Ground Improvement

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Lecture 39

Grouting (Contd.)

Hi everyone, once again I welcome you to this ground improvement lecture class and we are in grouting and some aspects of grouting we have discussed already, particularly what are the different types of grouting and their application and but when you do already, we have learnt the different application that whether it is jet grouting, whether it is permeation grouting, whether it is hydro fracturing or anything else, everywhere there are certain amount of grout material to be injected.

That injection sometime we need to apply certain pressure and sometime we need less pressure, sometimes we need more pressure and what should be the pressure for a particular type of application and also what is the amount, sometime most of the cases it difficult to estimate the amount accurately but at least once you in a project, you need to have some approximate estimation of the quantity of material.

For those purposes we need to have some sort of mathematical or some calculation, so to do calculation we need to have some theoretical background, here we are trying to take this when you particular grouting we are doing then what is the appropriate theory we can apply and based on that we can correlate the volume of grout, pressure, permeability of the grout material, void ratio many other things so we will see that one by one.

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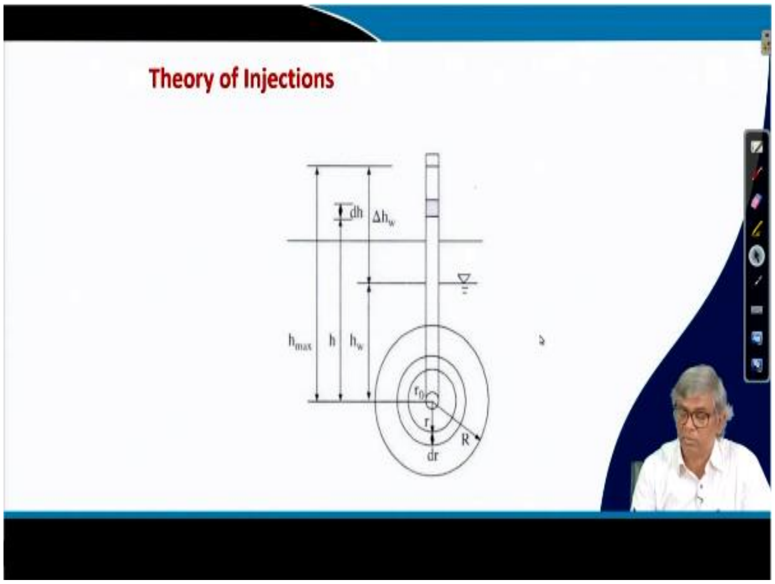

Let us take a typically one suppose, theory of injection grouting suppose and this injection grout you can see here, this is the injection pipe and we can say the ground water table is somewhere here and we are putting grout up to this so that the total head h max is this much over this point and the grout is injected through a opening which is having radius suppose R naught which will be quite small and then finally this grout will be permeate and it will be moving away from this and it will form a spherical.

From the from the opening, it will be coming out, your grout is coming out and it is spreading spherically that will be all direction, the side, even above, below everywhere, at any time we can imagine a sphere of radius r, small r and at when it will be finished, we can assume that it is formed a volume of sphere with equal to radius equal to capital R.

All those things are shown here and this is the hw, and this is to analyzed we are taking at any at any height h, we are taking a small thickness del dh and when a particular operation h max is the head suppose, and this is the injection, the one needle is having r naught radius and at a particular time, after some time it become a radius, a sphere equal to, of sphere of radius equal to capital R. with these we will try to establish certain things and based on some assumption.

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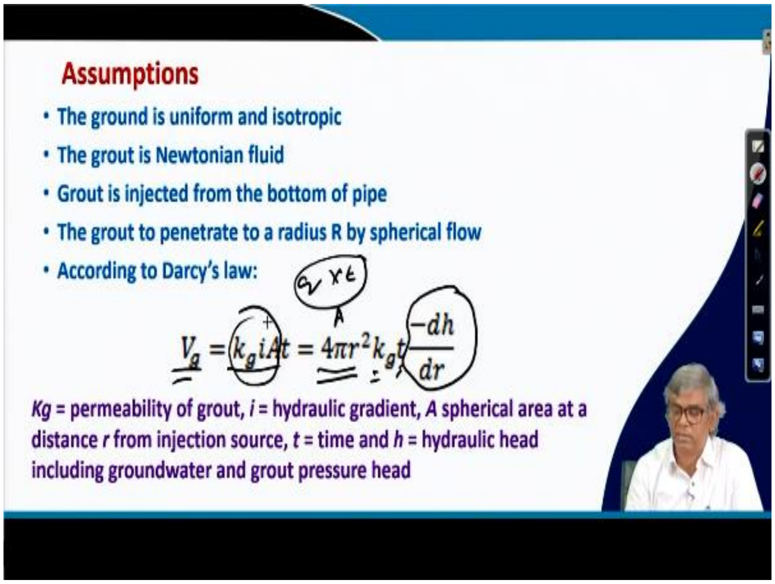

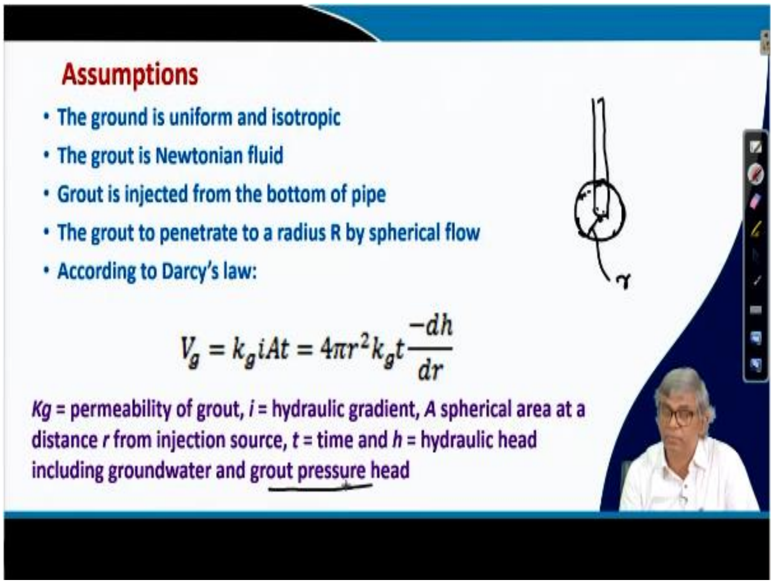

Let us see first those assumption and then try to correlate, so here our assumptions are the ground is uniform and isotropic, this is whenever we do any soil mechanics analysis, every time we need to assume this of course, it is not necessary or not possible, it is not like that, it is not possible to if the soil is not uniform or soil is not isotropic nothing can be done, it can be done but things will be complicated and in fact in the higher level that can be taken.

For the time being we are taking uniform soil and isotropic soil, uniform isotropic ground and grout is Newtonian fluid, Newtonian fluid means there are some properties that this grout material will follow those properties, whether it will follow or not that is immaterial, for the time being we are assuming that it is a Newtonian fluid that these are the in fact most of the characteristics may not follow here, but we are assuming to establish at least a roughly something.

$$V_g = k_g iAt = 4\pi r^2 k_g t \frac{-dh}{dr}$$

$$k_g = permeability\ of\ grout$$

$$i = hydraulic\ gradiet$$

$$A = spherical\ area\ at\ a\ distance\ r\ from\ injection\ source$$

$$t = time$$

$$h = hyraulic\ head\ including\ groundwater\ and\ grout\ pressure\ head$$

Then grout is injected from the bottom of a pipe, so this is very important so whatever previous diagram I have shown the grout injection pipe will be there and it could have been over a number of holes can be kept and then it would be injected, then of course, injection velocity will be less and all you know it will become ineffective, sometime permeation is possible but otherwise it is not effective.

We are assuming that is from a very small opening at the bottom of the injection point it is getting injected and the grout to penetrate to a radius R by spherical flow. That means we are assuming that through that opening it will form a sphere of radius R, the capital R, is a spherical flow that means when it will come out from the opening it will move in all direction, so that it will form a sphere.

And according to Darcy’s law if we apply since Newtonian flow although the flow through soil we know we effectively use Darcy’s law and if this is Darcy's law then Vg volume of grout will be k i t, k i A is the small cube discharge and discharge multiple time quantity and which is nothing but volume.

So this is as per your Darcy’s law V, volume of grout can be k grout, that means permeability of grout I, that mean gradient multiplied by A area, surface area through which it is going and t is the time over which it is passing and then you know that at any point so we have considered, we have considered at a radial distance r and that time height is, head is h and then at radius r the volume of surface area of the sphere through which it is permeating is 4pi r square.

So surface area of the sphere is 4pi r square, so A is substituted, this is nothing but A and kg is kept, t is kept unchanged and i actually minus dh dr, so this is the hydraulic gradient minus dh dr. And so that means this is the fundamental equation we could get that volume of grout will be equal to 4pi r square kg t minus dh by dr, so this is the equation and now this equation can be, we can try to solve.

So let us go to the next one and you can see here each and everything is explained here, whatever parameters we have used here kg is the permeability of grout, i is the hydraulic gradient, A is the spherical area at a distance r, we from injection source. We can go back to the previous, you know it is not going, anyway suppose, if you have this is the one and this is the injection point and at a this is the one actually, this is the small r.

So the A spherical surface area this is spherical surface area, spherical area at a distance r from injection source, this at a distance r, t is the time and h is the hydraulic head including ground water and grout pressure head, this together.

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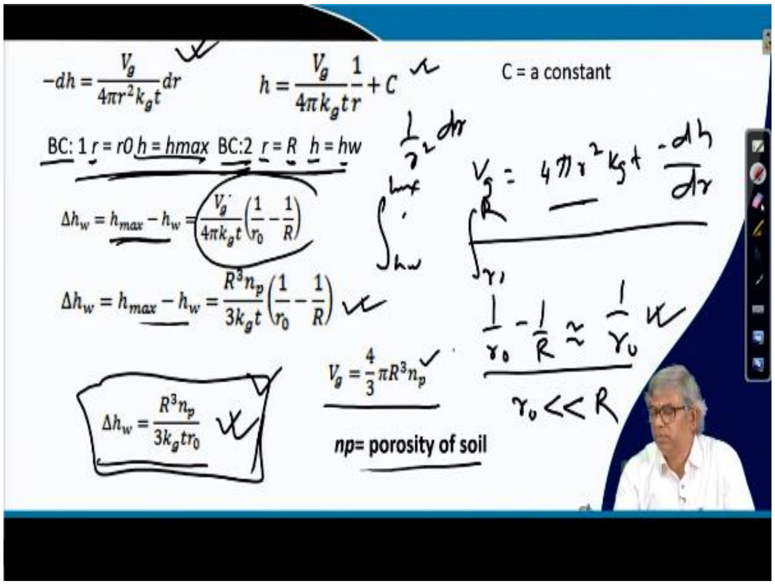

So now with these let us move next one and you can see here that you can, the previous equation which one we have already done, which is actually Vg equal to 4pi r square kg t minus dh dr this is the equation was there previous page, and we can see, you can take minus dh and then it will be Vg dr, Vg dr 4pi square kg, so this is from this equation I can write this and now I can integrate both sides.

So, h function and r is a function, h can be integrated then it will be h will become h and r will become dr, so you can see by integration you can get this. So this is 1 by r square dr, so 1 by r square dr actually integration I can do then I will get 1 by r and I can get one constant, so this to solve this constant generally we can apply boundary condition, so the boundary condition one are actually when r actually r naught that means opening radius, h equal to h max and boundary condition two when r become capital R then h become hw suppose, and that means what I can do?

$$-dh = \frac{V_g}{4\pi r^2 k_g t} dr \quad h = \frac{V_g}{4\pi r^2 k_g t}\frac{1}{r} + c \;\; c = a \text{ constant}$$

$$\text{BC=1} \;\; r = r_0 \;\; h = h_{\max}$$

$$BC = 2 \;\; r = R \;\; h = h_w$$

$$\Delta h_w = h_{\max} - h_w = \frac{V_g}{4\pi r^2 k_g t}\left(\frac{1}{r_0} - \frac{1}{R}\right)$$

$$\Delta h_w = h_{\max} - h_w = \frac{R^3 n_p}{3k_g t}\left(\frac{1}{r_0} - \frac{1}{R}\right)$$

$$\Delta h_w = \frac{R^3 n_p}{3k_g t r_0}$$

$$V_g = \frac{4}{3}\pi R^3 n_p \;\; n_p = porosity\ of\ the\ soil$$

$$V_g = \frac{4}{3}\pi r^2 k_g t \frac{-dh}{dr}$$

$$\frac{1}{r_0} - \frac{1}{R} \approx \frac{1}{r_0}$$

$$r_0 << R$$

$$\frac{1}{r^2} dr$$

I can integrate h, not h, h equal to hw to h max and r actually r naught two capital R, so that is nothing but that actually. In this equation if I apply two boundary condition then I will get h max minus hw which is nothing but delta h which is shown in the figure, delta hw is nothing but the h max minus hw, so which is shown in the figure itself and if I apply this boundary condition I can get this from this I get this one and from this side I can get this equation.

So that means h max minus hw or delta h equal to this expression and so del hw this again I can Vg can be substituted, Vg means volume of grout is actually volume of sphere, so 4 by 3pi R cube is the volume of sphere but entire volume is not occupied by the grout, there is a soil, so that can be how much then grout if I multiply by np which is nothing but porosity of the soil, if you multiply the porosity then volume of grout you can get within the radius there.

within the sphere of radius r how much grout is there that can be obtained 4 by 3pi R cube np. So, if I substitute Vg by this expression then this can be simplified R cube np 3kg t 1 by r naught minus 1 by r. Now compared to small r capital R is quite large and 1 by r naught minus 1 by r can be approximately 1 by r naught minus 1 by r can be approximated at 1 by r naught, because r naught is very, very smaller than capital R.

If I do this then this equation can be this delta h can be approximated, the R cube np by 3kg t r naught, this is the one relationship or how much head to be applied to get this some relationship we have got how to apply this one, we will discuss separately under design consideration there how this equation will be used that time we will discuss.

Otherwise for the time being what we have assumed that through a pipe the grout is injected through a small opening and that through opening when grout is coming out it is forming the spherical way, it is injected spherical way, that means it is all direction is moving and if it happens and some assumption like soil is homogeneous and isotropic and grout is that Newtonian fluid.

Then we can write some fundamentally from Darcy’s law some equation and that equation again further simplify and then apply this boundary condition then we can get finally with some this as approximation, we can get this equation. So this is the one of the important thing which we are getting and this can be seen later on in the design guidelines, how this equation can be used or with some modification it will be used that I will show you that the latter stage.

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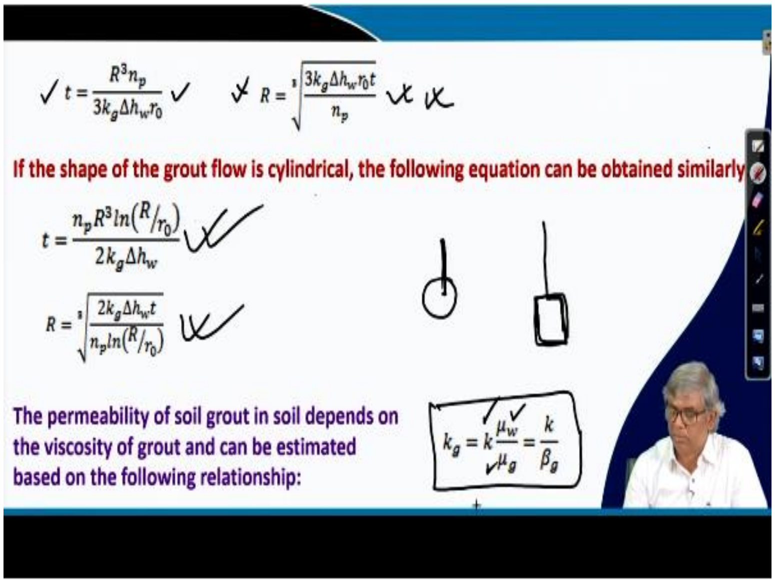

So this is actually the one part, so that means whatever equation we got then sometime we may require t time, how much time is required so that can be converted in this form, t can be obtained by this expression or sometime we may require what is the area of influence or radius r up to which it will go, then I can from this again I can find out this equation. So suppose, I am grouting over this much time, with this much opening, this much head difference everything is known, porosity is this much then up to what area or what radius this grout will be effective.

So that sometime we may require to find out R, sometime suppose I want to make radius R and then the porosity is known, permeability is known, head difference is known, opening size also injection point is known, then how long I have to do to reach radius R, so sometime t is required.

So like that this equation, same equation can be modified different according to the requirement, so this is previously delta h given an expression in terms of parameters, again t can be given in terms of this parameter, R can be expressed in this term, number of parameters, so this is depending upon your requirement it can be utilized.

Now, if the shape of the grout flow is cylindrical, so what we have assumed that when through this pipe when grout is coming out it is going spherically but another thing is suppose when it is grouted and then it is form a cylindrical, it is forming that means it is moving in such a way which is difficult but assume that it is cylindrical, in that case the same equation will be modified, this can be again done from the first principle, all those thing and then ultimately t can be obtained like this and R can be obtained like this. This equation is for spherical grout flow and this equation applicable when cylindrical grout flow, that means if I inject grout, so that it is form the cylinder, then this equation will be applicable. The permeability of soil grout in soil depends on the velocity of grout and can be estimated, from this is the equation kg can be obtained, the k permeability of soil and mu viscosity of water, viscosity of grout, so this is the way it can be obtained.

$$t = \frac{R^3 n_p}{3k_g \Delta h_w \gamma_0} \qquad R = \sqrt{\frac{3k_g \Delta h_w \gamma_0 t}{n_p}}$$

If the shape of the grout flow is cylindrical, the following equation can be obtained similarly

$$t = \frac{n_p R^3 \ln\left(\frac{R}{\gamma_0}\right)}{2k_g \Delta h_w}$$

$$R = \sqrt[3]{\frac{2k_g \Delta h_w t}{n_p \ln\left(\frac{R}{\gamma_0}\right)}}$$

The permeability of soil grout in soil depends on the viscosity of grout and can be estimated based on the following relationship

$$k_g = k\frac{\mu_w}{\mu_g} = \frac{k}{\beta_g}$$

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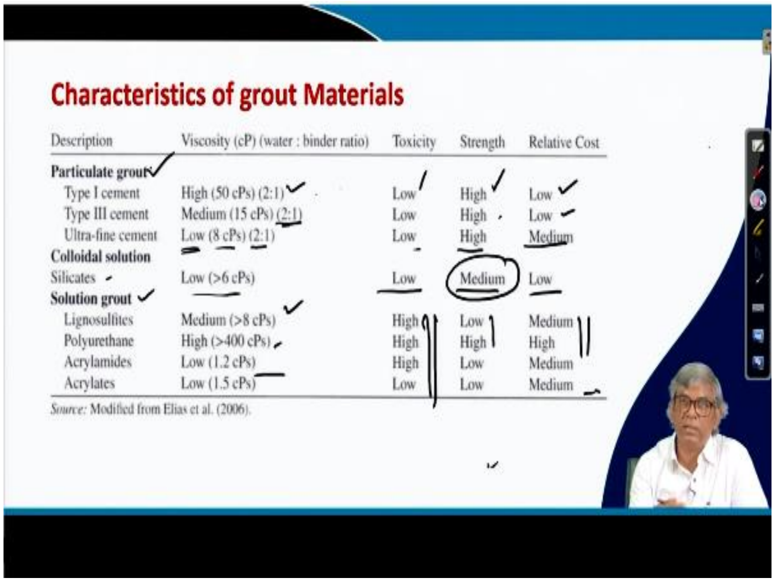

Next, characteristics of grout material as we have mentioned, the k is required because in the equation itself and you can see particulate grout, there are different types of particular ground, again type one cement, high viscosity 50 centipoise and water a binder ratio two is to one, and toxicity is low, strength is high and relative cost is low, when cost is important and no other things are important then this can be used.

Similarly, type three cement, it is medium viscosity 15 centipoise and again the ratio two is to one and toxicity low, strength is high and relative cost also low so almost these two categories almost similar. Ultra fine cement again it is low viscosity, 8 centipoise and it has again ratio is two is to one, the toxicity is low, strength is high and relative cost is little higher, medium actually, that is also it can be seen.

Colloidal solution, this is particulate grout and colloidal solution like silicates it will have low viscosity, it is less than 6 centipoise and so viscosity is low it is beneficial to inject and it is having low toxicity, strength is medium, you can see that you are sacrificing strength here, cost is low which is many a times when suppose you want to use as a barrier then strength is not that much required, so we can go for this.

Then solution grout you can see, Ligosulphites then there is a Polyurethane, Acrylamides and Acrylates and you can see this is medium viscosity less than 8 centipoise, this one is high viscosity is more than 400 centipoise and this is again low, 1.2 centipoise and this is again low 1.5 and you can see here everywhere toxic they are all highly toxic material, mostly except this one and they are strength is generally low except this one Polyurethane and the cost is medium to high.

In some area where some requirement it may be required, you can use Acrylates you can see toxicity is low, strength is low, cost is medium. This is when you will be selecting that particular grout, then you have to see the characteristics somewhere, toxicity is a problem then you have to eliminate those who are toxicity high.

Somewhere you have strength is the requirement then we have to see something where we can get the good strength, somewhere we may require high viscosity, low viscosity or high viscosity accordingly you can choose. There are number of things are given here this table can be referred and can be chosen depending upon your requirement.

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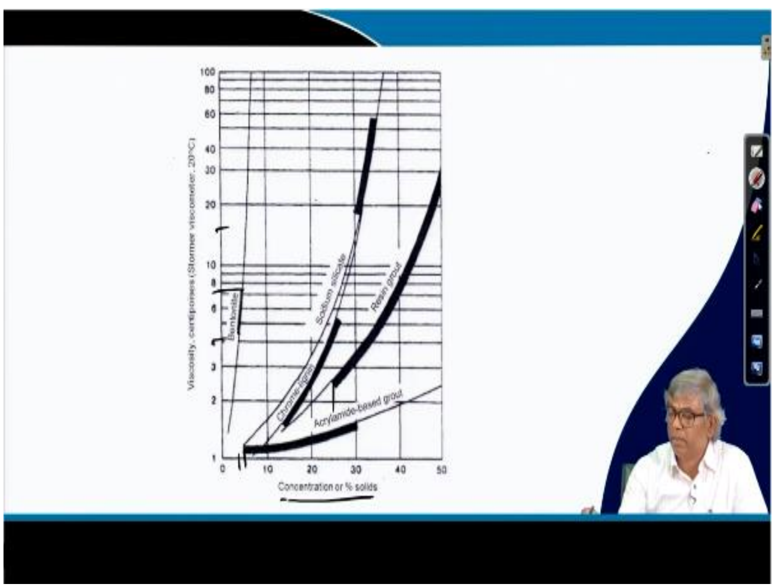

And this is you can see viscosity centipoise in this at 20degree centigrade and concentration or percent of solid and you can see 10 percent, 20 to 30 percent, then there are this axis percentage and this axis viscosity and you can see bentonite and generally use range of use from here to here, this is the range, that means we use the viscosity range is this and again what is the range of the concentration also fixed for this.

Similarly, sodium silicate this is the range of viscosity and we can from here you can find out range of the percentage or concentration similarly, chrome lignin then this is a range of viscosity and again you can see the range of proportion is quite wide. Similarly, for resin grout you can see the range of proportion we can have a quite wide and similarly we can have quite wide range of viscosity and when acrylamide-based grout you can see, you can have wide range of mix but with limited viscosity, range is quite low.

o again by seeing this figure whatever the requirement based on that the grout, particular route can be chosen.

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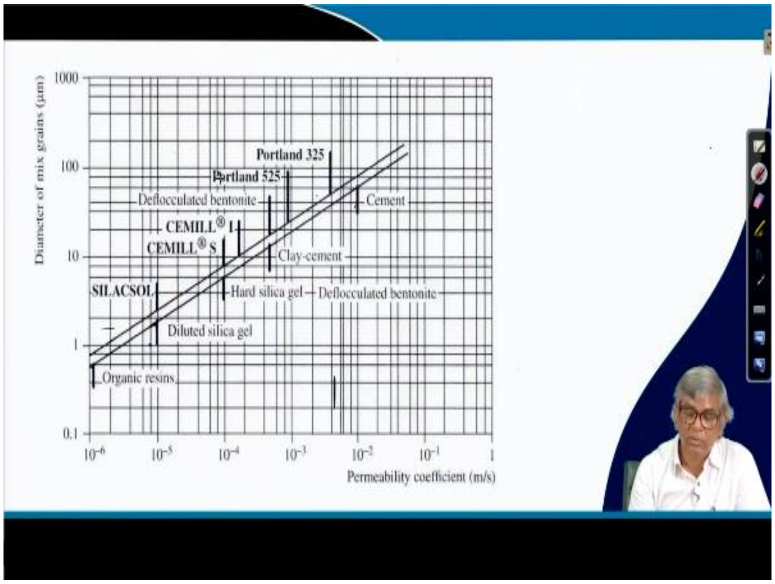

Again, this is again another figure where it is shown, you can see the permeability range and this side diameter of mix grain. Diameter of the particles that you can see here that there are organic resins, the range of particles from here to here quite small and you can see the permeability range close to 10 to the power minus 6.

Then again, a diluted silica gel you can see the diameter of this range and it is close to 10 to the power minus 5 is the permeability and again hard silica gel it has size of the particles little bigger and permeability is less low, at 10 to the minus power 4, like that there are different materials, and their particles are diameter of mix grains and their permeability range is given, so depending upon your requirements.

So groutability etcetera, whatever we have mentioned that I will show later on again that diameter is important there, this is again another, guidelines can be used.

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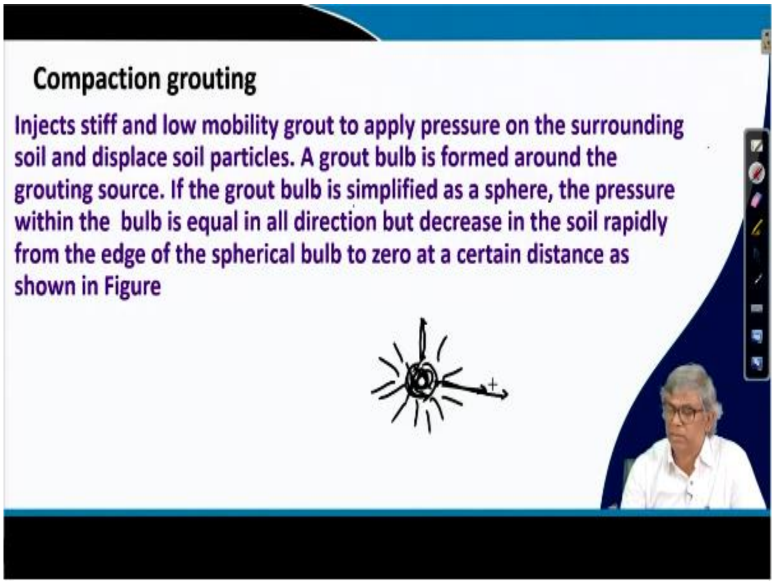

Now the compaction grouting, in these injects stiff low mobility grout, that means it will not move, it will stay, remain in place. stiff that the comparative stiff and low mobility grout to apply pressure on the surrounding soil and displace soil particles, you can imagine, if you imagine this is the one and through this open grout is coming, so slowly all-around soil but because of this pressure it will displace the soil and it will form some volume and that means this soil will be solid or densified or displaced.

The grout bulb is formed, this is the grout bulb around the grouting source, this is the grouting, this is the grouting source, this is the grouting source and if the grout bulb is simplified as a sphere, the pressure within the bulb is equal in all direction but decreases in the soil rapidly from the edge of the spherical bulb to 0 at the certain distance.

If this is the bulb and then from here, from here to here it will be decreasing, so that is what will try to see that one in the next slide. The grout bulb is simplified as a sphere, the pressure within the bulb is equal in all direction, pressure within this bulb, within this bulb is equal in all direction, pressure within this bulb is equal in all direction like this and but decreases in the soil.

That means beyond this, this is the soil decreases in the soil rapidly from the edge of the spherical bulb, so here whatever pressure is there in the bulb same pressure and it will be decreasing towards this and at some distance will become zero, so that is what it is the it is mentioned, so let us see that in the next slide.

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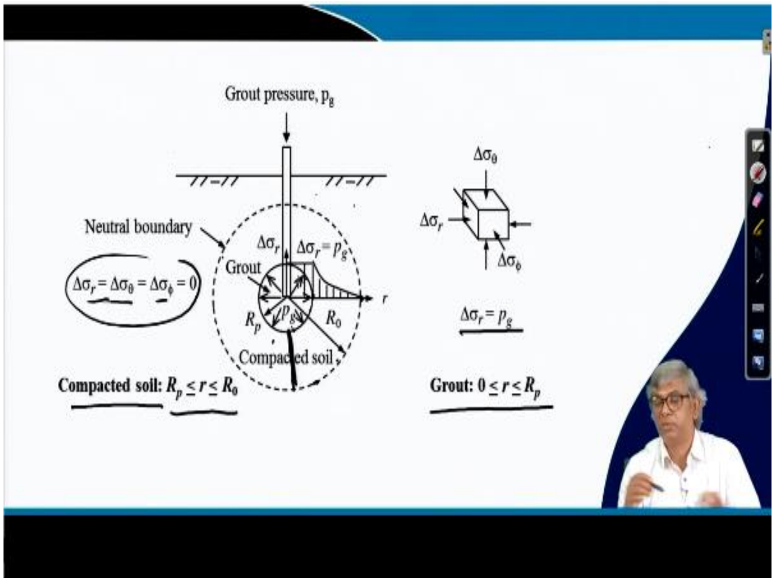

So you can see here, so this is the suppose bulb, the grout bulb is formed and as it is indicated that is giving all direction same pressure that is p grout pg and you can see here that pressure distribution you can see at the surface of this grout, at the surface of this ground is equal to sigma r pressure pg that the grout pressure and you can see it is decreasing and at this point it is becoming 0.

$$\Delta\sigma_r = \Delta\sigma_\theta = \Delta\sigma_\phi = 0$$
$$\Delta\sigma_r = p_g$$

$$Compacted\ soil = R_p \le r \le R_0$$
$$Grout: 0 \le r \le R_p$$

So that is the thing wanted to say and you see for grout from 0 to r actually at Rp, this is actually is Rp the radius Rp, so the sigma r equal to rho g between this and sigma r, sigma theta, delta sigma, delta sigma, delta sigma equal to zero at this surface and compacted soil in this that is r equal to Rp to R naught. when it is a compacted soil this within this compacted soil it is compacted soil will be between Rp to R naught, so this is R naught and this is Rp, this is R naught and this is Rp.

This zone, the zone between R naught to Rp is the compacted soil and this is the grout and at this surface this is the pressure and at this point delta sigma are actually pg at this point. This is one observation based on this whatever we have explanation we have given the previous slide. Next one when there is this type of pressure is applied within the soil then there will be strain, so how what will happen to those the soil strain.

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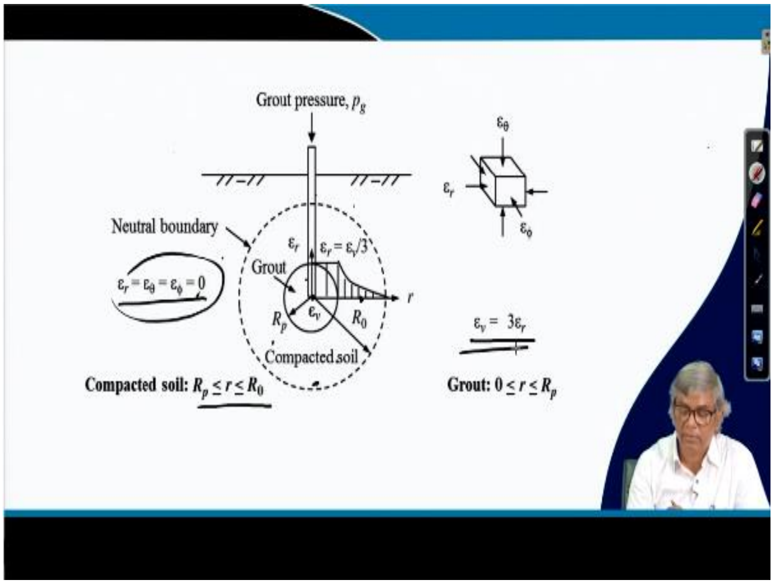

Let us see in this you can see here that strain also similarly it will be maximum strain will be at this point and there will be 0 strain here, you can see here at this point neutral boundary, that means no strain and the compacted soil will be between Rp to R naught and the soil grout will 0 to Rp is the grout and here epsilon v can be three times epsilon r. So this can be established.

$$\varepsilon_r = \varepsilon_\theta = \varepsilon_\phi = 0$$
$$\varepsilon_v = 3\varepsilon_r$$
$$Compacted\ soil = R_p \le r \le R_0$$
$$Grout : 0 \le r \le R_p$$

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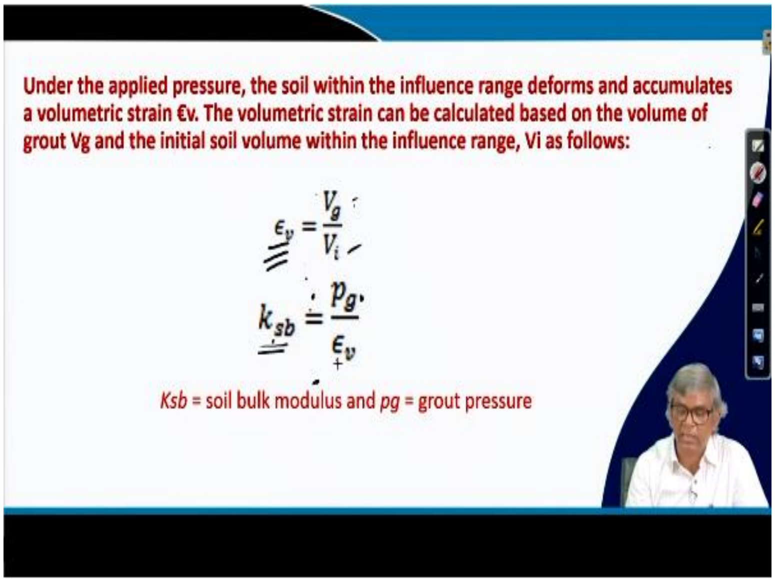

Let us see in the next slide and you can see that under the applied pressure the soil within the influence range deforms obviously and accumulates a volumetric strain epsilon v. that as I have mentioned, so volumetric strain will be there and that volumetric strain can be expressed like this epsilon v will be equal to Vg by Vi, how much Vg we have given that is because the volume change because of that it entered an original volume and k sb actually sub modulus will be pg by epsilon v, so these two.

$$\varepsilon_v = \frac{V_g}{V_i}$$

$$k_{sb} = \frac{p_g}{\varepsilon_v}$$

$$k_{sb} = soil\ bulk \text{ modulus and } p_g = grout\ pressure$$

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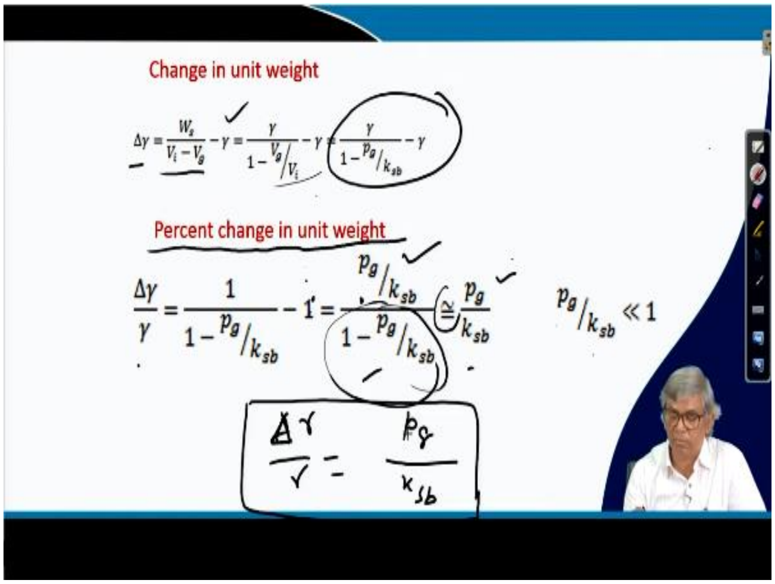

And then when it happens then you can, what is the improvement by change of unit weight you can find out, so change in unit weight will happen delta gamma will be Ws by Vi minus Vg minus gamma W, this you can write in this form, Vi minus Vg this was the actually original volume, Ws by this and minus gamma, this is the change in the unit weight and if I can simplify then it will become like this and ultimately it will become like this, so 1 minus Vg by Vi, Vg by Vi pg by k sb so this is the expression again.

Now if I want to express percent change in unit weight that means delta gamma by gamma then it will become this minus 1, ultimately, I can get this by this and this can be simplified and it can be pg by k sb, why it is pg by k sb? pg by k sb which will is much, much smaller than 1, this quantity if it is a very small compared to 1, I can ignore so this part will become 1, and ultimately delta gamma by gamma can be expressed. delta gamma by gamma can be expressed by that will be grout pressure divided by modulus of sub grade modulus, coefficient of sub grade modulus k sb, that means the change in percent change of unit weight can be expressed that coefficient of sub grade modulus and the pressure of grout by that, so this is the final expression.

Change in unit weight

$$\Delta\gamma = \frac{W_s}{V_i - V_g} - \gamma = \frac{\gamma}{1 - V_g/V_i} - \gamma = \frac{\gamma}{1 - \frac{p_g}{k_{sb}}} - \gamma$$

Percentage change in unit weight

$$\frac{\Delta\gamma}{\gamma} = \frac{1}{1 - \frac{p_g}{k_{sb}}} - 1 = \frac{\frac{p_g}{k_{sb}}}{1 - \frac{p_g}{k_{sb}}} \cong \frac{p_g}{k_{sb}} \quad \frac{p_g}{k_{sb}} << 1$$

$$\frac{\Delta\gamma}{\gamma} = \frac{p_g}{k_{sb}}$$

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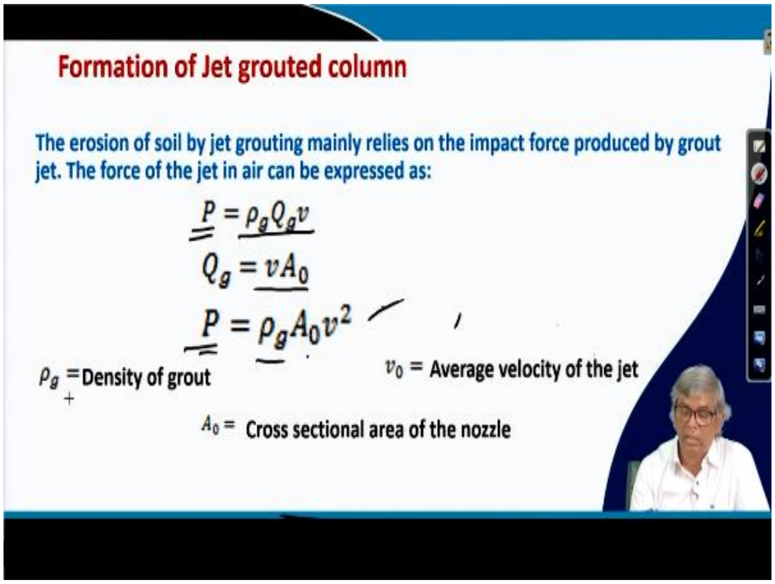

And formation of jet grouted column, when jet grout you do then the column will form and that column related to pressure P, the erosion of soil by jet grouting mainly relies on the impact forces produced by grout jet. The force of the jet air can be expressed, this is the force can be expressed by this equation rhog Q_g multiplied by v.

$$P = \rho_g Q_g v$$
$$Q_g = vA_0$$
$$P = \rho_g A_0 v^2$$
$$\rho_g = Density\ of\ grout$$
$$v_0 = Average\ velocity\ of\ the\ jet$$
$$A_0 = Cross\ sectional\ area\ of\ the\ nozzle$$

This is the expression, Q_g will be v multiplied by A naught, ultimately force will be rho g A naught v square, that means square of velocity, important, the velocity is important here and with this, with this observation some of the things will be done, maybe I will try to take it in the next class.

With this let me close here and this is some of the fundamentals, assumption based on assumption we try to relate the pressure, velocity, quantity and all and maybe some more will see and then ultimately in the design guidelines how this formulation can be used that we will discuss and then I will take one design also, design application and with this the grouting aspect can be completed, with this today I will close here, thank you.