Ground Improvement
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Lecture No. 21
Design Steps

Hi everyone, once again I welcome you to this ground improvement lecture class. Today we have already started the new topic that is Vibro-Compaction. Two lectures already we have taken, I have discussed about the suitability than merits, demerits, limitations all those things.

And now, in this Vibro-Compaction, this is a third lecture in this I am trying to discuss about design steps. And of course, in the last lecture of course, this is part of design step, we have tried to take in the last class, but today once again I will repeat mainly because, last class it was not so clear and only I have mentioned about the equation, but how it is coming that we have not discussed. So, let me take with that.

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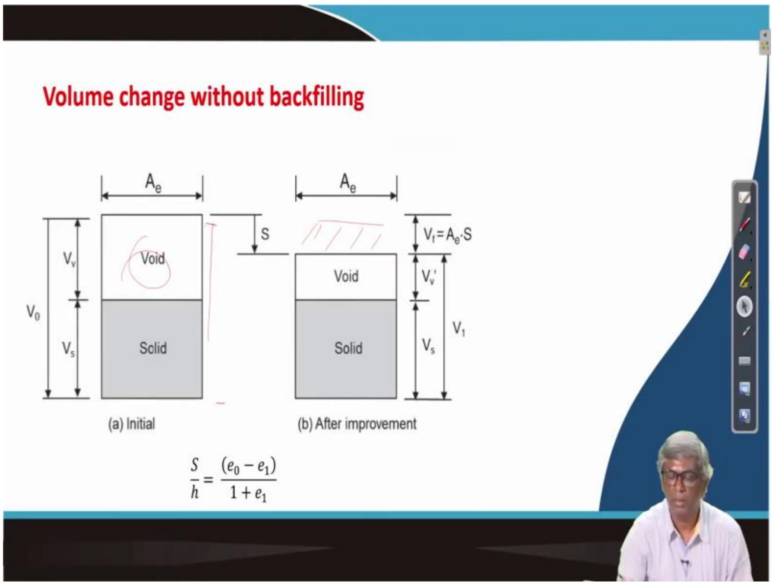

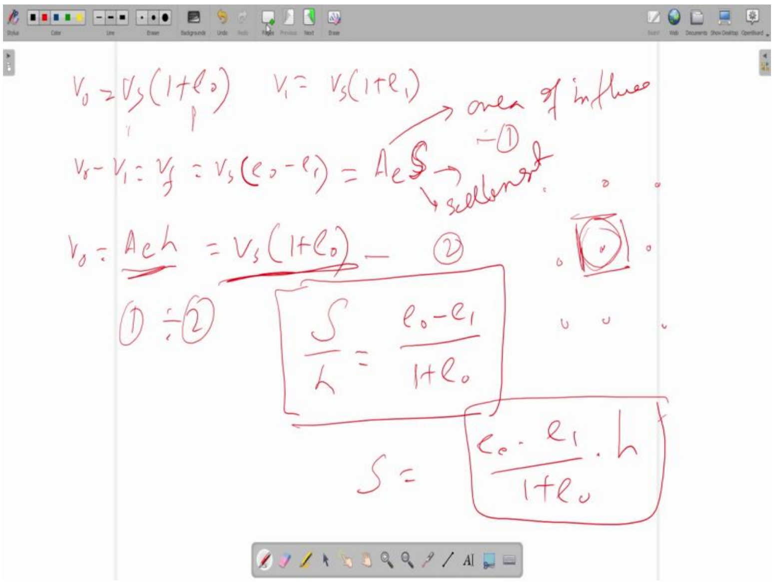

Then, volume change without backfill we have discussed that during Vibro-Compaction there will be volume change, volume change by, then only it is densification is possible that when some amount of voids will be removed from the soil mass and that will result void volume change and that volume change in nothing but reduction in volume. And you can see original volume is this one this is the entire quantity from here to here.

This one you can say total volume of the original solid and because of that can be idealized as a total equivalent solid volume and total equivalent void volume. Now, this is in soil mechanics perhaps you have seen that three-phase diagram and in that three phase diagram voids can be of two parts one will be volume of air and volume of moisture or water, but here we assume void mean totally whether it is water and here both together it is a holy void.

And then because of this Vibro-Compaction suppose, the new volume is this one and during Vibro-Compaction whether it is Vibro-Compaction or any compaction equivalent solid volume can never be changed, it will be same. All the volume changes because of the reduction in volume of voids. Here the voids volume was this much reduced to this much, then this much is the voids removed and because of that the volume change took place.

So, for these different notations are given, V naught is original volume, V_s is the volume of the solid, V_v is the original volume of voids, then V_f is the volume of, volume reduced you can say and V_v dash is a new voids and Vs of course, originally is there and V_1 is the final after compaction is of volume, and V naught is the before compaction is the volume.

So, if you do this then you can think of like this, we can, you can think like this V naught equal to Vs multiplied by 1 plus e naught, this is from the soil mechanics, we know that the original void ratio is e naught then Vs is that solid volume then original volume can be expressed like this. Similarly, V_1 can be expressed as Vs multiplied by 1 plus e1. So, like these two things can be there.

So, V naught minus V_1 equal to $V_{f,}$ which will be equal to again Vs multiplied by e naught minus e1 and which can be expressed as Ae multiplied by S, A is the area of influence that if it is a square pattern like this and like this, like this, like this, like this, like this, then this one area influence of this one will half this side, half this side, half this side, half this side. So, this is the area of influence which is nothing but a square, that I will come later on and S is the subsidence which is shown there, because of these compaction, Vibro-Compaction, what is the settlement.

Capital S, here is a capital S is used as a settlement, capital S as a settlement or subsidence. So, this is the one and this is Ae into S and this one and your again V naught can be expressed as Ae multiplied by h if the area of influence multiplied by the original height, so A_e multiplied by h. And which is nothing but Vs multiplied by 1 plus e naught. you can now, we can now, what you can do and so, you can divide this equation and this equation, this is suppose 1 and this is 2, then this by this if you do 1 by 2, 1 divided by 2, then you can see that S divided by h equal to e naught minus e1 divided by 1 plus e naught.

So, this is the equation we have shown. That means, if a particular site the original void ratio is e naught and your final desired vertices is e_1, then we can then in that case your, then how much is the settlement, sorry three things original void ratio, depth of improvement is required h and final void ratio if I know, then after compaction how much is the settlement that can be obtained S equal to e naught minus e1 divided by 1 plus e naught multiplied by h.

This is the equation can be used for your calculation of subsidence. Now, next thing is you can see that this can be as we have mentioned that Vibro-Compaction can be done with backfilling and without backfilling. So, this is without backfilling if it is with backfilling, let me see how it is coming.

$$V_0 = V_s\left(1+e_0\right)$$
$$V_1 = V_s(1+e_1)$$
$$V_s - V_1 = V_f = V_s\left(e_0 - e_1\right) = A_e S$$

$$V_0 = A_e h = V_s(1+e_0)$$

$$\frac{S}{h} = \frac{e_0 - e_1}{1+e_0}$$

$$S = \left(\frac{e_0 - e_1}{1+e_0}\right)h$$

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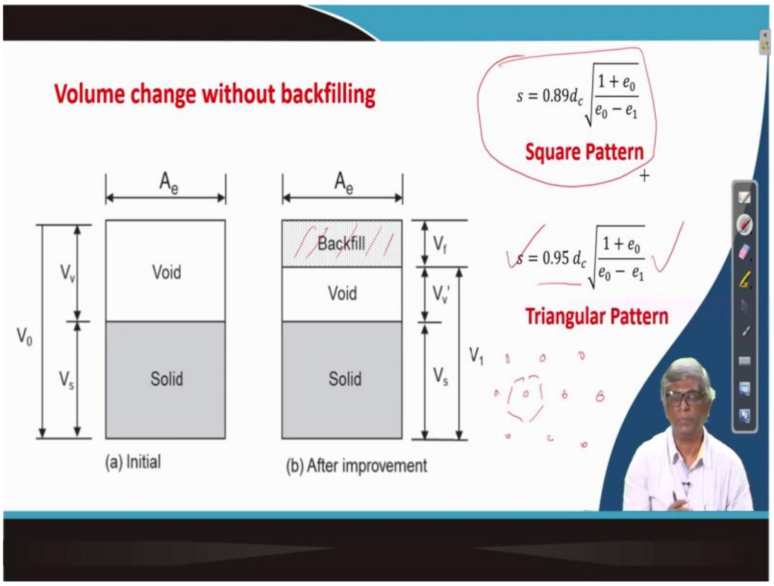

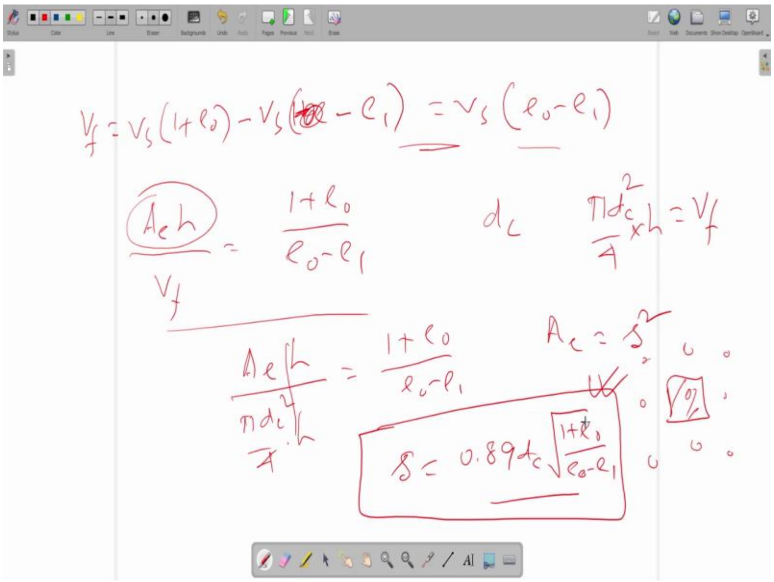

This is actually when you do with backfilling then this is the one and then you can see that initial these much voids. Now, it is backfilled, then it will be same level will be maintained. How that can be, from this how you can find out a spacing that can be seen. And you can see that V_f equal to nothing but Vs multiplied by 1 plus e naught minus Vs into 1 plus 1 minus e1. This one if I do and then it is nothing but Vs multiplied by e naught minus e1.

And so, previous equation whatever we have got already, so we can say A_e by, A_e multiplied by V naught and divided by V_f. See, if I do this, then you can see you will get 1 plus e naught because divided by e naught minus e1. Already we have Ae multiplied by h, already we have got and then V_f is this 1 and then if I divide these two equations, so, you can go back you can see Ae multiplied by h, A_e multiplied by h.

So, you can see Ae multiplied by h, which is this one and so, if you do that, you can see that if you equation that divide by this if you do then we are getting this. And then, and volume of backfields, V_f was shown you can see this one, V_f is shown nothing but if I consider, if I consider the column diameter is d_c, so, column diameter dc, then V_f will be, V_f will be π d_c square by 4 multiplied by h equal to V_f.

So, if you do this, then ultimately you are getting Ae multiplied by h divided by pi dc square by 4 multiplied by h equal to 1 plus e naught divided by e naught minus e_1 and from these I can get, and Ae equal to small s square. That is as I have told you, if it is a square pattern like this, like this, like this, like this, then the area of influence will be nothing but A square, same A square.

$$V_f = V_s(1+e_0) - V_s(1-e_1) = V_s(e_0 - e_1)$$

$$V_f = \frac{\pi d_c^2}{4} h$$

$$\frac{A_e h}{\frac{\pi d_c^2}{4}} = \frac{1+e_0}{e_0 - e_1}$$

$$A_e = S^2$$

$$S = 0.89 d_c \sqrt{\frac{1+e_0}{e_0 - e_1}}$$

If I substitute then finally, become considering square pattern 0.89 dc under root 1 plus e naught divided by e naught minus e_1. So, this is the equation is given in the seat I will go back there. So, this is based on squares pattern when you are using backfilling then spacing can be obtained by this one. So, let me go back. So, this is the equation you can see is given.

This is the equation given that spacing equal to for square pattern, this void it is a triangular pattern that means, when you are doing like this, when you are doing like this, when you are doing like this similarly, when you are doing like this, when you are doing like this, so the area of influence of this one will be half, half, half like there will be hexagon here and that hexagonal area I can relate to the spacing and then that can be converted and then you will get spacing equal to 0.95 dc multiplied by same quantity.

$$S = 0.89 d_c \sqrt{\frac{1+e_0}{e_0 - e_1}}$$

$$S = 0.95 d_c \sqrt{\frac{1+e_0}{e_0 - e_1}}$$

These are, when you are using backfilling then how to find out the spacing of the Vibro-Compaction that these two equations can be used, where what are the things involved, what is the diameter of the backfilling we are considering that dc and what is the original void ratio before compaction that is required and what is the desired vertices after compaction these three quantities if you know then you can find out the spacing.

The spacing of course, during design has to be adjusted depending on requirement, dc can be changed and accordingly this spacing also will change. Original void ratio is desired void will not change that is one is before a compaction what is the in the field, what is the void ratio existing that cannot be changed and what is the desired void ratio that is also cannot be changed.

These two things are unchanged. But to make it efficient, you can change the diameter and that diameter also how much it can be there is a limit. So, based on that you can choose the dc and based on that you can find out the value of s. These two parts last class I have taken but it was not completed. So, I just repeated this one. So, next thing is next, let me go to the next slide.

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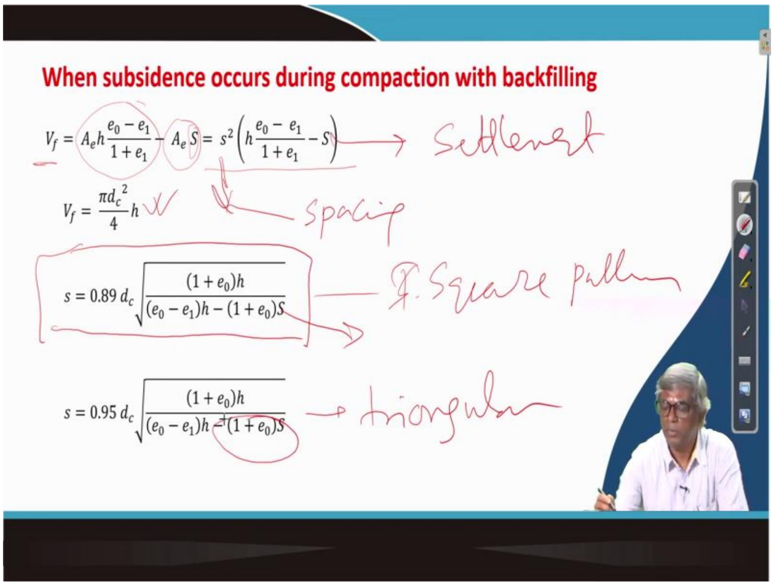

And you can see, when subsidence occurs during compaction with backfilling and backfilling also, we are doing still there is some amount of subsidence in that case your equation can be a little modified V_f, whatever we have calculated by these minus the final subsidence multiplied by Ae that can be used and if I do this, then this equation will be simplified. This is you have to see, 2s there, this is spacing and this is settlement, so these two things cannot be confused.

And V_f, if you substitute by this, then again s will be modified. So, when there is a subsidiary of s, whenever backfilling is used still there is a substance amounting s then if we want to find out the spacing this equation can be used, what are the unknowns here, before compaction what was the void ratio, after compaction what is the desired void ratio these two things are required.

Depth of improvement also is required and additionally required how much subsidence that you are allowing that also required. If you know that then based on that, this is for square pattern and this is for triangular pattern. This equation whatever I have shown previously they are similar only this portion is additionally coming. So, let me go to the next slide.

$$V_f = A_e h \frac{e_0 - e_1}{1 + e_0} - A_e S = S^2 \left(h \frac{e_0 - e_1}{1 + e_0} - S \right)$$

$$S = 0.89 d_c \sqrt{\frac{(1 + e_0) h}{(e_0 - e_1) h - (1 + e_0) S}}$$

$$S = 0.95 d_c \sqrt{\frac{(1 + e_0) h}{(e_0 - e_1) h - (1 + e_0) S}}$$

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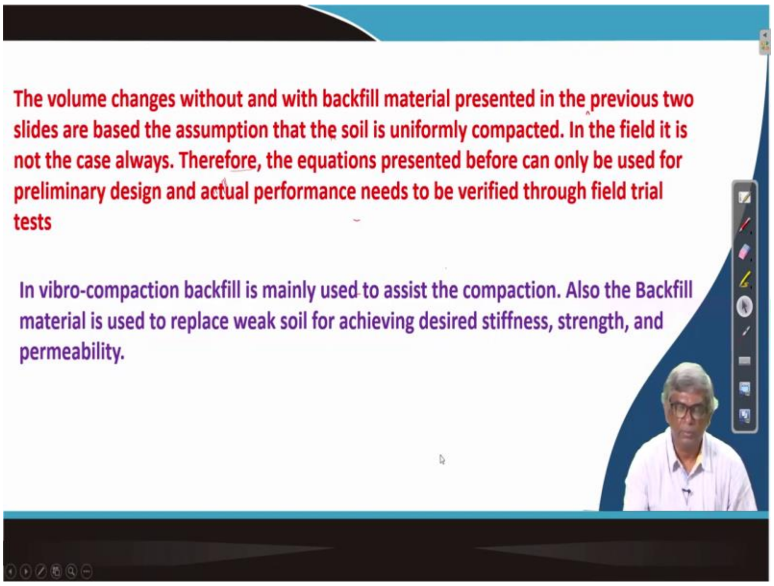

So, next, the volume change without and with backfill material presented whatever just you have discussed how to find out the spacing and all. And this is while deriving these it is assumed that the soil is uniformly compacted, but in practice is hardly it happens. This equation and because of that equation can be used for your preliminary assessment or preliminary design, but final design can be obtained based on our final decision can be taken based on trial test in the field.

Whatever we have, the equation we have derived those are based on a certain ideal situation, ideal situation is what that when you do the Vibro-Compaction we are assuming that the ground is compacted uniformly, but close to the probe compaction will be more, little array from the probe compaction will be little less. As a result, this is really not uniform. Because of that, how much, because of these how much difference etcetera is happening that can be assessed based on trial test. So, that is the warning it is mentioned here.

And Vibro-Compaction backfill is used mainly to assist the compaction. If I continuously Vibro-Compaction vibrate, then continuously it will be, soil will be losing, but if I put backfill, then those area can be filled up by the good material and finally, further compaction we can arrive at better compacted ground.

Also, the backfill material used to replace soil for the achieving desired stiffness and strength and permeability is advance, what is the desired permeability strength stiffness that is also for a particular project it will be different projects will be different. If we want to achieve a particular target value or permeability, strength, stimulus, everything in that situation sometime backfill material also a suitable, backfill material to be used. And when you use all backfill material sometime it is called the Vibro replacement. So, that is again there is a separate topic that will be discussed maybe later on, if I get some time. Let me go to the next slide.

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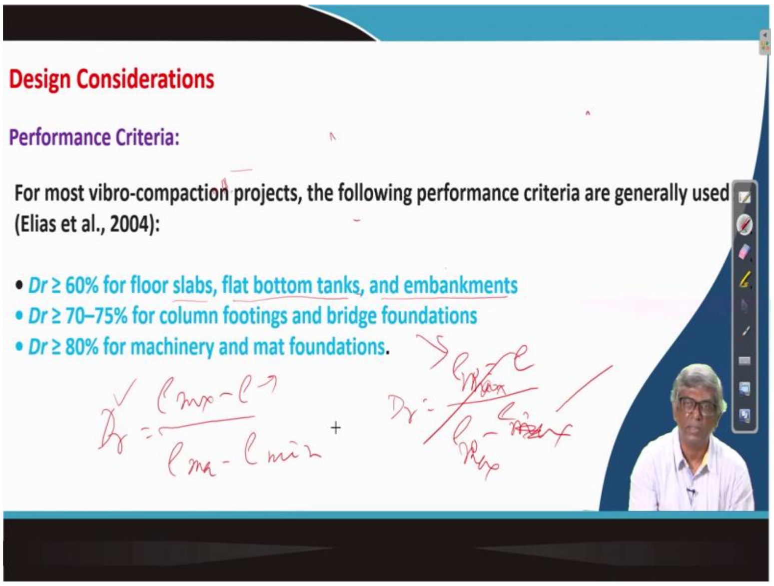

That design consideration in the Vibro-Compaction, the performance criteria first of all, and now, for most Vibro-Compaction project, there are a few things, most important thing to be considered the relative density and relative density for all projects, it may not be same relative density when it is slab or flat bottom tanks and embankments.

$$D_r = \frac{e_{\max} - e}{e_{\max} - e_{\min}}$$

This is larger area where a little settlement not make much different problem, under that condition we can D_r should be used as greater than 60 percent and when it is a column footing and bridge foundation, you know that to foundation based on that particular span of the bridge will be there if they separate settle differently, then it will be problem will be more.

As a result those foundation below the column footing or the bridge foundation the relative density should be much greater, it will be 70 to 75 percent or more than that. And sometime for machinery foundation or mat foundation again that relative density has to be greater than 80 percent. And what is the relative density, that is that relative density expression is Dr equal to e naught minus e divided by e naught minus e max.

So, here the void ratio they are all void ratios, one void ratio before compaction what is the void ratio and, this is e minimum, e max minus e and e max minus e minimum. Let me write,

D_r equal to e max minus e divided by e max minus e minimum. There are all void ratios in a particular site that you can find out in situ void ratio, this is e and that is all can be collected and it can be compacted maximum possible, then it will get the e minimum and when you consider that soil in a loses state, loses possible state and corresponding void ratio will be e max.

So, that means, any soil can have e max to e minimum and in the field, it is suppose e, then based on that you can calculate D_r and this D_r should be greater than 60 percent for some work and greater than 70 to 75 percent some other work and greater than 80 percent particularly for machinery and mat foundation. So, this is the requirement to be followed, this is the design criteria or performance criteria.

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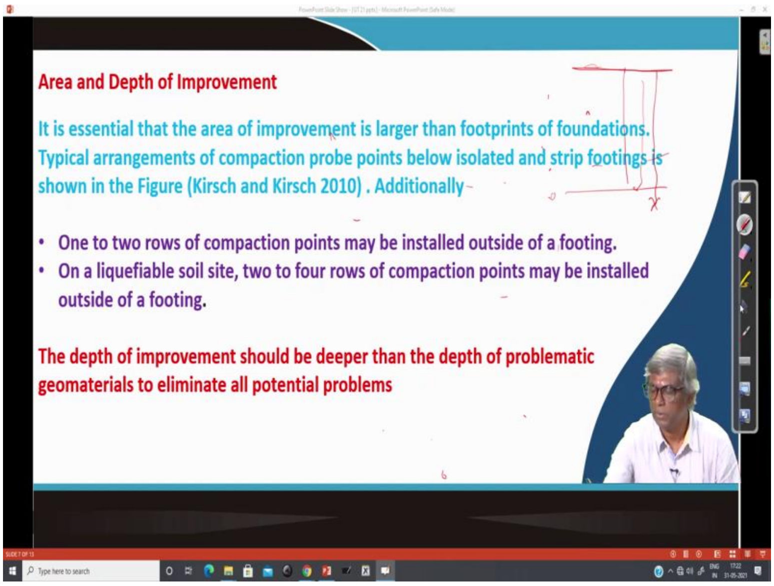

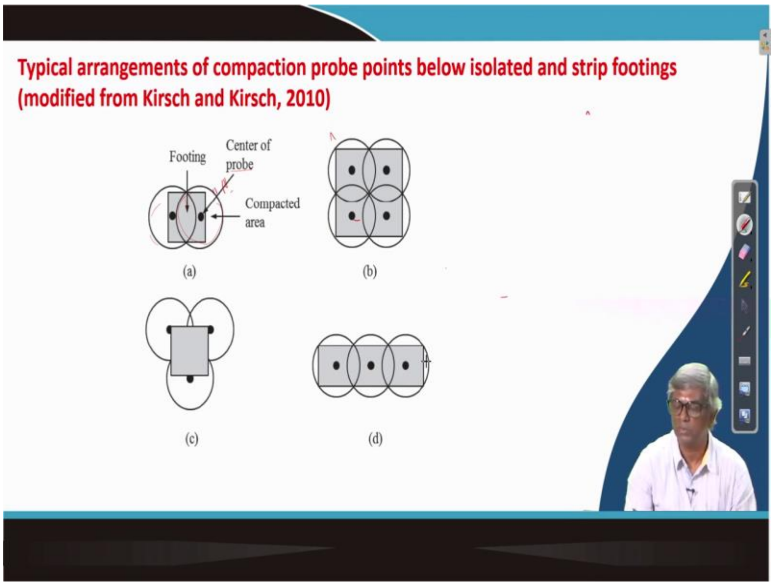

Next one is the area and depth of improvement and area it is essential that whatever footprint of the foundation, the area improvement at least to be more than that, that is the requirement, major requirement, but if you suppose to go beyond that. And the typical arrangement, which I will be showing maybe, let me show you first, this is the one.

Different ways, it can we arrange suppose footing the two column the Vibro probe can we use, Vibro-Compaction and then for corresponding to this area influence of these corresponding to this area of interest this much area is densified. This is sufficient for this foundation. Similarly, if there are going to be 4 Vibro-Compaction can be done and then the area of influence, area influence, area influence, area influence and again that it is covering the footprint of the foundation.

This is also one arrangement. Again, this can be another arrangement, and if it is a steep footing, that this can be the role of Vibro-Compaction can be done to support the foundation. This is one type of arrangement. That is what, so this is the one I was talking about. This is the one that at least it size should be bigger than the footprint of the footing. And next is, but additionally what you have to do one or two rows of compaction point may be installed outside of footing.

Whatever we have shown in the diagram that you have one compaction point and area of influence here and footing is this, but if this is desired that one or two more all around Vibro-Compaction, so that it will be having proper protection, if there is a settlement is there in the side soil it should not also move. So, that is the protection of an on liquefiable soil when the foundation is there two or four rows of compaction point maybe installed outside the footing area.

If this is the footing area and compaction point, and then two to four all direction can we Vibro-Compaction should be used. So, that is a large area should be compacted because he's already a liquefiable saw ground and is there any problem then entire things will be collapsed. Because of that this to prevent liquefaction that liquefiable soil when Vibro-Compaction is used.

The beyond the foundation your two or four rows of Vibro-Compaction can be used to give appropriate protection, and then next part is the depth. So, what will be the depth of improvement, depth of improvement should be deeper than the depth of problematic geomaterials to eliminate all potential problems. A particular side suppose this is the ground and you have up to this problematic soil and so that means, your Compaction by Vibro-

Compaction at least it should be up to this, it is better to go a little deeper, so that you will get all, you can eliminate all problems because of this presence of this problematic soil. Let me go to next point.

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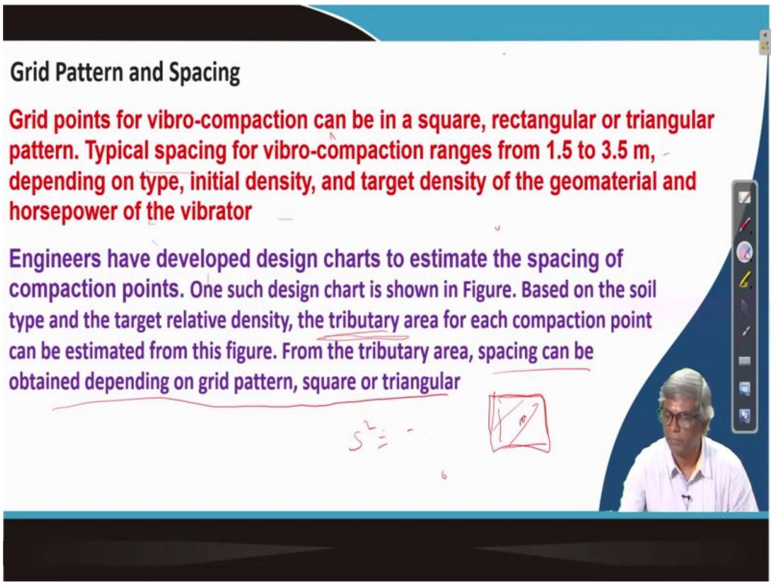

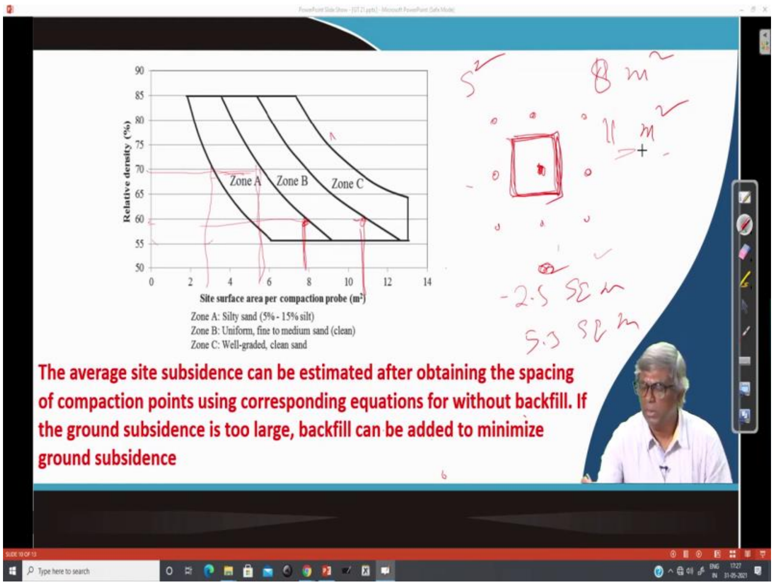

So, grid pattern and spacing, you can grid pattern in of course in Vibro-Compaction in general there are many, many ground improvement techniques there are you have to prove and you have to make a hole and then you have to use some material that is there are different patterns or you generally square and triangular pattern is very, very popular, but here Vibro-Compaction sometime rectangular pattern also can be used.

And typical spacing in Vibro-Compaction generally 1.5 meter to 3.5 meter, this absolute range 1.5 cannot be less than and should not be more than 3 point maybe little more, but range most work range between 1.5 to 3.5 meter and this is again how it will be, where it will be 1.5 meter, where it will be 3.5 meter or where it will be in between suppose 2 meter or 2.5 meter, it depends on type of material, initial density of the material, target density of the geomaterials, and horsepower of vibrator or what type of machine you are using that is also plays a role for finding out the spacing of the Vibro-Compaction.

And this of course, to finding out the spacing engineers have worked in the field over the period at different people suggested different methods of estimating the spacing, based on their experience and data, or the field data and there are quite a few methods one such may design chart is shown in the figure that I will, let me go to the next slide and show you.

This is the one this type, you have supposed, this side is relative density and this side is the side surface area par compaction probe. That means, as I have mentioned the compaction probe is this one if this is the compaction probe and this is the compaction probe and this is the compaction probe, this is the compaction probe, this is the compaction probe, this is, this is the, like that if it is there, then area of influence under a particular probe we can find out this. And this one, relative density will be there. And there are Zone A, Zone B, Zone C there are three different Zone.

So, relative density supposes 70 percent and Zone A silty sand, so 5 to 15 percent silt. So, this is the Zone. So, 70 percent I will enter here in between I can choose from 2.5 meter to around close to 5.5 meter spacing. So, 2.5 meters to 2.5meter square, 2.5 meters square meter, 2.5 square meter to near about 5.5 square meter, I can choose because if the soil is in the zone A, if this type of the silty sand is used, then and if the relative density requirement is 70percent then I can choose between 2.5 square meter to 5.5 square meter and then root of that will become s.

That will split that is the giving you the spacing. Similarly, if you have suppose another soil suppose 60 percent relative density requirement and you soil is B, that means uniform, fine to medium sand, then you can see it is projected here, then it duty in these two these that means 8 meter squared to 11 meter square. So, 8 meter square to, 8 meter square to 11 meter square area of influence I can consider, the area of influence this one.

This area of influence is nothing but A square, A square equal to 8 that means, what is the guess, I can root of that will be S. Similarly A square equal to 11. So, root of that will be the spacing. So, this chart sometimes, many times in the field they use to find out the spacing depending upon your relative density requirement and type of soil you are improving. So, let me go back to the previous slide once again something I missed.

This is the one. I was talking about this, that one size design chart which is I explained already, based on the soil type and target relative density, the tributary area, tributary area that means, whatever we have shown, if the my Vibro-Compaction point is this the area is like this to be taken.

And so, this is the area we are obtaining from the chart and from that you can find out the spacing that A square equal to that and for the tributary area spacing can be obtained depending on grid pattern and square triangle. Then again there is S square again we will, this will again depend on triangular and square pattern if the square pattern I am taking a square, but if it is a triangular pattern again that will be different, what it is actually I will sometimes discuss that one. What is the relationship between tributary area and the spacing?

Somewhere, I will discuss not right now, because it will take some time as I have shown that, for this is easy this is a square. So, S it is becoming a square, but when the it is a triangular pattern, the tributary area is becoming hexagons, you have to find out that area of a hexagon, hexagon and from there and that is a hexagon it will be 12 triangles, it will be there and equal area of 12 triangles and to be integrated with that area from there we will get the relationship between S and the spacing.

So, that we will discuss somewhere sometime later part. That means, ultimately tributary area is important to find out. Now, if you know this grid pattern, then from there we can find out what is the spacing, maybe while solving the problem, I will show that. This is the one already mentioned. And average site subsidence can be estimated after obtaining the spacing of compaction point using corresponding equation for without backfill and if the ground section is too large backfill can do so.

When is backfilling when you are doing this compaction and then already, we have discussed that equation equal to that spacing after knowing the spacing, we can find out what is a settlement that can be obtained. And if there is too much settlement then backfill can be used, this is the thing which you are already.

$$S = 0.89 d_c \sqrt{\frac{(1+e_0)h}{(e_0 - e_1)h - (1+e_0)S}}$$

$$S = 0.95 d_c \sqrt{\frac{(1+e_0)h}{(e_0 - e_1)h - (1+e_0)S}}$$

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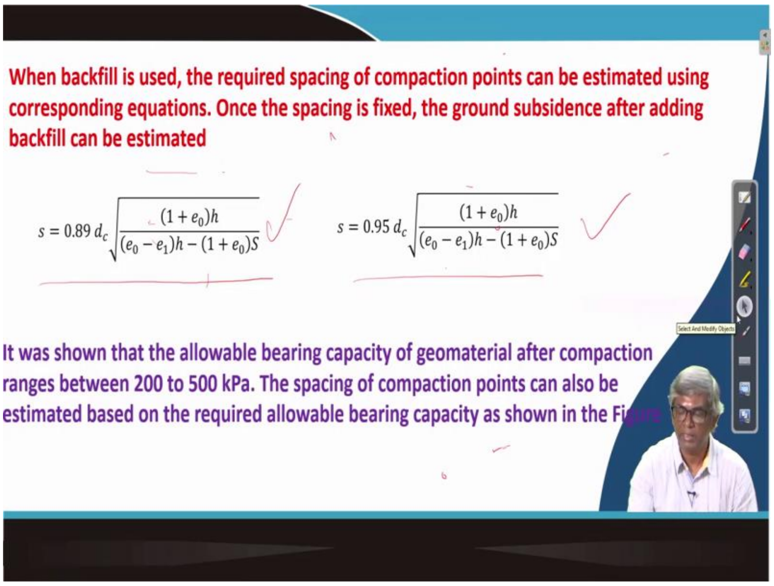

And this is the one when backfill is used the corresponding equation is when subsistence is there, already just the initial lecture I have discussed this equation we used for square pattern and this is the equation to be used in a triangular pattern. Also, it is shown that after compaction that the range of bearing capacity fall between 200 to 500. Sometime using that also people can find out the spacing that is given in the next slide.

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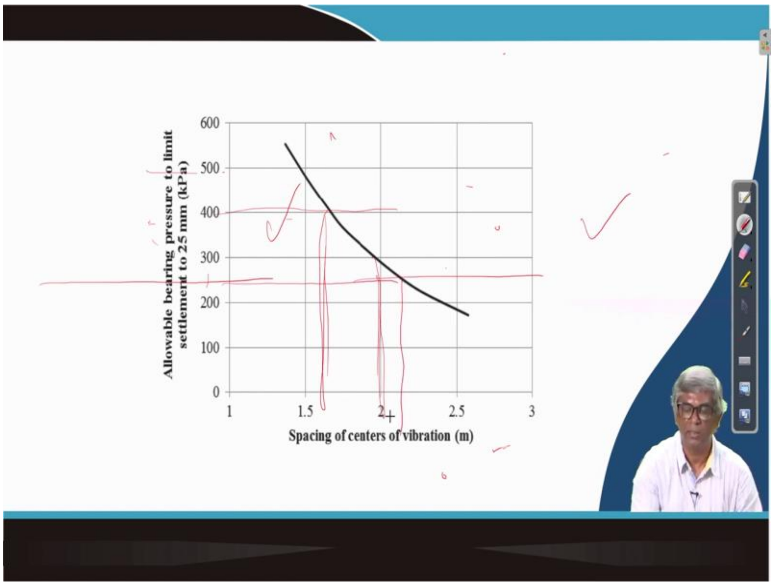

You can see here, that if it is a suppose 300 bearing capacity and then it corresponding from these and the spacing we can find out from here 2meter. If it is a 400 then corresponding spacing is 1.5 meters that means when more bearing capacity was a requirement of bearing capacity is higher than spacing will be reduced. When the spacing the requirement of bearing capacity is lesser, the spacing will be wider. So, that is what, if it is, if you take 200 or 250 then your spacing is 2.5 meter like that.

So, with this with using this chart also one can find out the spacing. There are many other methods. We are already discussed these two methods and you will be sufficient. And if you want to know more, you can see the literature. With this I will close this lecture and let me close here, thank you.