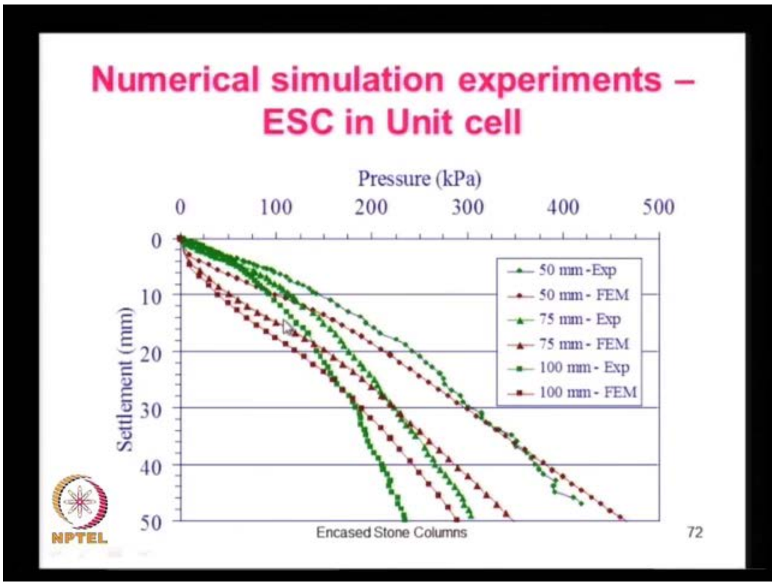

And this is the numerical data, for different diameters is actually these shows the comparison between the numerical and then the experimental one. The comparison seems to be very good; that means that the module the numerical module is able to predict the real behavior.

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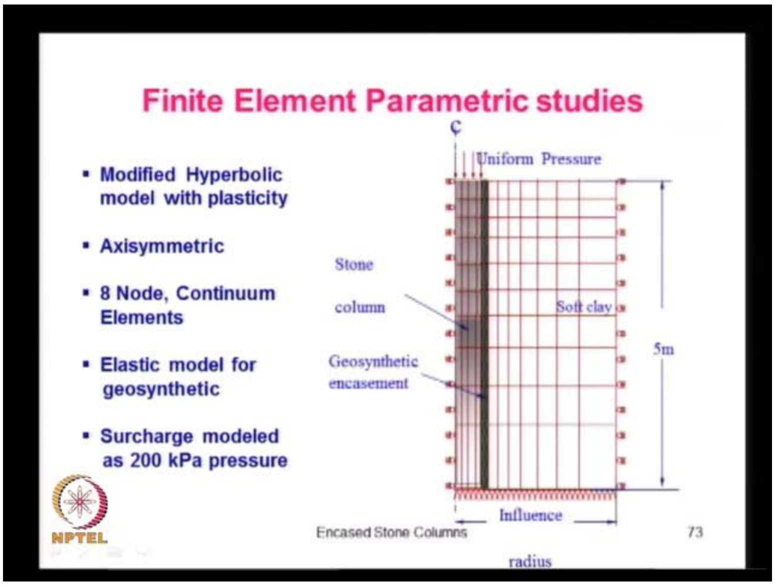

And this is the finite element module that we have used for simulating embankments constructed on soft clays using geo synthetic encasement. Is actually here, the type of constitute module used was a modified hyperbolic module, with plasticity and because we are only simulating, one single stone column that is circular in shape we have used axisymmetric modeling. And the element that is used as an 8 node quadrilateral type element and the geo synthetic is an elastic material. And the surcharge pressure that is simulated was 200 k P a.

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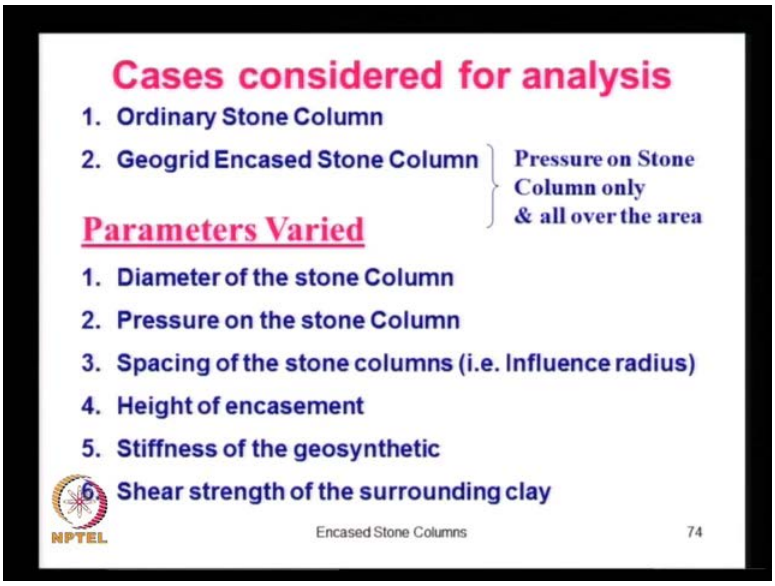

And the different cases were considered, the ordinary stone column. And then a geo grid encased stoned columns and two cases were considered wherein, the pressure is applied only on the stone column area whereas, and in some cases the pressure is applied on the entire area that is to simulate, the embankments. And the parameters that were varied in the analysis, diameter of the stone column, the pressure on the stone column, the spacing between the stone column that is the radius of the influence area. Then the height of the encasement stiffness of the geo synthetic. And then the shear strength of the surrounding clay, all these parameters were varied and lot of data was generated. So, that we can come out with some practical recommendations on the, applications of encasement for the stone columns.

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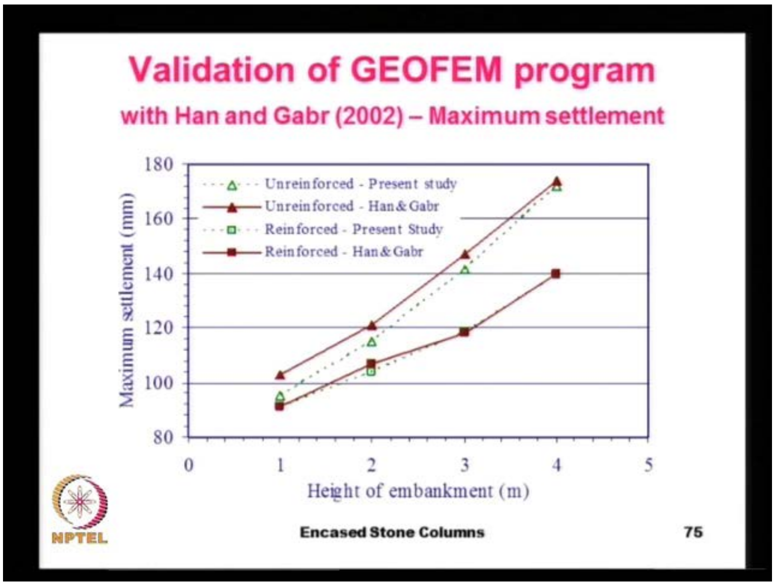

And before we do any numerical simulations, we need to calibrate the module and see whether the numerical module that is employed is able to predict realistic data. And the Han and Gabr in the year 2005 they have published some data from, their own analysis in 2002 sorry for different heights of embankment and the settlements. And here, we see the comparison between their data and the results predicted by this current analysis. And the current analysis, they were generated using finite element program called GEOFEM and it is actually it is written at IIT madras, through several students. And it is a reasonably easy software to use, for performing any geotechnical analysis.

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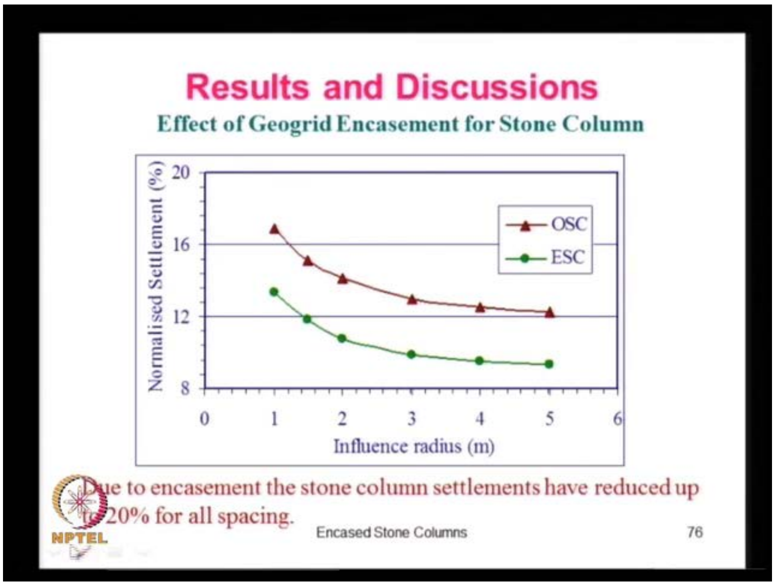

And this is one typical data that shows the maximum settlements for different influence radius values, for the normalized settlement against that is given in terms of the height of the soil layer. And we see that because of the encasement the stone, the settlements have reduced by about 20 percent for all the settlement ratios. And for all the influence radius values.

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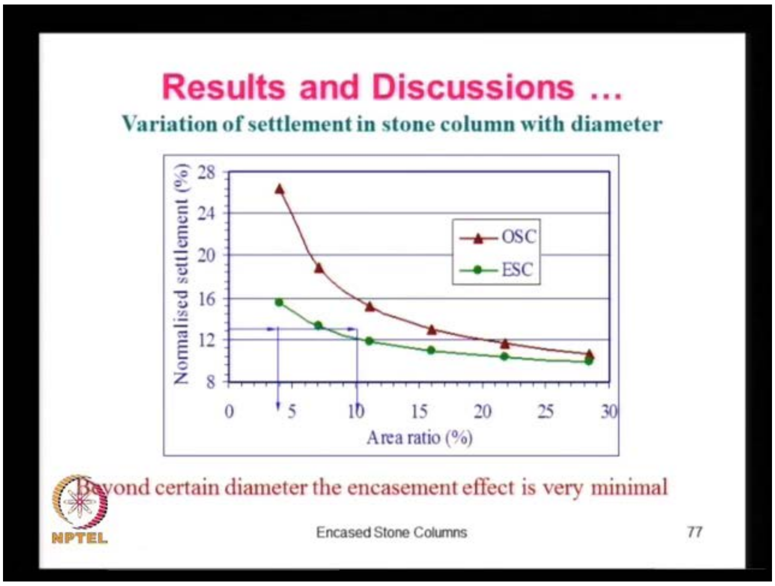

And here, this is with different area ratios the replacement ratios, the normal replacement ratios are about 10 to 20 and more than that, it becomes very uneconomical. And here, we see that even with very small replacement ratio about say 5 percent, with encasement we can reduce the settlement by about 16 percent the sorry the normalized settlement is only 16 percent of the column height, whereas in the case of ordinary stone column, the settlement is about 26 percent. And beyond certain diameter of the encasement the because the confinement that is generated is a small, the encasement effect is reduced and this is what we see, at very large replacement ratios the response of both, the ordinary stone column and the encased stone column is very similar yes.

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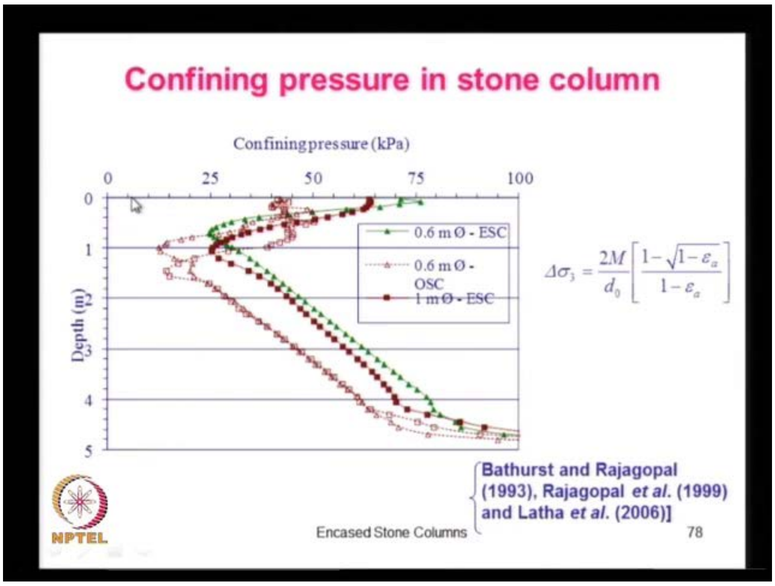

So, the reason why we perform finite element analysis is that look at, what is really happening inside. And if you look at the confining pressure that is developed in the stone column, in the aggregate that gives us a better picture of how the encasement is helping us in improving the, strength and stiffness. And this particular line is corresponding to the confining pressure or the sigma 3, within the ordinary stone column.

And within the top about 1 meter sorry 1 meter depth, the confining pressure is increasing because of the bulging. And this particular beyond a depth of about 1 or 2 meters, this sigma 3 is more or less equal to the k times sigma v; that means, that the ordinary stone column, is not able to supply additional confining pressure. Whereas, the if you look at the, geo synthetic encased stone columns. The confining pressure as increased, by this much.

Is actually it is quite significant, so about 20 to 30 kilo Pascal's and the k P for this stones, is very high because the friction angle is of the order 45 degrees. So, the k P is almost 5 to 6. So, even a small increase in the confining pressure, can lead to very large increase in the vertical pressure that we can apply, and this theoretical analysis can be done through this equation that we have from, the Henkel and Gilbert.

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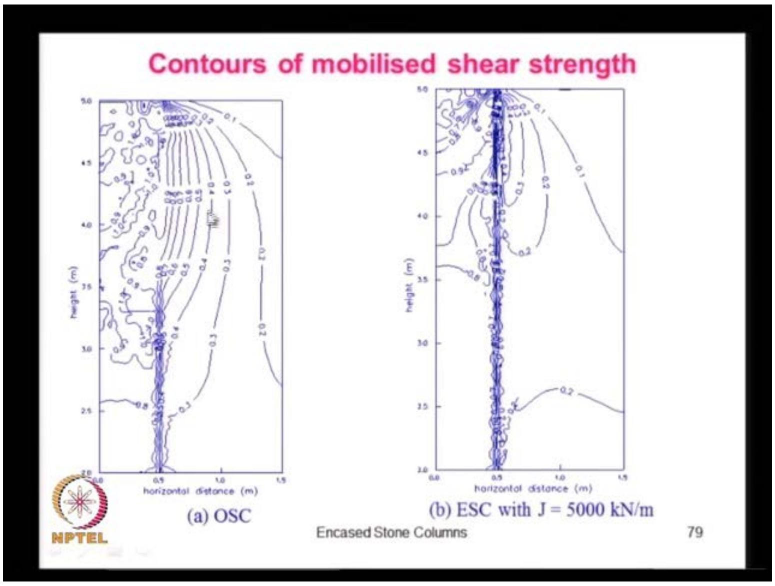

Is actually, this graph shows the mobilized sheared strength that is the shear stress divided by the shear strength. And the maximum value is 1 and for the ordinary stone column most of the contours around the stone column they have value of 1; that means, the full shear strength of soil is mobilized for the ordinary stone column. Whereas, for encased stone column, this is with a J of 5000 that is J is the modulus the secant modulus at 5 percent strain it is only about 0.7, 0.7 to 0.6. And most of the, stress contours the shear stress contours they show very low mobilized shear strength; that means, that the soil has not failed around the stone column. That means, that we can apply when higher pressures.

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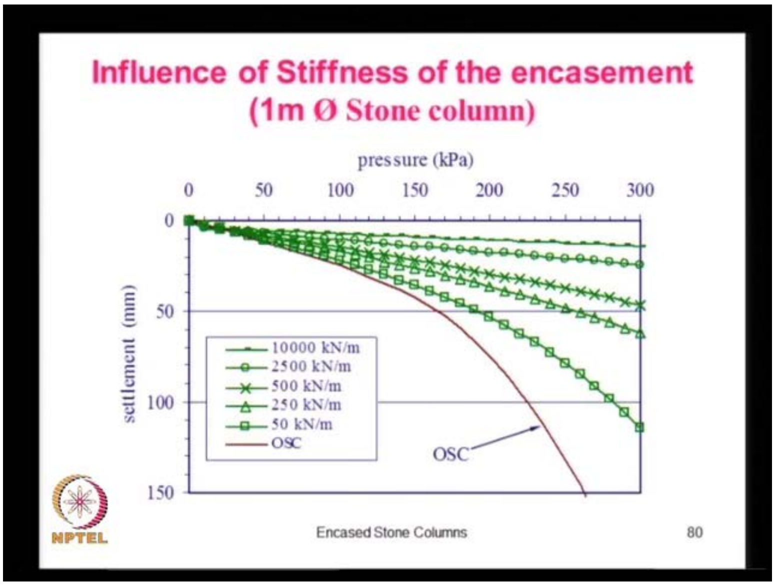

And this graph it shows the influence of the modulus of the geo synthetic on the stiffness. The ordinary stone column, this data is corresponding to 1 meter diameter of the stone column, the pressure settlement data for ordinary stone column is something like this. And if you are able to, say use a geo synthetic having a tensile modulus of 50 kilo Newton's per meter. Even a very soft geo grid or a geo textile will have this much stiffness and the pressure settlement data is like this.

And if you are able to use, let us say a material having a modulus of 500 kilo Newton's per meter, the pressure settlement data is something like this. And with 2500 it is something like this, is actually most of the geo grids and geo textiles, the oven geo textiles they have a tensile modulus as high as about 3 to 4000. And there are some very high strength products that develop strength of 600 kilo Newton's per meter at 10 percent strain; that means, their modulus is of the order of 6000 to even higher. So, this if you are able to use a material with say 10000 kilo Newton's per meter, many commercially produced woven geo fabrics they have, this much modulus. Even at a very low settlement, the pressure can be increased to 300 k P a.

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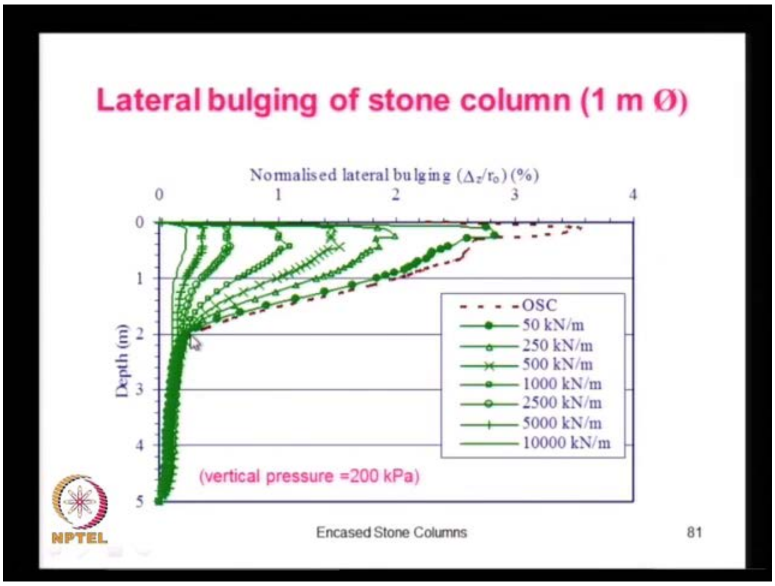

And this graph which shows the amount of bulging that is placed, with ordinary stone column there is a very large bulging of the order of about 3.5 percent of the column diameter. Whereas, the with different modulus values the bulging reduces and when we use very high strength or high stiffness geo textile bulging, it is practically reduced.

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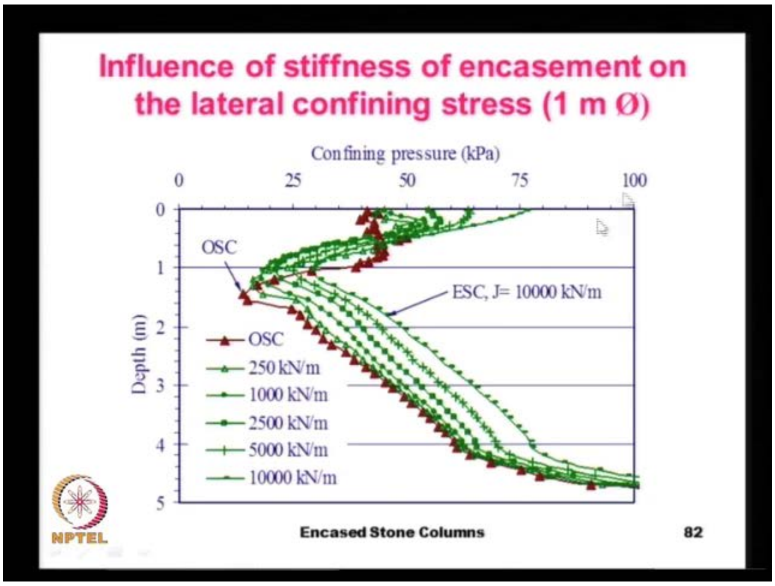

And the influence of the stiffness on the lateral confining pressure. And we see that, as we increase the modulus, the confinement increases and as the confinement stress increases the strength and the stiffness of the column increases.

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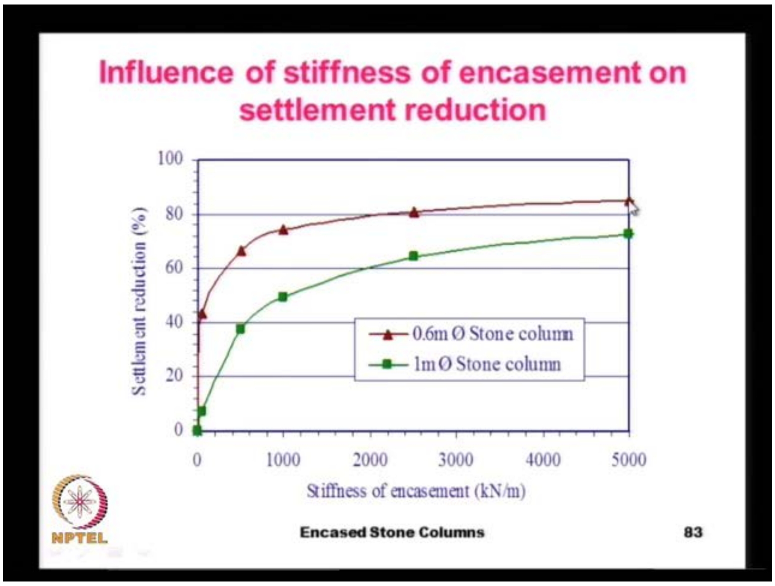

And the once again, the settlement reduction is a function of the stiffness. And beyond certain value of stiffness, there is no further improvement that we can see. And we can decrease the stiffnesses up to almost 80 percent, by using proper amount of geo synthetic and then the proper replacement ratios.

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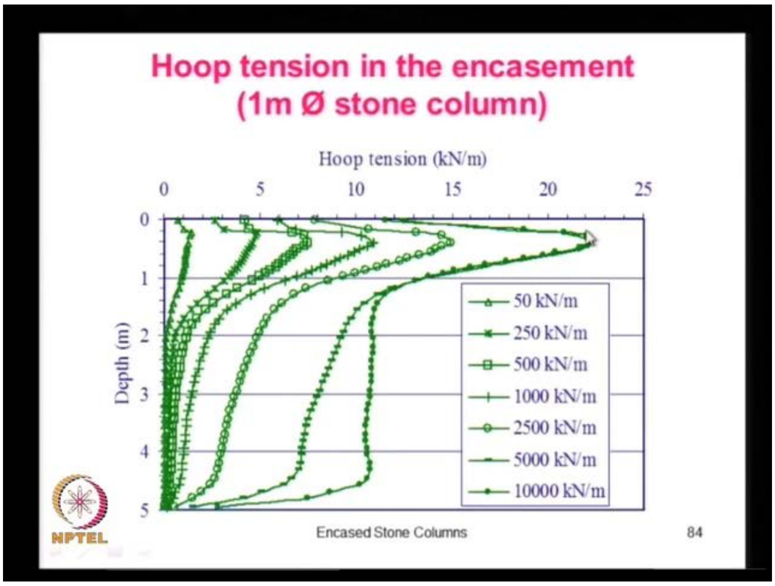

Then the this graph, it shows the hoop tension that is developed, is actually it is not very much the maximum force that is developed is about 22 kilo Newton’s per meter.

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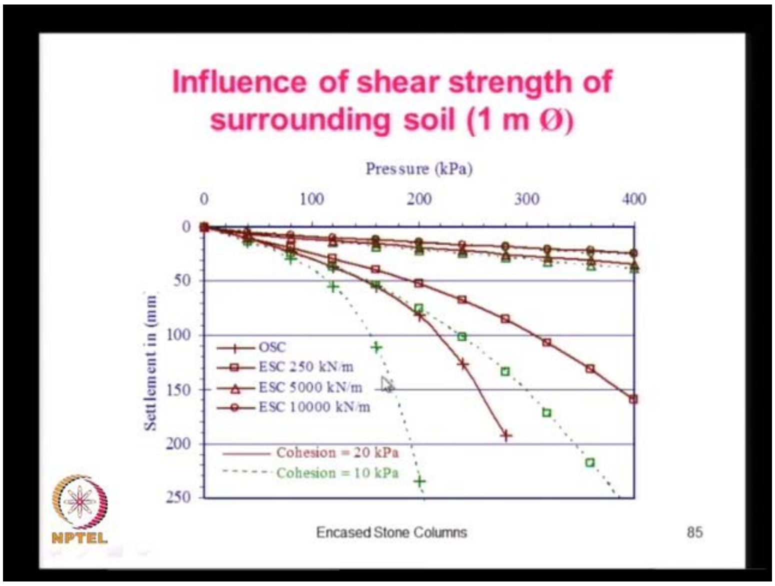

And this is an important graph that shows that, the this the behavior of the geo synthetic encased stone column is not very much function of the cohesion at the surrounding soil. Here, this brown line it shows the data with the cohesion of 20 k P a whereas the green line shows the data with 10 k P a, as the modulus of the geo synthetic increases the response, the pressure settlement response is almost same similar. Only at very low modulus, there is some difference. In the response with softer clay soil showing a softer response, but once the geo synthetic modulus increases about 5000 kilo Newton's per meter, practically there is no difference. That means, that if you are able to use very high strength, geo textile fabric. We can increase the stone column capacity irrespective of the type of soil that we have.

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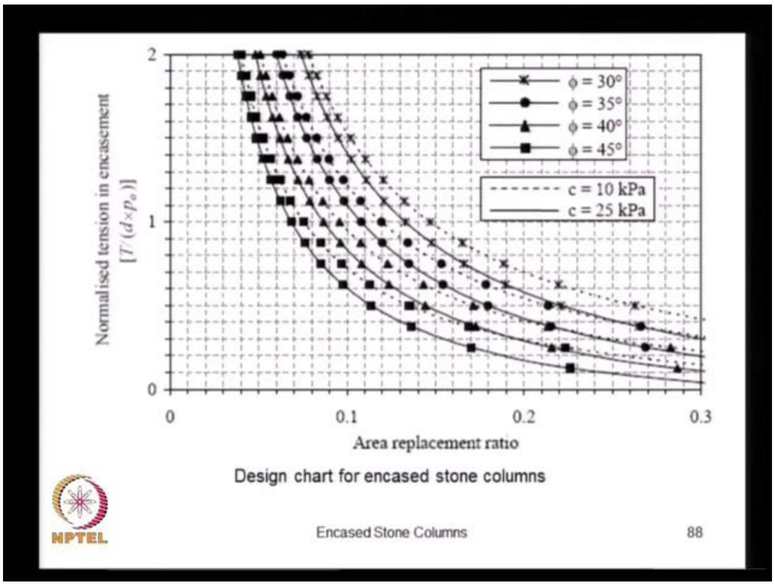

And all this data is presented in a form of chart. Because, basically a design engineer cannot expected to go through all these finite element analysis, the data should be given in a simple form. And this particular graph, it synthesizes the entire data that was generated through the laboratory test and then the field data that is collected and then there is a result from different finite elemental analysis. And it basically, it tells the for different area replacement ratios and for a different type of infill materials. And two different type of clay soils, how much should be the tensile force and tensile modulus. And we will work out some examples later on, how to utilize this chart for our design purposes.

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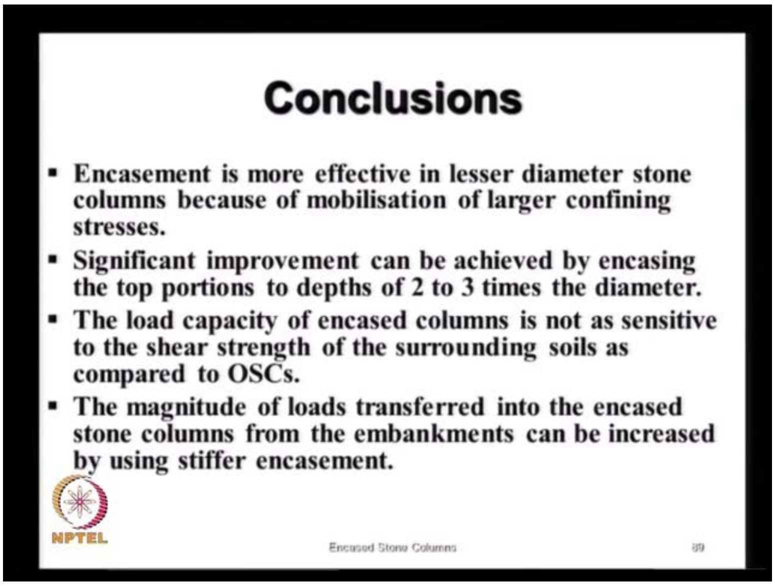

And just summarize, we have seen that the geo synthetic encasement can increase the strength and stiffness of the stone columns by an order of magnitude. And the main advantage, is if you are able to increase the load current capacity, we can have much larger spacing for the stone columns leading to more economical designs. And the magnitude of the loads transferred into the encased stone column, can be increased by using stiffer encasement. See here, we have a choice by using stiffer encasement materials; we can transfer higher loads into the columns, thereby reducing our settlements.

So, thank you very much.