Environmental Geotechnics
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Lecture – 35
Contaminant transport through porous media – 4

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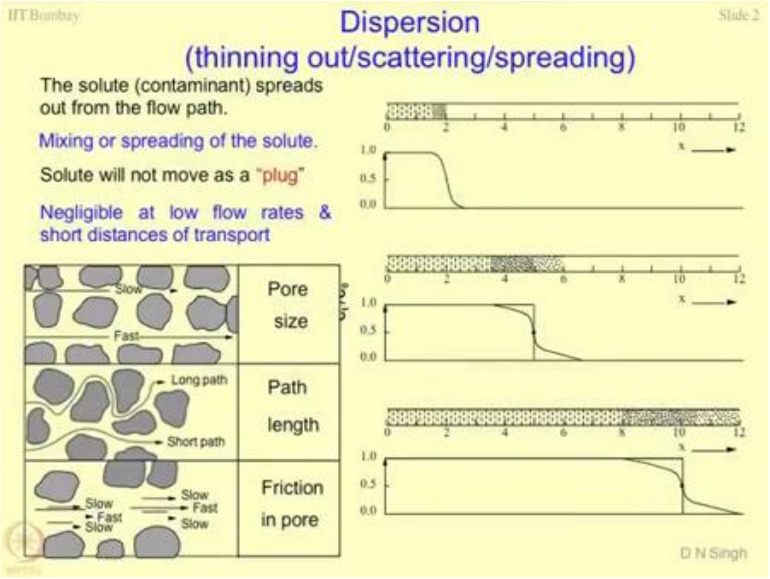

Dispersion
(thinning out/scattering/spreading)

The solute (contaminant) spreads out from the flow path.

Mixing or spreading of the solute.

Solute will not move as a "plug"

Negligible at low flow rates & short distances of transport

The third mechanism of contaminant transport is dispersion. It is also the dictionary meaning of word dispersion is something which disappears or thins out, scattering or spreading. So, you can say spreading of contaminants is dispersion phenomena alright. Now, if you consider this figure, what you notice in the first part of the figure is that there is a flow shown as the positive values or dotted lines, and followed by a concentration dose over here ok.

So, this is the plug of concentration which is flowing along with a flow stream. Now, what I have plotted here is on the y-axis C_t/C_0 there is concentration of contaminants at a given time and normalized with initial concentration c naught as a function of spatial variation that is the distance. So, what you notice is that at x equal to 0, C_t/C_0 is 1, and then dispersion starts taking place after certain distance, and then by the time you reach some value of x the C_t dies down completely, that means, this a complete dispersion of the contaminant in the flow stream.

Similarly, as the front increases or moves further, you can see now dispersion taking place in the much more control volume. And then after certain time or after certain distance, the dispersion predominates. So, the flow is taking place at the same time dispersion is also taking place.

So, let us now consider the issues which cause dispersion to occur in the porous system. So, this diagram basically shows the contaminant or the pollute spreading out from the flow path. So, this is the flow path, and then there is a concentration which keeps on dispersing, flowing out, disappearing and so on. The mechanism which governs these processes mixing or spreading of the solute. So, in day to day life, when you add sugar to a cup of tea, you need not to stir it that could also be a way is it not, but then you have to wait for how many hours when the entire cup of tea become sweet. So, what do you do?

Stir it.

You stir it. What is the meaning of that? You are accelerating the dispersion phenomena this becomes a sort of a mechanical mixing, so that is the fourth mechanism of contaminant transport, where mechanical dispersion comes into the picture. So, this is somewhere in between diffusion and mechanical dispersion alright. So, when you encounter a situation where mixing or spreading of solute takes place, this is what is termed as simple dispersion phenomena.

I am sure during your undergraduate courses when you are studying environmental engineering, you must have come across a mechanism which can be classified as a dispersion mechanism. Can you name it? Dispersion is you have a chimney or a stack, and from the stack the few gases are going into the environment, and then air is also flowing at a certain velocity. So, what happens to the plume? This plume gets dispersed from the point of origin to a certain point and there the concentration is almost negligible. So, it is a good example of dispersion in air. But because we are talking about geoenvironmental engineering our aim is to understand dispersion in geomaterials that to in geoenvironment clear, where you have porous media and the fluid in the form of water table.

So, you think of a situation where pollutants are being discharged in the geoenvironment and dispersion phenomena takes over. So, in simplest possible form as we studied here, if mixing or spreading of contaminant is taking place is a simple dispersion process. The only difference between the stack emitting the gases in air and contaminants being disposed in geoenvironment would be; did you follow the question? The basic difference between stack emitting pollutants in the air and the pollutants getting discharged in the geoenvironment would be, the media itself first of all, there you have very rare media air, here you have a media which has certain properties.

So, first of all the difference in the media, second thing is flow velocities. If flow velocities are much more in air as compared to the flow velocity is even in ground water, clear. So, these are the two attributes we got change and the mechanisms getting completely changed, is this part clear? So, when you say mixing or spreading of the solute, what becomes important? The flow velocity of the medium or the carrier becomes much more important, clear.

The attribute is you will not have any plug formation here. What happens to the plug? If you remember in the previous lecture you are talking about the plug moving from one point to another point to another point without showing any significant physical distortion to itself and that was the mechanism of advection or convection clear.

But here what is going to happen if you consider this plug; what is happened to the plug? The plug had got physically distorted. So, this is the difference between advection and dispersion phenomena. Another good example is most of your colleagues who are working in hydrogeology or maybe in hydraulic structures analysis, they must be talking about you know jet flow in a reservoir. So, think of a situation like BMC, Bombay Municipal Corporation where the entire sludge is going to be disposed of in the sea. So, you have a water column of the sea, and then there is a pipe which is disposing of the entire waste into the sea, clear.

So, the pipe interface when it comes in contact with the water column of the sea, this is where the dispersion is going to take place. If dispersion does not take place, the intensity of the contaminants will always remain very, very high. So, we have talked about three situations. One is dispersion in air which is very rare, rare in the sense density wise; the second is dispersion in geoenvironment whether attributes of the material are totally different and the velocities are totally different. And third is the situation dispersion taking place in a water body clear. So, ultimately what happens is there is a physical deformation or distortion to the contaminant plug which takes place in dispersion mechanism.

Now, another attribute is the concentration is going to be negligible at flow rates which are very low, and short distance of transport dispersion phenomena. But when you talk about the micromechanics that what is causing this to happen, this is where this type of model become very important. So, what you will notice is, if you want to model dispersion phenomena in a geomaterial, we have to take into account three things.

The first one is sizes of the pores. And this is where I think you will appreciate the point that why pore size analysis becomes much more important than particle size analysis. If you remember when you had come to the to my lab, I had told you that, nowadays, we do not talk about particle size distribution much, we are more interested in knowing how pores are interconnected, how pores are communicating with each other, whether they are dead end pores, whether they are well connected pores, whether pores are saturated or partially saturated, what type of capillary tubes are existing and so on.

So, this is where pore size analysis becomes very important. The second attribute is path length; what type of path lengths are being covered by the solute or the contaminants. And third one is the friction within the pores itself, alright. So, these three attributes become very important.

Now, let us understand what is the influence of the pore size. I hope you will appreciate this point if the inter spacing between the pores is too much the flow velocity is going to be fast clear. Now, you can imagine it like this, a fast flow path getting mix, with a slow path what is going to happen. There is a velocity contrast within the pores and hence dispersion is going to get actuated. If the velocities were same, dispersion would not have occurred, it would have been advection. But because there is a contrast in the velocity of the porous media because of different pore sizes which are available in the system, the dispersion is going to get actuated is this part clear.

The second model to consider would be path length. The chances are the contaminant or the solute may follow this path, clear, or it may follow this path. So, there could be a short path there could be a long path again this is going to lead to the velocity of flow. Whenever there is a contrast in the velocity of the flow, the dispersion phenomena will dominant, friction in the pores. Do you find this type of situations somewhere in civil engineering which you might have analyzed much more in details, where?

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Very good flow in a.

(Refer Time: 10:37) open channel.

Never, never, in open channel, it has to be in conduits and pipes.

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No, no please. This type of situation occurs as you rightly said this is the peculiarity of a conduit or a pipe flow, clear. What is the property, why do you define friction coefficient what is the friction coefficient which we use in pipe flow?

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What is the name of the friction coefficient, Manning's.

Manning's

C parameter. So, what is the significance of this? The significance is if you draw a velocity profile within the pores, again what you will notice is the central portion has a higher velocity as compared to the velocities on the edges. So, these types of models help you in understanding what typed this.

(Refer Time: 11:37) rugosity.

Rugosity, that is right, correct. Manning's is basically this is Manning's equation is used normally for open channel flow, but the equivalent is C parameter which is for chess is constant, so that can be used for your pipe flows. So, here what happens is the friction between the grains is always less in the central portion as compared to the friction which is very close to the grains. So, this is the micro mechanics model which is normally used to understand dispersion, and the modeling of the dispersion alright. I hope you will agree with the point that our job is more challenging as compared to the flow taking place through a conduit or even the open channel, because here we have to deal with something which is quite stochastic and probabilistic and nondeterministic. So, that is why this becomes a challenging task.

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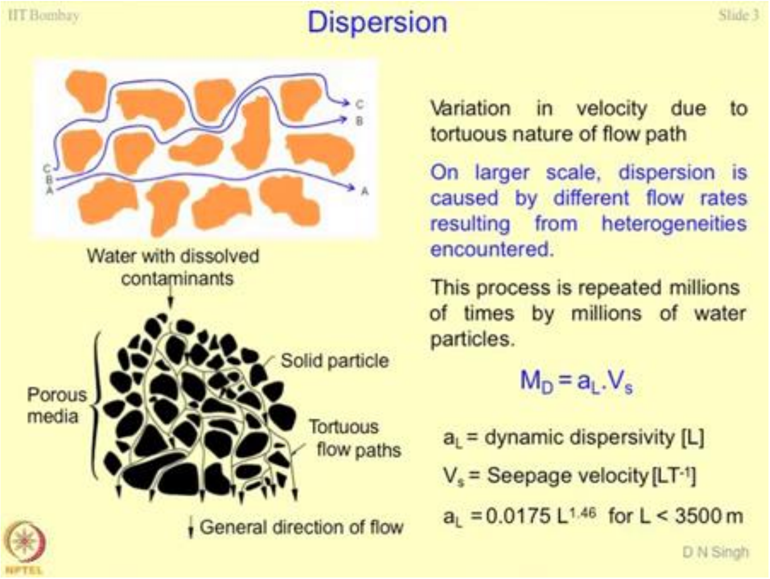

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Slide 3

Dispersion

Variation in velocity due to tortuous nature of flow path

On larger scale, dispersion is caused by different flow rates resulting from heterogeneities encountered.

This process is repeated millions of times by millions of water particles.

$$M_D = a_L.V_s$$

a_L = dynamic dispersivity [L]

V_s = Seepage velocity $[LT^{-1}]$

$a_L = 0.0175\ L^{1.46}$ for $L < 3500$ m

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Now, if you magnify this model, let us say the solute has different opportunities to travel from one end to another end. One is solute may adopt a path a to a, it may adopt the path b to b, and it may adopt a path c to c. Now, this is where the concept of tortuosity comes into the picture. If you draw a straight line from this point to this point that is the length of the sample, physical length of the sample, but the tortuous structure of the soil or the pores allows the effective length of the flow path much higher than the physical length.

So, that means, what is the root cause of dispersion, the root cause of dispersion is flow path and which can be quantified in the form of tortuosity factor, clear, that is one of the reasons when you talk about seepage analysis that tortuosity factor is not much taken into account. It is normally assuming to be some constant value.

But when you are talking about the contaminant transport dispersion mechanisms, all those parameters become quite significant. Just wait a minute here. And if you try to understand one more mechanism which may be going on simultaneously, if flow path is more, the time taken is much more, what is the literal meaning of this, contaminant get more time to interact with the porous media. So, this is where the interaction is starting, is this part clear? So, the interaction is going to start when you talk about the flow of the contaminants in the porous structure, and their enough time for contaminants to interact with it, alright.

In today's lecture, after two-three slides, I will introduce the concept of sorption and followed by desorption. Now, this point is the genesis of sorption, is this clear. So, the biggest challenge is how to quantify all these mechanisms, and that is where you require some parameters which are nothing but quantification of a mechanism, the way you have define consolidation by using C_v. So, what is C_v basically, C_v is nothing, but coefficient of consolidation how much consolidation is taking place can be define mathematically if you use parameter C_v.

Now, if I ask you a question, how much dispersion is going to take place? You need a parameter to define either the inter pore structure or the connectivity of the pores or the frictions which is acting on the contaminant flow because of the edges of the pores or because of the micro mechanism which is going on between the contaminants and the pore structure. So, the basic idea is if you want to quantify all these terms processes, you just require some mathematical terms.

So, we will be talking about now mathematical terms which will define a mechanism of contaminant transport. So, let us go much more into the complexities of the pore structure. If there is no dissolved contaminants in water is a simple case of seepage alright. And you always assume till now that the porous structure is inactive, water is also inactive. So, you talked about only seepage flow. When you complicate it a bit, your porous structure is active, contaminants are also active. What is going to happen is going to get guided by all these mechanisms put together. This is where we use a word retardation factor.

Now, what is the meaning of word retardation? Something wants to move, but porous media is trying to retard its motion. Why it is so, because it has affinity towards contaminants. You got this point? Now, why this affinity coming, either the system is hyper or active or the contaminants are hyper or active, any one of them being passive this type of situation will never arrive, that means, retardation will never take place in systems which are passive. So, then the question is whether retardation is a good mechanism for engineers or not?

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It is. So, nature is trying to retard the flow of contaminants from one point to another point. And this is the fundamental property of the porous media contaminant interaction. So, let us consider this bit more. This is how the porous media is being depicted. You have solid particles, they could be semisolid also, they could be porous, they could be whatever. Then you have lot of tortuous flows which is taking place and then there is some general flow direction of the; this is nothing but the discharge, and this part is nothing but the seepage.

So, you think of a system where seepage velocities are predominant as compared with discharged velocities. What is going to happen this type of systems, dispersion is going to be much more, what is significance of this. As compared to sands, dispersion should be less or more in clays?

More in clays.

No, less, because you remember flow is going to take place. So, flow, yes that is right. Jain you goofed up see the more flow is taking place the chances of flow contrast within the porous media are much higher in sands as compared to clays. Clays are going to show you pure diffusive contaminant transport, because there is no advection taking place, alright ok. So, basically the way we define dispersion phenomena is nothing but variation in the velocity due to tortuous nature of flow path.

On larger scale, dispersion is caused by different flow rates resulting from heterogeneities which are encountered in the porous media. Now, let me ask you one more question. When you say heterogeneities encountered, what is the significance of this in what form these heterogeneities are getting implicated in your analysis, in other words these heterogeneities correspond to what, this is material heterogeneity? Yes. Is this the flow behaviour heterogeneity?

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Yes, all sorts of heterogeneities are in built into the system k_x, k_y, k_z in three dimension is a sort of a flow phenomena heterogeneity.

So, I hope now you can understand very easily as long as you talk about isotropic homogeneous material, you will never be able to capture these mechanisms which are going to contaminate your aquifers much more, and that is the reason why these type of studies are becoming much and more important ok. This process is repeated millions of time times by millions of water particle. So, this process keeps on going. And this is the equation which is normally used as to define dispersion phenomena.

Now, $M_D = a_L.V_s$, where a_L happens to be dynamic dispersivity. If you see the units, they are always going to be meters unit of length. V_s is the seepage velocity meter per second.

Now, a_L is normally defined as point naught one seven five multiplied by length to the power 1.46, if length happens to be less than 3500 meters. So, 3.5 kilometers systems can be assumed to be working with this. So, what is the M_D? M_D is nothing but the coefficient of dispersion, so which term is more important. Now, you can see I think my session to you is that do not look it as a mathematical equation, it is not a mathematical equation truly speaking, it is a sort of a supper imposition of two things, one is a_L. What is a_L? a_L depends upon the physical dimension of the aquifer. And what is V_s, V_s is nothing but the flow. So, this is where the porous media is coming in contact with its straight how seepage is going to take place.

So, if V_s is very less, your dispersion coefficients are going to be extremely less. However, if V_s is more your M_D is going to be more clear that is the difference between sands and clays.

Sir.

Yeah.

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Everything, that is right. So, a gross model is something like this. If you consider a certain unit length of the porous media which is nothing but capital L, the value of a_L would be some factor multiplied by that term. Of course, these models are being developed by several people, and there is no clear clarity about which model to be used and how to be used.

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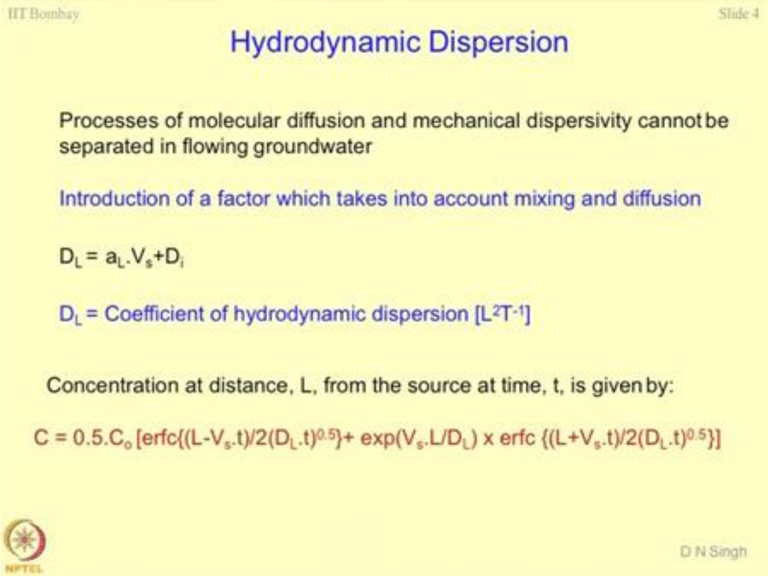

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Slide 4

Hydrodynamic Dispersion

Processes of molecular diffusion and mechanical dispersivity cannot be separated in flowing groundwater

Introduction of a factor which takes into account mixing and diffusion

$D_L = a_L.V_s+D_i$

D_L = Coefficient of hydrodynamic dispersion [L^2T^{-1}]

Concentration at distance, L, from the source at time, t, is given by:

$C = 0.5.C_o\,[\mathrm{erfc}\{(L-V_s.t)/2(D_L.t)^{0.5}\}+ \exp(V_s.L/D_L) \times \mathrm{erfc}\,\{(L+V_s.t)/2(D_L.t)^{0.5}\}]$

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Now, let us talk about hydrodynamic dispersion. So, we have discussed about advection, diffusion, dispersion, and now hydrodynamic dispersion. What is your guess? If you remove the word hydrodynamic, we have already talked about dispersion. Now, if I add hydrodynamic, what is the significance of this term? Hydro dynamic this is nothing but stirring your cup of tea with.

Mechanical mixing

Mechanical mixing. So, mechanical mixing, that means, it should have two attributes one is.

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No. One is there should be a dynamic in the flow or in the fluid, and there should be a fluid phase. So, fluid phase which gets agitated because of external disturbance, the dispersion which is getting caused because of this is hydrodynamic dispersion. So, these are the attributes. Processes of molecular diffusion and mechanical dispersivity cannot be separated in flowing groundwater, truly speaking hydrodynamic depression is a very fascinating field not to geotechnical engineers, why, but more to hydraulics people. Why? Look at this. So, our seepage velocities are very, very less. So, we rule out completely hydrodynamic dispersion in porous media, for that matter even dispersion we do not talk about.

So, for us the most important mechanisms are advection and diffusion, clear. So, processes of molecular diffusion, molecular diffusion we have discussed already. So, diffusion is always because of molecular activity and mechanical dispersivity. So, when you are stirring the fluid with a spoon or with some stirrer, you are providing lot of energy into the system and the entire sugar disappears. And this and the tea becomes sweet or saturated. So, introduction of a factor which takes into account mixing and diffusion will yield this type of a function, where D_L is the coefficient of hydrodynamic dispersion which is the function of simple dispersion plus what is D_i diffusion coefficient.

So, D_i correspond to molecular diffusion and a_L, V_s corresponds to mechanical dispersivity, clear. So, it is nothing but the combination of the two. So, if you put V_s equal to 0, what is the significance of this, seepage is very, very less in pervious material. What is significance of this, clays, compacted clays, intact rocks, where truly speaking there is no flow of water. What is going to govern? Your diffusion coefficient molecular diffusion coefficient is nothing but hydrodynamic dispersion, but then because V_s term is not appearing, we will never use the term D_L, we will say that this is the diffusion mechanism which is going to control contaminant transport. At a geological level, how deltas are formed? Sundarbans; I think you can imagine the situation now. So, rivers are bringing tons of loads of sediments, and they come and they mix on the interface of sea. So, there is the density contrast there is the reduction in velocity or enhancement in the velocity.

Reduction in the velocity.

Reduction in the velocity, clear. So, sediments deposit and deltas are formed, and then your diffusion mechanism starts. So, from fresh water, sorry from saltwater to the freshwater. So, it is a back action of the sea into the deltas. As of now Kutch is formed where you cannot drink the water because the entire land is contaminated because of diffusion clear. So, these types of situations become very important. So, D_L is the coefficient of hydrodynamic dispersion, again the units are same as what you are being using always L square by T meter square per second or whatever, alright.

Now, hydrodynamic dispersion modeling is very interesting. And most of the time people use, if you remember the type of situation I have discussed earlier, you are setting up an industry somewhere, and the basic question is down the time line or maybe down the distance line, what is going to happen to the geoenvironment. So, the question is what is the concentration of a contaminant at a distance L, from the source at a given time t.

So, this is the equation which is used where C is nothing but c t that is the concentration at a given time equal to initial concentration half of this. You must have done error function analysis, no, anyway. So, this is error function of L minus V_s upon into t is nothing but the distance divided by 2 times diffusion coefficient of hydrodynamic dispersion multiplied by time to the power half. Is this ok? So, this is a simple model which you can use to obtain C at a given time if distance is known or vice versa. Now, most of the environmental agencies, what they are doing, any guess how they are using this equation, what is known, what is unknown in this expression? You can obtain V_s.

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Exactly; so, if you drill a bore log, or borehole, you take out a sample from there of the groundwater, you know the value of C_t. So, L is fixed, C_t is fixed.

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Now, you have choice either you can find out after how much time exactly or you can verify your models by computing D_L, if time is also known. So, this is where the concept of observation wells comes into the picture, so every unit where the disposal of contaminants or hazardous waste is being done. It has to be surrounded by a series of observation wells, so that whenever you dose the landfill, immediately you should find out, what is happening down the strain in terms of time and distance, and whether your disposal facilities are working perfectly alright or not. This is a broad philosophy of how landfills can be designed in such a way, so that the environment remains unaffected, for that matter not only landfills any industry.

So, this becomes a simple mathematical modeling exercise. I am sure if you go and use the MATLAB or your excel sheet format, there you will find error function. So, you just compute V_s value multiplied by a given time, distance is known D_L, you can obtain by doing some experiments easily. So, this term is known and you can find out the error function of this, clear. And then you can get the C_t value. So, this is the simplest possible form of the dispersion modelling, when you are designing projects of importance. Is this part clear?

The most challenging thing would be lot of people are using finite element codes or doing groundwater modelling, hydrogeological modelling. What is the biggest challenge in this whole study, what is easily predictable, what is easily not predictable, what is you know unreliably predictable and so on? Are you getting my point? So, mathematically this equation looks very simple and straight forward.

If the porous media (Refer Time: 30:50).

That is true, yes, porous media does not remain same. So, first thing is how you are going to develop an equivalent model for your entire domain of length L. How many boreholes I should do, how many samples I should take out from the ground, how much time I will be taking to analyze this samples. And at the last what is the predictability and accountability and dependability of the parameters which I am going to get from this analysis, but the bottom line is we are all engineers. So, we should not ask this type of questions again and again. Why? At least we are getting some answer to a real problem which is better than no answer that is it, alright. So, this is how you can use these simple models in determining, the environmental impact analysis.

Now, nobody can now you should not cut a sorry figure in front of anybody that you do not know how to do environment impact analysis. So, this is the simplest form, alright of environmental impact analysis for which when you become a consultant you can earn lakhs of rupees as your consultation fee. So, most of the people are working right now in these areas. Any doubts?

Now, let us complicate this further. In your opinion what is the degree of uncertainty and degree of complexity if you are doing this type of analysis? See, here it looks very easy to say that you can obtain D_L. How you are going to obtain D_L either you are going to devices laboratory setup? So, what you are going to do, you are going to cut out a sample which you are assuming to be representative of the entire soil mass and testing you know and getting the results dependent on the properties of that sample, which may not be a real representation of the entire domain.

If you are talking about the field test life is easy or more cumbersome? I think there have been lot of efforts where people have done in situ testing to obtain dispersion coefficients, diffusion coefficients, seepage coefficient and so on, but there you have to conduct the experiments for several years or few months to obtain the results and that is where the climatic conditions environmental conditions material properties have, no control over alright. So, this becomes a very intricate exercise and you require lot of dedicated efforts to model the parameters, alright.