Ground Improvement

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Lecture 40

Grouting (Contd.)

Hello everyone, once again let me welcome you all to this ground improvement lecture class, and today we are in grouting chapter and already I have taken a few lectures about application, suitability and then some background theory and I have already mentioned that I will try to discuss about that design criteria, the ultimately the design say in a particular area based on ground condition.

If it is decided to ground improvement technique to be applied, to improve the ground or make it suitable then we have to choose first method, suppose in a particular area your grouting is chosen as one of the ground improvement techniques and in that if it is done. Then again simultaneously you have to do some certain things like what quantity of grouting is required, at what depth it will be required, then many other things like what is the spacing, what will be the pattern.

Like that so many other things are there that is that can be considered as a design criteria, that means when you execute in the site how will you proceed and what are the requirements, so those things will be discussed one by one and then immediately after that we will try to discuss one problem, all aspect will not be able to discuss because of the complexity of the problem. Only a few aspects how to compute we will just try to show, so that will come to that part I will discuss in the next lecture but for the time being I will try to concentrate on the design criteria for grouting.

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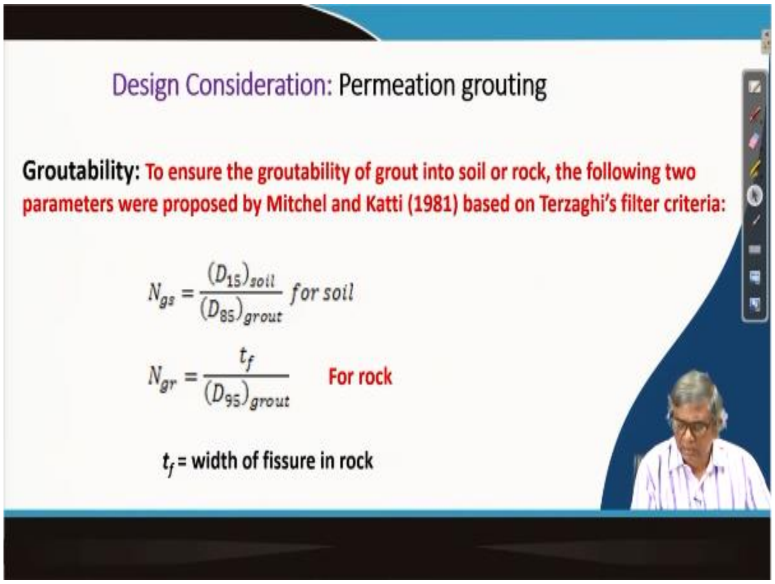

First one as this is already I have defined the groutability, that means first of all there can be there are number of grout materials available so and depending upon soil type you have to choose based on groutability condition, so groutability is defined by D15 of soil divided by D85 of grout, and so this number, this will give you some number and when it is a rock, when this is applied for rock, this groutability number will become tf by D95 grout.

So tf actually width of fissure in the rock, so when we grout in the rock generally the grouting will be entering through the fissure, so that fissure width will be considered to calculate the groutability in rock, and whereas groutability in soil it will be D15 soil by D85 grout, what is D15? The diameter percent, 15 percent fine particle at 15 percent fine particle, so that is the definition of soil mechanics you know that and so if you have a grain size distribution of the curve from there we can find out D15. Similarly, grain size distribution curve of grout if you know from there you can find out D85.

$$N_{gs} = \frac{(D_{15})_{soil}}{(D_{85})_{grout}} \ for\ soil$$

$$N_{gr} = \frac{t_f}{(D_{95})_{grout}} \ for\ soil$$

$$t_f = width\ of\ fissure\ in\ rock$$

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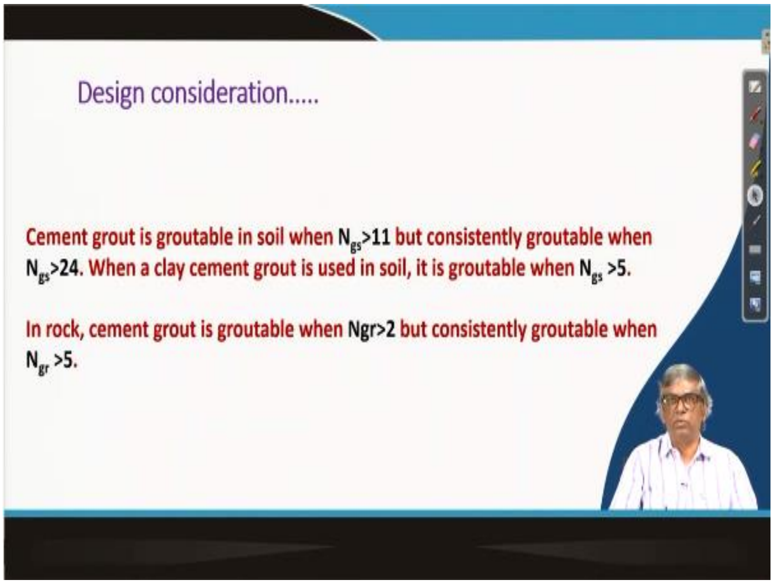

So this number once you get then the criteria is cement grout is groutable in soil when Ngs is greater than 11, so if it is greater than 11 it is groutable, but it may not be that consistent, so to make it consistently groutable the number supposed to be greater than 24, so greater than 11 means we can use but if it is greater than 24 then it is better. So consistently grotable when Ngs greater than 24.

And when clay cement grout clay, clay cement grout is used in soil then the groutable, it will be groutable when Ngs greater than 5, so that is the criteria for soil. Similarly, in rock the cement grout is groutable when Ngr greater than 2 but consistently groutable when it is greater than 5. So, you first calculate the number and based on that number you decide whether it is groutable or not.

So you can choose accordingly the soil cannot be changed, soil at a site particular site, soil or rock is cannot be changed but you can change the grout material so based on that you have to find out the number and if that number does not give you satisfactory result that means this can it cannot be effectively used and should not be used.

cement grout is groutable in soil when $N_{gs} > 11$ but consistently groutable when $N_{gs} > 24$.
when a clay cement grout is used in soil,it is groutable when $N_{gs} > 5$.
In rock,cement grout is groutable when $N_{gr} > 2$ but consistently groutbale when$N_{gr} > 5$.

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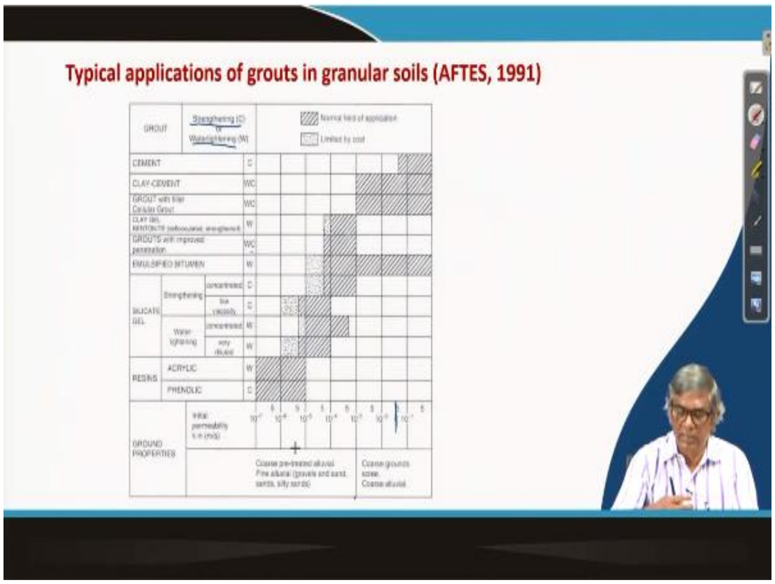

So, next part you can see here there are number of things given in the tabular form, grout can be used or different types of use already I have mentioned, one is to stop seepage, that means and another is strength, to increase the strength. So here grout can be classified in two part, strengthening purpose if it is used that is C is noted and water tightening that means seepage control then W, only W.

And you can see that the grout when it is C, when it is cement and when it is a strength purpose used and then you have to have permeability of ground, of the ground permeability of ground should be in the range of something 10 to the power, it will be is coarse soil, when this grout cement is used and particularly for strength purpose then permeability of the soil should be very high, it is a coarse soil it will be applicable.

Similarly, if it is a clay cement to use and if it is a water tightening, clay cement generally used in the water tightening purpose, sorry, both water tightening plus strength both purposes clay cement can be used and that you can see the permeability range for the soil 10 to the minus 3 to this value, 10 to the minus 1 then it will be 1, it will be in meter per second.

Similarly, grout with filler cellular grout, again it can be water tightening, it can be of strength and that time also same the permeability range is same and clay gel bentonite it can be used for water tightening and if it is used then permeability range should be 10 to the minus 4 to 10 to the minus 3 and sometime less than that permeability also some limited use is there by this dotted box.

Similarly, grout with improve penetration that is can be used both water tightening and strength purpose, there also permeability range of the soil is same and then emulsified bitumen generally used for water tightening purpose and the range of permeability of the soil is required from you can say 10 to the minus 4 to 1 so this is the wide range and some limited application is there lesser than that permeability also.

Similarly, silicate gel again strengthening and water tightening, there are two group, that again strength, concentrated and low viscosity, so there are both are for strength purpose and for their what is the permeability range that is also here its mentioned, then silicate gel again water tightening purpose also can be used, it can be used again concentrated form, it can be also very diluted form and this is used for water tightening purpose and what is the permeability range that is also given there.

So these are guidelines you can use it for selecting the particular materials, there are number of materials, number of purposes we use. Similarly, resin you can acrylic resin and phenolic both are there. Acrylic is used for water tightening and phenolic is used for strength, and what is their range of permeability that can be, you can see here 10 to the minus 7 to 10 to the minus, very fine soil it will be useful. So this is another in the tabular form the groutability you can find out but again you can what is the purpose and what is the permeability range based on that again one can choose the grout material.

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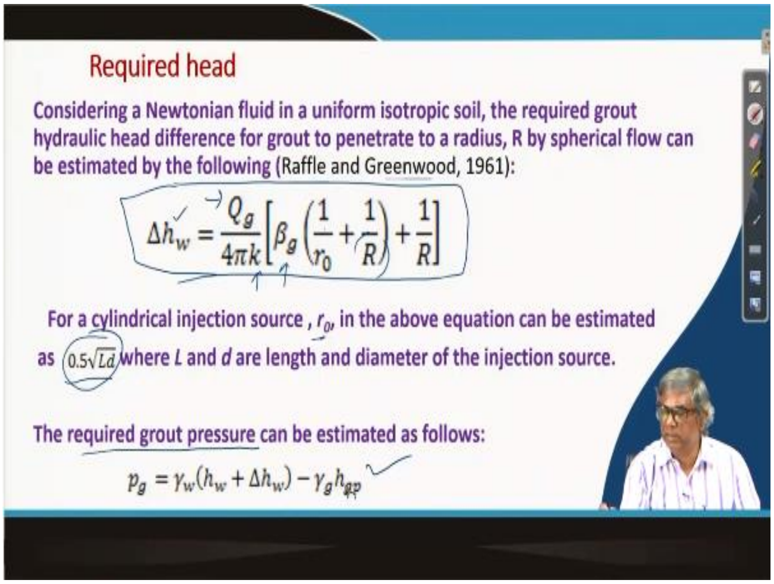

Here then required head, already we have discussed that to grout you need to apply some head and considering Newtonian fluid a uniform isotropic soil, the required grout hydraulic head difference for grout to penetrate to a radius R by a spherical flow that equation as per Raffle and Greenwood is given by this. we have derived similar type of equation almost but it is slightly modified, this is the one is used that delta hw there is a quantity of grout and this is the permeability of the soil, these are constant already we have mentioned, this is injection point radius from which injection is taken place and this is the penetration radius.

Considering a Newtonian fluid in a uniform isotropic soil, the required grout hydraulic head difference for grout to penetrate to a radius,R by spherical flow can be estimated by the following(Raffle and Greenwood,1961):

$$\Delta h_w = \frac{Q_g}{4\pi k}\left[\beta_g\left(\frac{1}{r_0}+\frac{1}{R}\right)+\frac{1}{R}\right]$$

For a cylindrical injection source,r_0, in the above equation can be estimated as $0.5\sqrt{Ld}$ where L and d are length and diameter of the injection source.

The required groout pressure can be estimated as follows:

$$p_g = \gamma_w\left(h_w + \Delta h_w\right) - \gamma_w h_{gp}$$

Once you are injecting then the spherical shape actually it be permeate and then what is the radius of that, so this is the equation by using the delta hw that hydraulic head difference can be calculated and for a cylindrical injection source that r naught can be calculated by another like 0.5 under root L by Ld and L and d are the length and diameter of the injection source.

Injection when you are doing a point injection that is from a spherical and when it is a cylindrical injection, we want to make then there must be some length and some diameter, so then only it will be cylindrical it is possible, that is also same equation can be used if it is cylindrical then equivalent R can be obtained by this equation from this equation.

And then required grout pressure can be estimated again, required grout pressure can be estimated again from this equation and you can whatever parameters are here once again I will explain once again what though already some of them, I mentioned gamma w is the unit of water, hw is the water table height from the grout source, del hw is what is calculated here h gp from the ground water table to the actual top point.

So, let me, which one I have already shown in one of the derivation, once again I will explain this one by one.

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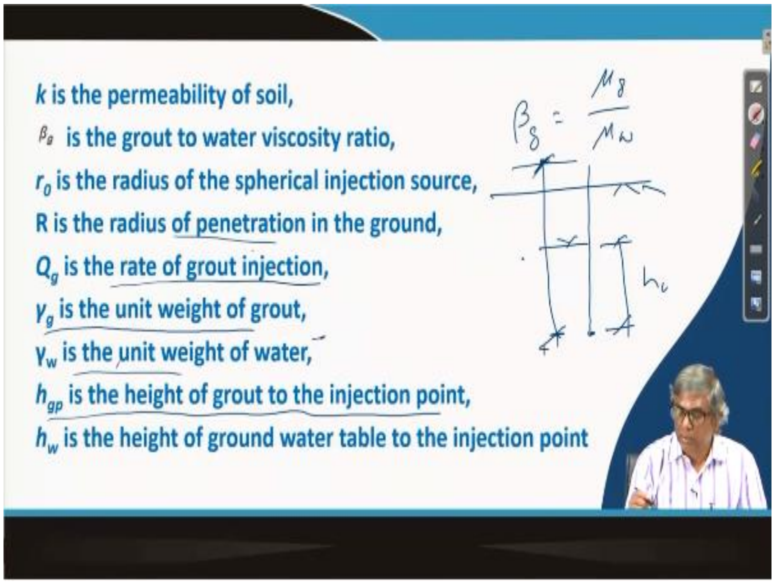

You can see here is all are listed here k is the permeability of the soil, beta g is the grout to water viscosity ratio, so grout to water that means it is beta g this is already also I have, mu g by mu w this is we have mentioned, then r naught is the radius of the spherical injection source, so that injection source that from a particular point injection is that radius is r naught and R is the radius of penetration.

Then finally what the spherical volume it is permitting that is the R, Qg is the rate of grout injection, what is the per hour or per minute what is the amount we are injecting, gamma g is the unit weight of the ground, gamma w is unit of water, h gp is the height of grout to the injection point, h gp is the height of the grout to the injection point.

$$\beta_\delta = \frac{\mu_g}{\mu_w}$$

k is the permeability of the soil
β_g is the grout to water viscosity ratio
r_0 is the radius of the spherical injection source
R is the radius of penetration in the ground
Q_g is the rate of grout injection
γ_g is the unit weight of the grout
γ_w is the unit weight of the water
h_{gp} is the height of the grout to the injection point
h_w is the height of ground water table to the injection point

So, that means if you have the injection point somewhere here, ground water table somewhere here, and your grout started from here so h gp is this, total height is the h gp and hw is the height of groundwater table to the injection point, so hw, this is hw and ground may be somewhere here and grout head started from here, so this total distance is h gp. So these are all different terminology can be used in calculation.

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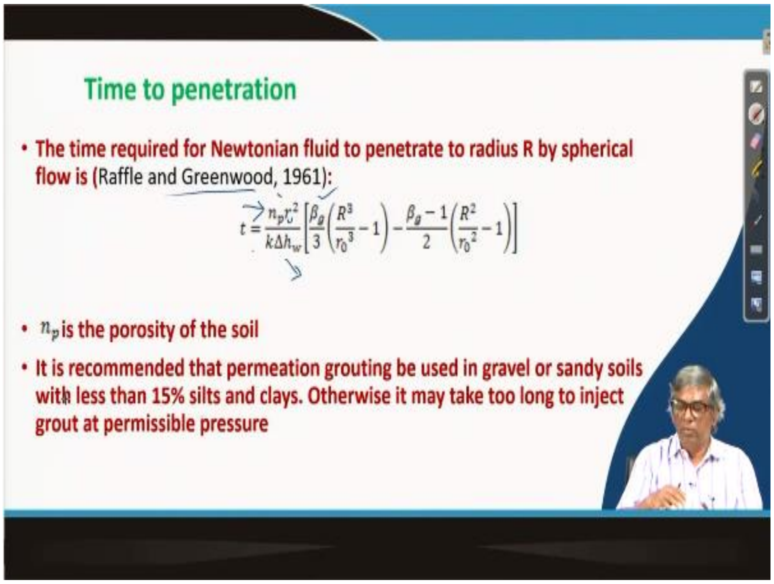

And let me, then time of penetration, so if you want to make a particular radius and particular rate of grout you are putting, so for that time can be calculated, time required for Newtonian fluid to penetrate to radius R by spherical flow and that is also again given Raffle and Greenwood and you can see that np is the porosity of the soil, R is the radius and then k is the permeability, del hw is your head difference, beta g is the viscosity ratio, R is the spherical radius and this must be r naught and then this is r naught and nothing else is known all are known quantity, so this R must be r naught, np is the porosity.

The time required for Newtonian fluid too penetrate to radius R by spherical flow is(Raffle and Greenwood,1961):

$$t=\frac{n_p r_0^2}{k\Delta h_w}\left[\frac{\beta_g}{3}\left(\frac{R^3}{r_0^3}\right)-\frac{\beta_g-1}{2}\left(\frac{R^2}{r_0^2}-1\right)\right]$$

n_p is the porosity of the soil

And it is recommended that permeation grouting be used in gravel or sandy soils, so permeation means only there is no pressure and pressure may be there, head will be there but not additional pressure. Under that is just gravity flow, gravity flow it will be entering if the void space is large then all it will happen, if the void space is very small the permeation grouting will not be effective.

Because of that is recommended that a sand and gravel only permeation grouting can be there and with maximum that means less than 15 percent silt and clay, if it is more than that again it will be affected otherwise it may take too long time because the fine particles are there, the movement will be automatically very slow and it will take longer time, so that is what if permeation grout is used that is the recommendation that only for gravel and sand to be used.

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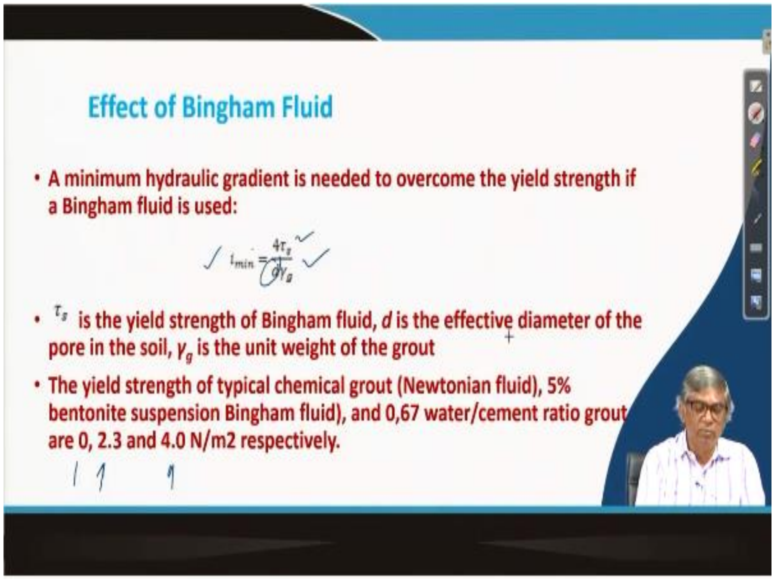

And then effect of Bingham fluid, you can see that when the Newtonian fluid we are assuming but when you are mixing something that is a Bingham fluid and then to make the flow then there should be minimum hydraulic gradient to be maintained and that i minimum is given by 4 tau s by d gamma g and here in a Newtonian fluid or grout, Newtonian fluid yield strength tau s is actually zero.

A minimum hydraulic gradient is needed to overcome the yield strength if a Bingham fluid is used:

$$t_{\min} = \frac{4\tau_s}{d\gamma_g}$$

τ_s is the yield strength of Bingham fluid,

d is the effective diameter of the pore in the soil

γ_g is the unit weight of the grout

The yield strength of typical chemical grout (Newtonian fluid),5% bentonite suspension Bingham fluid), and 0.67 water/cement ratio grout are 0,2.3, and 4.0N/m^2 respectively

And whereas when a Bingham fluid there will be a tau s, yield strength will be the tau s, tau s is the yield strength of Bingham fluid and d is the effective diameter of the pore in the soil and gamma is the unit weight of the grout. So by this one can find out minimum hydraulic gradient to make the flow when Bingham fluid is used, whereas if Newtonian fluid is there that shear strength is not there, so yield strength is not there.

So, that equation will not be involved. Now here is given some example that how it is, the yield strength of typical chemical grout, chemical grout is a Newtonian fluid and it and 5 percent betanioid suspension Bingham fluid, so 5 percent bentonite suspension fluid that is a one of the Bingham fluid, another Bingham fluid 0.67 water cement ratio grout that is another Bingham plight, Bingham fluid.

And if these three top fluids if I consider, the Newtonian fluid as I already have mentioned yield strength is zero whereas if it is a bentonite, 5 percent bentonite fluid that yield strength is 2.3 and 0.67 water seven ratio that cement grout, that there actually you have yield strength equal to 4.

So that means when you are using different materials you are getting some yield strength because of that if there is a yield strength then penetration will be resisted and because of that you need to maintain some hydraulic gradient to make the flow or to cause the flow, so that is what this is the equation can be used and whereas in this d is the effective diameter, effective diameter of the pore fluid.

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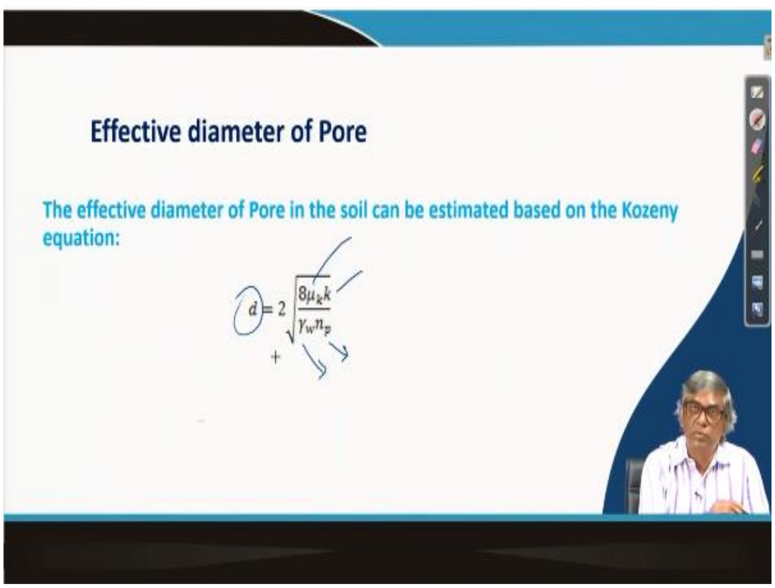

And next, so the effective diameter are Kozeny equation there is a permeability, the equation given by Kozeny, it is given effective diameter can be estimated by this mu k is the viscosity and k is the permeability, gamma w, np is the porosity, if we know all those parameters then we can find out the effective diameter of the soil and that can be used to find out the i minimum.

The effective diameter of pore in the soil can be estimated based on the kozeny equation

$$d = \sqrt[2]{\frac{8\mu_k k}{\gamma_w n_p}}$$

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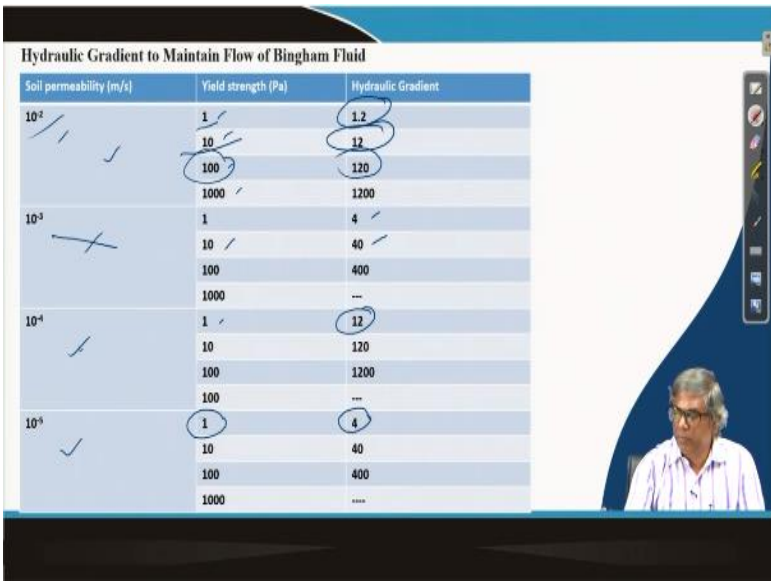

Soil permeability (m/s)	Yield strength (Pa)	Hydraulic Gradient
10^{-2}	1	1.2
	10	12
	100	120
	1000	1200
10^{-3}	1	4
	10	40
	100	400
	1000	---
10^{-4}	1	12
	10	120
	100	1200
	100	---
10^{-5}	1	4
	10	40
	100	400
	1000	----

And you can see here that depending upon soil permeability is 10 to the minus 2, 10 to the minus 3, 10 to the minus 4, 10 to the minus 5, it can happen different soil, these are towards sand and when you are going towards this is a clay silt and if you see yield strength if it is 1, 10, 100 or 1000 then that the hydraulic grain to be maintained to make Bingham fluid to flow that if it permeability is 10 to the power minus 2 and yield strength is 1 then we require hydraulic gradient 1.2.

Similarly, permeability is 10 to the power minus 2 and your yield strength is 10 then you require a hydraulic gradient of 12. Similarly if the 10 to the minus 2 and yield strength is 100 then you require a hydraulic gradient is 120. So like that similarly if you have a permeability of 10 to the minus 3 and yield strength of the Bingham fluid is 1 then you require a hydraulic gradient of 4, 10 to the minus 3 is the permeability and yield strength is 4.

Then you require to maintain the flow by Bingham fluid that requirement is 40 hydraulic gradient, like that if it is 10 to the minus 4, then you can see the yield strength is 1 then you require to Bingham fluid to maintain flow that hydraulic getting is 12. Similarly, if it is a 10 to the minus 5 is the permeability of the soil and yield strength of the Bingham fluid is 1 to cause flow that required minimum hydraulic gradient is 4.

So like that you can see the different requirement is there and based on that one can maintain that in the calculation while executing the grouting and then accordingly it has to be maintained, if it is less than that it will not work, if it is more than that only then only flow will be maintained. So this is the minimum, so if you cannot create more than that then it will not be effective that is what it is the summary of this table.

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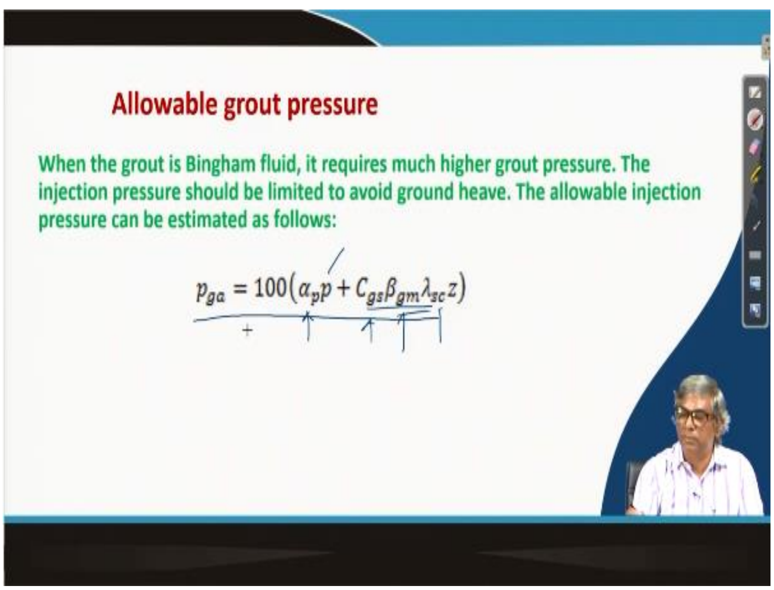

So next is allowable grout pressure, this is another thing is based on calculation, suppose to maintain flow you may arrive at some pressure quite large but if the pressure exceeds by certain value then the soil will start fracturing and flowing also, a lot of other problems, so because of that there will be allowable grout pressure that has to be also calculated and whatever pressure we are applied it should be less than that.

when the grout is Bingham fluid, it requires much higher grout pressure.The injection pressure should be limited to avoid ground heave. The allowable injection pressure can be estimated as follows:

$$p_{ga} = 100(\alpha_p p + c_{gs}\beta_{gm}\lambda_{sc} z)$$

So p ga is given equation for Bingham fluid, that equation is given, that equation is given by p ga that is allowable grout pressure 100 multiplied by alpha p into p C gs beta gm alpha, these three are constant are factors, this is also one factor, if there is a surcharge is there, then that surcharge pressure to be calculated and correspondingly alpha p to be used and alpha p value also there is a range given.

Similarly, p has to be calculated, C gs also it is a grouting sequence factor that means whether it is a primary grouting, secondary grouting or tertiary routing accordingly there is a factor to be used. Similarly, beta gm, that means it is some factor then this is lambda sc is the soil characteristics factor, so all three there are recommended value when you try to do particular operation according to the requirement you have to pick up those values and you have to apply. So once again I will explain what are those factor and what is the recommended values in the next slide.

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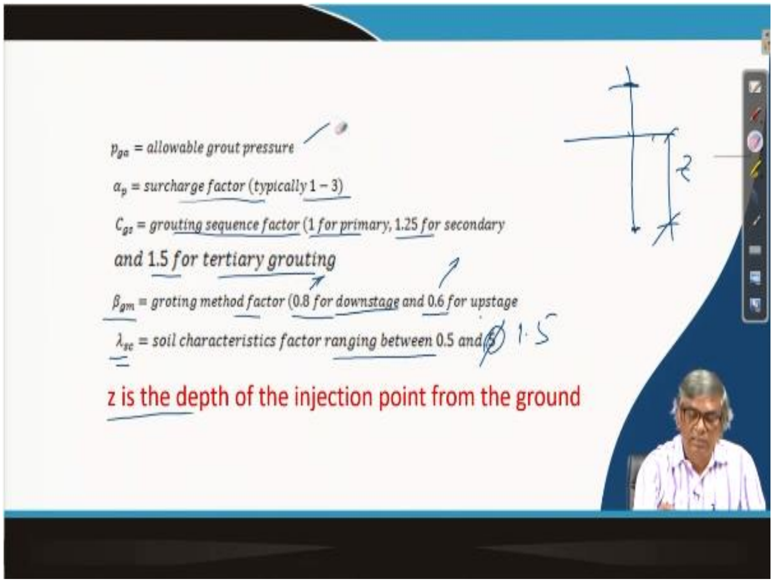

You can see this all are listed here you can see p ga is the allowable grout pressure and alpha p is the surcharge factor, typically 1 to 3, so one value can be range between 1 and 3, so typically it can be taken 1.5 to 2.5, C gs is a grouting sequence factor and if it is 1 for primary 1.25 for secondary and 1.5 for tertiary grouting, so there can be what is primary, what is secondary, what is tertiary again we will discuss later on.

But so for the time being I am telling you the operation is primary, the factor will be 1 that C gs and if it is a secondary then factor C gs will be 1.25 and if it is a tertiary grouting then the factor C gs will be taken as 1.5. And beta gm is a grouting method factor, the grouting method factor means it is a down stage and up stage, if 0.8 value can be taken for down stage grouting activity and 0.6 for off stage grouting activity.

So, these 2 beta gm value also 2 values are there because 2 different types of grouting method is used, so depending upon that either 0.8 or 0.6 can be used for beta gm. Similarly, lambda sc this is again another soil characteristics factor and that is range between 0.5 to it will be not 0.5, this will be wrong I think it is 1.5, this is 0.5 to 1.5, so this is typo error.

$p_{ga} = 100\left(\alpha_p p + c_{gs}\beta_{gm}\lambda_{sc} z\right)$

$p_{ga} =$ allowable grout pressure

$\alpha_p =$ surcharge factor(typically 1-3)

$c_{gs} =$ grouting sequence factor(1 fooor primary,1.25 for secondary and 1.5 for tertiary grouting

$\beta_{gm} =$ grouting method factor (0.8 for downstage and 0.6 for upstage)

$\lambda_{sc} =$ soil characteristics factor ranging between 0.5 and 1.5

z is the depth of the injection point from the ground

So lambda sc will be soil characteristics factor ranging between 0.5 to 1.5 and z is the depth of the injection point from the ground, so that means if the ground and injection point is here, so this is the suppose the pipe, so grout head is there but injection point to z from the ground this distance will be taken as z, so these are the things recommended here and while designing it can be taken according to this given recorded value, only thing note down this is not 0.5 it is 1.5.

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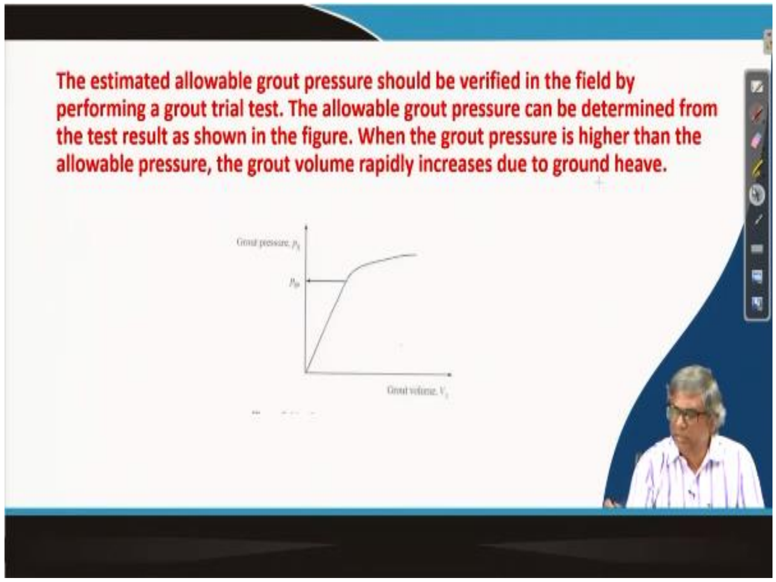

And then when the estimated allowable grout pressure by theoretical equation we can get but this can be also verified by trial and while doing trial this is the mechanism by which one can find out that grout volume versus grout pressure, this can be obtained and typically you can get a curve like this, when you get the end of the straight portion actually can be taken as P ga, so you can see estimated allowable grout pressure should be verified in the field by performing a grout trial test.

The allowable grout pressure can be determined from the test result as shown in the figure that is the one and when the grout pressure is higher than the allowable pressure the grout volume rapidly increase due to the ground heave. So that heaving will be so that is not proper so because of that you have to whatever value you get from the calculation by trial test you have to do that, if this value is less, if you estimate quite high but less then you may apply more pressure.

And that if you apply more pressure than this, it will when the grout pressure is higher than the allowable pressure the grout volume rapidly increase due to ground heave, so that means your estimation, you have estimated a value quite large but actually it is much lower and accordingly you have given grout pressure you are applying but that grout pressure is much higher than the allowable pressure in that case heaving will be there, so that will not be desired, so this is the way one can verify.

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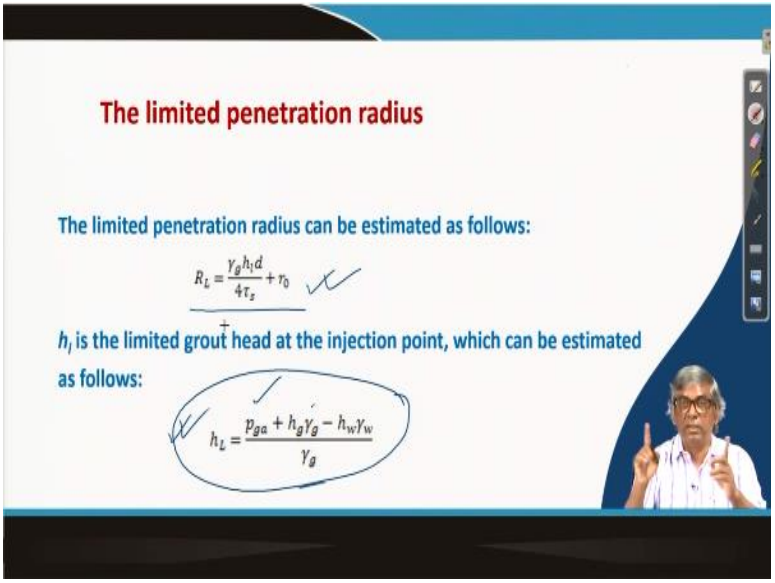

And then the limited penetration radius, so this is can be again can be obtained by the limited penetration radius, can be estimated by this equation where Rl limited radius where gamma g is the unit weight of your grout, then hl is the limited grout head, d is the effective diameter and tau s is the yield strength and from this equation one can find out.

And then this hl is the limited grout head again can be estimated by this equation where P ga allowable grout pressure plus hg gamma g minus hw divided by gamma g, so this is the way one can find out hl and then I can find out what is the radius we can get.

The limited penetration radius can be estimated as follows:

$$R_L = \frac{\gamma_g h_l d}{4\tau_s} + r_0$$

h_l is the limited groout head at the injection point, which can be estimated as follows

$$h_L = \frac{p_{ga} + h_g\gamma_g - h_w\gamma_w}{\gamma_g}$$

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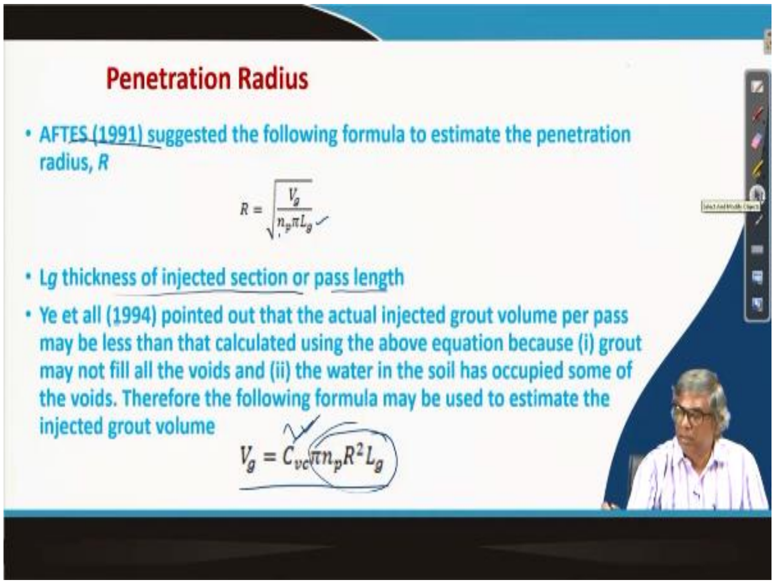

And then penetration radius sometime to be estimate sometime it is required so how much, you can get in on a particular operation accordingly you have to find out the spacing, so R can be can be calculated based on this volume of grout divided by porosity Lg, Lg is the thickness of the injection section or pass length, so that is the given data will be there and then once again this whatever Vg we get this person Ye et all pointed out that injected grout volume per pass may be less than that calculated using the equation.

And so reason is the grout may not fill all the voids, so it may pass but leaving some void and that is one thing and there may be water in the soil and that which may occupy some volume, so because of that is a misleading and so to correct that Vg, so therefore following formula that equation given here this equation Vg is equal to C vc pi np R square Lg, that means this is actual volume but again we can apply a correction factor C vc. So this one actually by a table for different condition, the value of cv is given the next one.

AFTES (1991) suggested the following formula to estimate the penetration radius,R

$$R=\sqrt{\frac{V_g}{n_p \pi L_g}}$$

L_g thickness of injected section or pass length

$$V_g = c_{vc} \pi n_p R^2 L_g$$

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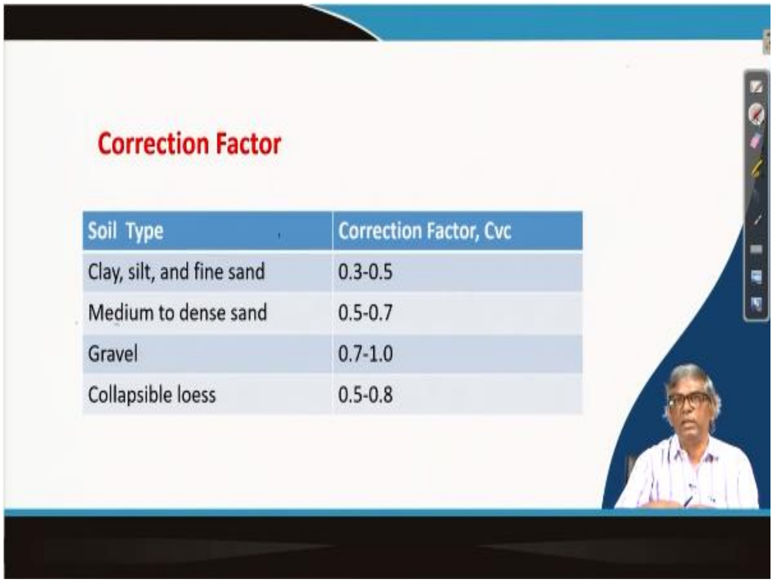

So you can see here the value of cv clay, silt and fine sand the correction factor C vc will be 0.3 to 0.5 but designer can choose any appropriate value. Similarly, medium to dense sand it will be 0.5 to 0.7 and gravel 0.7 to 1 and collapsible loess it will be 0.5 to 0.8, so this is the C vc so by and large while designing whatever calculation is required one after one I have listed, may be one or two aspect is still pending.

That what will be the spacing and what will be the rows, whether its number of one or two or three, multiple rows or single row or even if it is a multiple row or single row what is the spacing, so this one only one aspect is not covered yet, so I will discuss this one in the next one and simultaneously I will try to use one example to illustrate this problem whatever we have discussed so far, thank you I will close here.