Environmental Geomechanics
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Lecture No. 39
Contaminant transport through porous media - I

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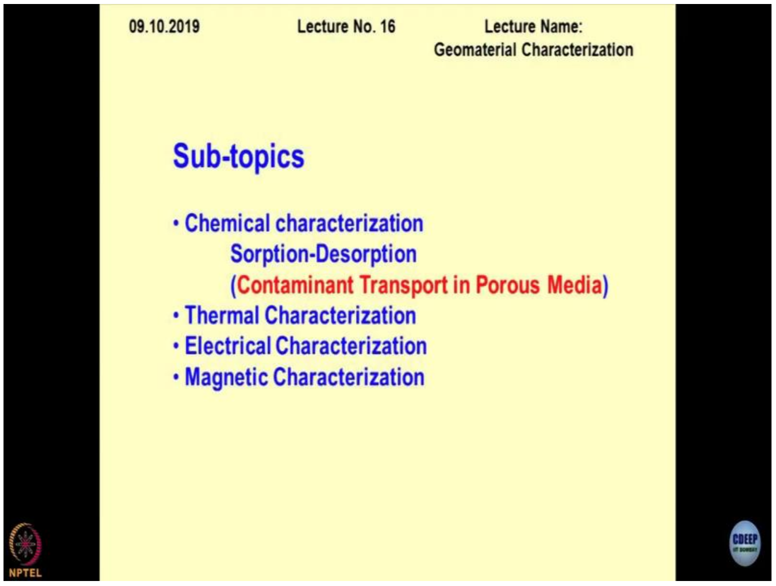

We have been talking about geomaterial characterization in general and in particular the chemical characterization, and I will continue with this. In today's discussion, I will give you a brief idea about the contaminant transport in porous media. And this is important to be studied at this juncture before we start delving into this sorption and desorption studies because the pretext of sorption and desorption is contaminant transport in porous media.

When the interaction of contaminants occurs with the porous media, then only we talk about sorption and desorption process. Now, this is a multidisciplinary subject. Many technologists would utilize the concept sorption and desorption and very evolving area, particularly in the realm of environmental geomechanics. And hope you will realize that this becomes very, very important due to the fact that it is the quantification of the interaction which you have been studying since long.

So, if you want to study how to quantify the interaction between contaminants and the porous media, the best way would be to study the sorption, desorption mechanisms and from there you quantify the whole process, and of course, we will continue with our discussions on thermal, electrical and magnetic characterization subsequently, so, to begin with, the contaminant transport in porous media.

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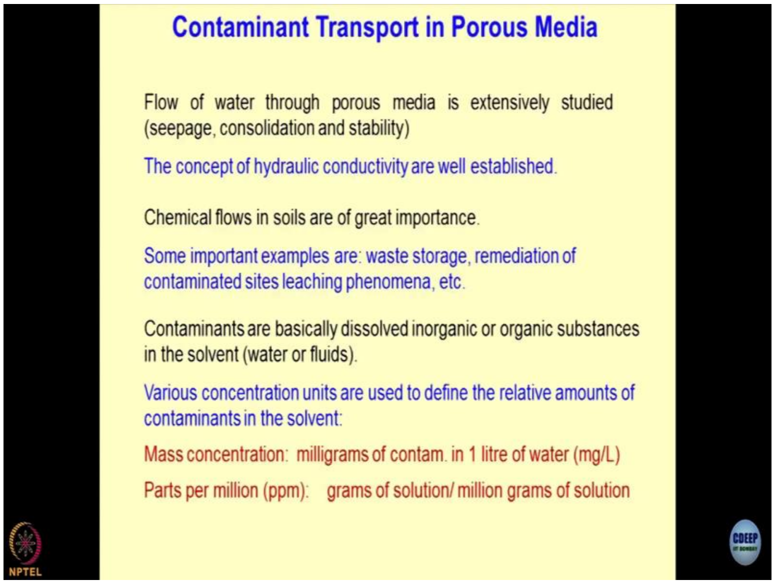

Hope all of you understand we have cited several situations examples where the contaminants come in contact with the porous media or the soils of the geomaterials, and this also has the pretext to the fact that flow through porous media is very well understood when we deal with water that is you have already talked about the seepage, consolidation and stability of the structures, where we have discussed the influence of water seeping through the porous system.

Now, if this water contains contaminants and these contaminants are migrating through the porous media, then the entire mechanics or the interaction process becomes difficult and intricate to understand. And that is what actually we are trying to attempt to study. So, the concept of hydraulic conductivity is quite well established. You have done the constant head test and falling head test. The simple analogy which comes to my mind is, if I adulterate the water with some contaminants and if I allow this water to migrate through the porous media.

And if I asked you how the hydraulic conductivity has changed this is one question the second question would be, what is the concentration gradient of the contaminant which has been retained by the soil mass when the contamination is passing through this. Third could be what is the contaminants in the soil so, these are the three issues, which we are bothered about and we would like to study. So, when chemicals flow through the porous media, this becomes a very, interesting important and contemporary situation, a very practical situation.

Because under no circumstances the water which is flowing in the porous media and real life is going to be demineralized water or saline water, it could be contaminated water. So, we have cited several examples where the liquid form of contaminants starts migrating through the porous media, waste storage facilities, landfills mostly and when the soils become contaminated, and how would you remediate them, and particularly when the leaching is occurring in the liquid phase.

Contaminants have to be defined here before we enter into this discussion of contaminant transport to porous media. So, we have to understand what is the basic characteristics of contaminants these are the inorganic species or these could be organic species also this could be reactive or non-reactive also this could be radioactive and non-radioactive also, sometimes we call the non-reactive contaminants as conservative contaminants.

And conservative contaminants are normally used by us every day we consume a lot of salt through our food through different types of eatables and the medical scientists would be using a different type of salts for tracers suppose if you want to find out what is the problem with your digestive system, so, they do the biopsy, they do the endoscopy and all those things. So, that is also a good example.

You drink some tracers barium chloride, mostly those of you who might be aware of this and then they trace how much of the barium chloride has been sorbed by the intestine and other places, there is some damage done to the intestine. So, you can do the endoscopy, and you can find out, what is the extent of damage to the colon, or intestine? So, in this context, we use some units to define what the amount of contaminants which is present in the solvent is?

And the best way to define the concentration of contaminants in the solution would be milligrams of contaminants in 1 litre of water. So, we call this as mg/litres another unit could be parts per million, so, parts per million is 1 gram of the solution which is dissolved a million grams of then another solution. I am sorry, this should be the grams of the solute divided the by millions of grams of the solution. So, please correct this is not correct, it should be the grams of the solute, which is dissolved in the solvent, millions of grams of solvent.

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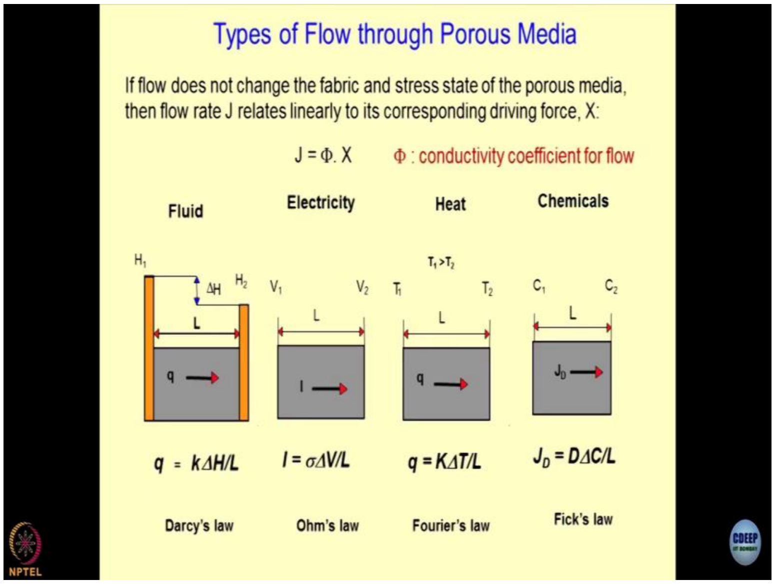

Now coming to the types of flow to the porous media, the basic equation which you have used in the form of Darcy's law if you remember, velocity is proportional to hydraulic gradient. Now, this equation can be extended to study how the contaminants are going to migrate to the porous media provided the fabric and a state of stress of this soil sample is not changing, or the porous media is not changing. So, in these circumstances, we can assume that $J = \phi \times X$, where J is the flow rate and ϕ is a constant.

We call this as conductivity coefficient or for flow and X is the driving force. So, if you use this equation, what it shows is that there is a flow of the flux which is occurring and this is equivalent to or equal to the coefficient of the flow multiplied by the driving force. So, one of the ways to correlate this equation with Darcy's law would be $q = k \times I \times A$. So, A is the area of the cross-section and Q/A, q is discharge per unit area, $q = k \times i$.

So, here k is nothing but ϕ gets a place by k and hydraulic conductivity which is known as hydraulic conductivity and X is nothing but I the driving force. So, this part you have already mastered is it not Darcy's law. Take a sample and apply H_1 and H_2 occur two ends and the $\Delta H = H_1 - H_2$ acting over a length 'L' of the sample is nothing but the hydraulic gradient, and $q = k \times i$. Now, I can extend this concept to the flow of current also through the samples, is it not?

So, in that case, what I have to do is the sample length remains L and if I know what the amount of current which is passing through the sample is, what I have do is I have to apply V_1, and V_2 voltage across the sample and then V_1 - V_2 gives ΔV, and the ϕ term becomes the conductivity term, and j is nothing but the flow rates is I current, this is equal to $k \times \Delta V/L$.

So, $\Delta V/L$ is also defined as the electric field, if you remember is ΔV upon this electric field. Now, here in case of electricity, we use ohm's law and this ohm's law is nothing but i equal to specific conductivity multiplied by voltage drop. This can also be extended to heat flow through the geomaterial, provided the length of the sample is L., And I am applying temperatures T_1 and T_2 across the two ends. If $T_1 > T_2$ the way it was same as V_1 and V_2 and $H_1 > H_2$.

So, delta t gives me the temperature gradient and L is the length. So, temperature gradient upon L is the temperature gradient multiplied by K. Now this K is the thermal conductivity and Q is the heat which is passing through the sample. And this is what we define as Fourier's law. Now what is remaining is the chemicals. So if I apply the concentration of chemicals C_1 and C_2 across the two ends of the sample, this type of situation may occur in the coastal areas where you have aquifer of a certain length and one side the aquifer is exposed to the seawater, saline water and on the other side it is connected to the land towards the land.

So, C_1 is greater than $C_{2,}$ and hence there is a flow of concentration in this direction. So, D becomes here the diffusion coefficient multiplied by concentration gradient delta C upon L Fick's law. Now, I hope you can understand that what we have done is we have discretized all the fluxes in their components. Then we are saying that if any type of flow has to occur through the porous media, it can be modelled by using Darcy's law case of advection flow of water if the water is having a species of chemicals, then we can use the Fick's law and if this water which is having the species of chemicals is at elevated temperature and it is migrating through the porous media.

I can utilize Fourier's law to solve this, and there could be a situation where the voltage is also acting across the sample electrical voltage, or the sample is exposed to the electromagnetic field. So, this is where I can use ohm's law. So, the point is any type of flow which is occurring through the porous media can be discretized into different flux conditions and then I can superimpose them depending upon the nature of the problem, and I can solve it all it. So, this is the general philosophy of the concept when we talk about how the flow or contaminant transport takes place through porous media.

One thing which I would like to highlight is, I hope you understand when you apply this law or this equation, what is the principle unknown. The principle unknown would be the phi term. So, small k hydraulic coefficient or hydraulic conductivity or coefficient of permeability you have obtained by doing different tests in the laboratory or in the field. So, you did falling head test, you did the constant head test, you did the triaxial test, you did consolidation test also to get a small k value and in the field, if you have to obtain the hydraulic conductivity, then you can do packers test and pumping in and pumping out the test and so on.

So, that means, the big question is how would you obtain the coefficient of flux transport. So, this was quite easy in case of conductivity electrical conductivity; I have to pass a current of some value measure the voltage across the two ends and obtain the signal value in case of heat will have to pass heat through the soil sample and making sure that heat does not alter the state of the material including the moisture content because I hope you understand that if you are passing the DC current through the sample DC the heating current.

So, when you pass DC current to the soil sample, the chances are the moisture content may get altered. And I am not interested in that so, I will be using AC current most of the time so, that AC is a non-heating current and then I can get the value of thermal conductivity of the soil. Similarly, I will have to do some tests to obtain the diffusion coefficient of the contaminants through a porous area. So, I am sure you must be realizing that this is a complicated issue; first of all, you should be having proper devices, which you can utilize to obtain these parameters. Is this correct?

So, unfortunately, or fortunately, when we started working on all these problems, there was nothing which was existing in the market, you could not order anything to get off the shelf and say that I will start doing my experiments. So, what we have done mostly is we have devised different types of equipment, we have to devised different types of methodologies to obtain all these coefficients. And this is where our major emphasis has been once you have obtained these coefficients, then the life is simple, you can plug them in mathematical models.

And you can do the analysis where you have done the seepage analysis by using flow nets. Is this part clear?. So, the basic challenge is how to get electrical connectivity, how to get thermal connectivity, how to get diffusion coefficients. So, from this point onwards, my emphasis would be to explain to you how these coefficients were obtained. Of course, this is a very elaborate manner, in which we have done this, and most of these studies have been done by my PhD scholars. And each thesis has been attributed to finding out these parameters and the setups which have been done **"Professor - student conversation starts"** sir when the chemical flow is taking place like if there is some sorption along with Darcy flow.

The soil fabric will change. Let us start things as very simple situations. And then we will complicate it as much as you want do not worry. **"Professor - student conversation ends"** first, to begin with, start with the simple things so that life becomes easy. Is this correct? This rule of life. I will answer your question. How everything has been done. Now I am sure you must have realized that what is the coupling. Now, if I couple these modules with each other, this becomes a coupled flow, is this okay?. That is a simple mathematical superimposition.

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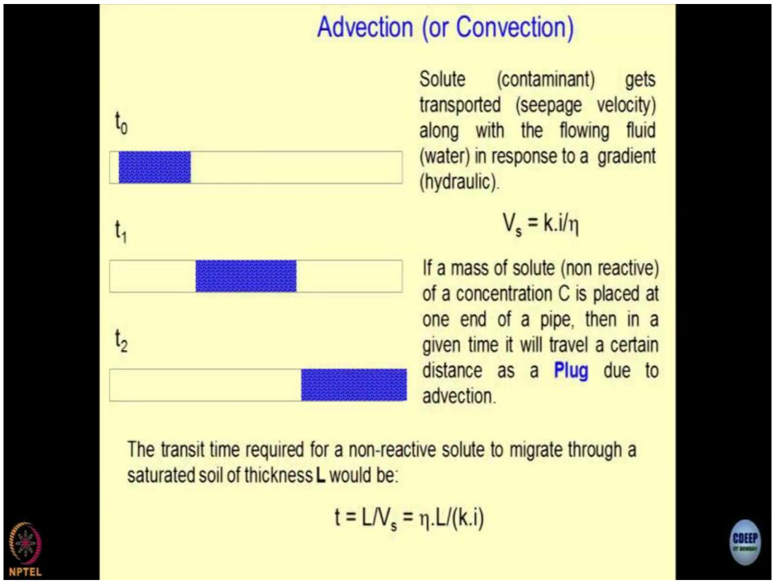

So, let us start understanding the flow through the porous media. So, the first thing that comes to mind is you were talking about the advection and all the flow of water because of the hydraulic gradients is advective flow, Clear?. Now, we also define this as convection process; the more idealization would be something like this; if I consider a certain volume of a chemical, we call this as a plug. So this is a solute which is getting transported from left to right.

And this is a situation at t equal to zero time. Now when t_1 is approached, this plug simply gets displaced by a certain distance and at t_2 gets further displaced by some distance without losing its integrity that is more important. So, solute, which is also contaminant, gets transported through the seepage velocity along with the flowing fluid, which is water in response to a hydraulic gradient. So, we define this as seepage velocity equal to hydraulic gradient multiplied by hydraulic conductivity and divide by the porosity of the porous media.

Now, this is where I can answer your question that what we are assuming here is that the solute and the porous media both are conservative. So, it is a simple situation we are talking about floats will accept perfect glass tube and contaminants or the solute is let us say conservative salt, which is not going to react with the walls of the tube or the soil particles. So, under these circumstances, what is happening is the entire concentration simply moves from one point to another point without reacting with the porous media and without getting decayed or changed, altered.

Now, these conditions are valid, this contaminant transport is known as advective containment transport, and then I can find out what is the relationship between the time and the seepage velocity. So, if I want to find out the time for which is required for this plug of contaminant to travel from one point to another point, I can use this relationship V_s is known L is the distance travelled by the contaminant and I can get the relationship as porosity into L upon k into i.

I am sure you must have utilized this equation in your undergraduate. When we were talking about, let us say, in the open channel flow if I ask you to find out the velocity of the water, how will you do it. So, you will add some conservative contaminant at a given point, and you will measure the concentration at another point the time the distance you can find out what is the velocity of the flowing water.

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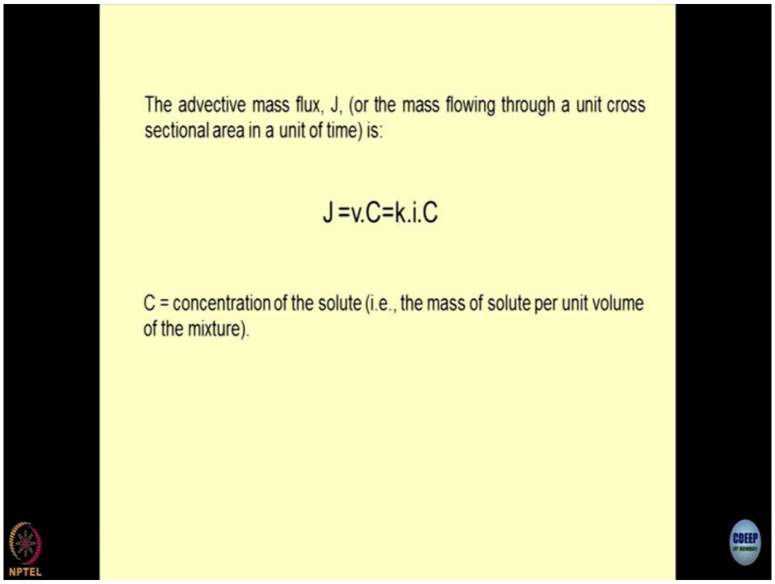

Now, again coming back to the point suppose, if I want to find out what is the advective mass flux which is passing through the porous media. So, advective mass flux is velocity multiplied by concentration, and you must have done this analysis V1 into C1 is equal to V2 into C2 conserving the mass flux in an open channel flow. So, C happens to the concentration of the solute, which is a mass of the solute per unit volume of the mixture.

And we know other parameters hydraulic conductivity the hydraulic gradient this is nothing but the discharge velocity and then I can equate this. So, this is a simple situation, where I can find out what is the mass flux which is entering the soil mass and which is coming out of soil mass. And remember, we are assuming that both contaminants and the porous media are conservative; they do not react with each other.

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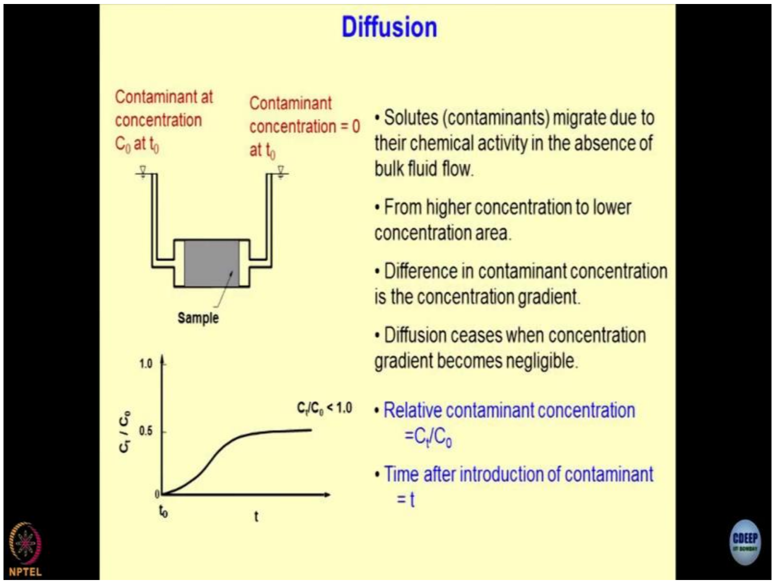

The second mechanism of containment transport is diffusion, what is happening here suppose, if I take soil sample in a glass tube, and if I connect it upstream as well as the downstream side of the water bath and if I eliminate the delta H, how would you eliminate the delta H by keeping H1 and H2 are constant, but what I will do is I will use the water which is going to pass to the sample by adding some salt into it. So, what I have done is by maintaining the heads I have eliminated the advection process.

But now, what you will observe is because of the concentration gradient between this and this, this side is freshwater the side is contaminated water. Now, if you do this experiment, what you will observe is I have to take out the sample of the discharge water or even if it is not discharging let us say in the study state condition, I can take some sample from here, and I can do ICP MS or atomic absorption spectroscopy to find out what is the concentrations of the water on the downstream side.

And then if I plot the C_t value, C_t is the concentration of the contaminants present in the downstream side, and this is normally normalized with the C_0 value initial concentration. So, this becomes a non-dimensional term C_t upon C_0. Now, this is plotted on y-axis and time is plotted on the x-axis. Any idea what this graph is known as? Have you ever use this anywhere? Suppose if I change C by the population of a nation, yes so environmental scientists or the anthropologists will be very eager to find out what will be the population after a certain time in our case C is concentration. So, this is the concentration which is coming out of the sample at a given time, and C_0 is the initial concentration.

So this becomes a breakthrough curve BTC. Have you heard about it? Breakthrough curve. In your environmental engineering, I am sure you must have talked about BTC. It so happens that BTC cannot be equal to one, why if soil mass and contaminants both are reactive, so this is what answers your question. Now, the moment you take a reactive soil mass and reactive contaminants, some sorption is going to occur. And because of that, C_t is always going to be less than C0 value.

In a totally conservative system, we do not talk about the concentrations, but there could be another situation that you have a reactive contaminant which is passing through a conservative soil mass, so there will not be any sorption. So, C_t/C_0 could be equal to one. Now this graph, the moment you get will give you the diffusion coefficient D. So, this is a simple way. Now, what I have to do is I have to create an instrument in such a manner, where I will expose the sample on one side to higher concentration another side to the lower concentration wait for some time.

Let the study state diffusion process set up into it, draw this relationship get the slope, and that is the difficult coefficient. So, by definition, the way we define this is solute or contaminants; this is migrating through the sample in the absence of any hydraulic head. In real life, we would have a situation where advection also gets coupled with diffusive contaminant transport because you cannot stop it. So, this becomes advective diffusive contaminant transport where the heads are also acting what is flowing to the porous media.

And there is a difference in concentration of the chemicals which are being carried by the water when it enters the sample. When it comes out the sample, So, this becomes a typical advective diffusive contaminant transport, again, the flow will take place from high concentration to the lower concentration, and ΔC is caused by $C_1 - C_2$ and when this process is going to end when C_t tends to be equal to C_0.

So, the moment the concentration gets equilibrated on both the sides, the diffusive contaminant transport is going to seize. Till what point we will be taking the slope for diffusion coefficient normally we take the linear portion and what I can do if I can manipulate the whole thing in such a manner that I can plot t because these diffusive times are extremely long times. So, normally t can be plotted on a log scale. So, this becomes a semi-log scale. I will take the central portion of the curve, which is almost a straight line, and that slope is used.