Flow through Porous Media
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Lecture - 47
Interception of Suspended Solids

I welcome you to this lecture module of Flow through Porous Media. Now, we are going to start a new section and that is Interception of Suspended Solids. So, if fluid contains some suspended matters that could be very very small because see our the largest porous medium that we have been talking about is macro porous medium where almost the pore size is 1 micrometer. So, these suspended solid matters have to be much smaller than this so that this is entering into the porous medium.

It is not forming a if the if this suspended solid matters are larger than the pore mouth obviously, it will form a cake at the at the inlet at the porous media. It will not enter into the porous medium. We are not exactly looking at this filter cake we are looking at interception of these particles because these particles are entering into the porous medium and then it is somehow plugging the pores and thereby the permeability is getting reduced and there are certain changes.

So, first we will look at where all these kind of applications are there where such kind of a flow through porous medium is involved where suspended matters are important.

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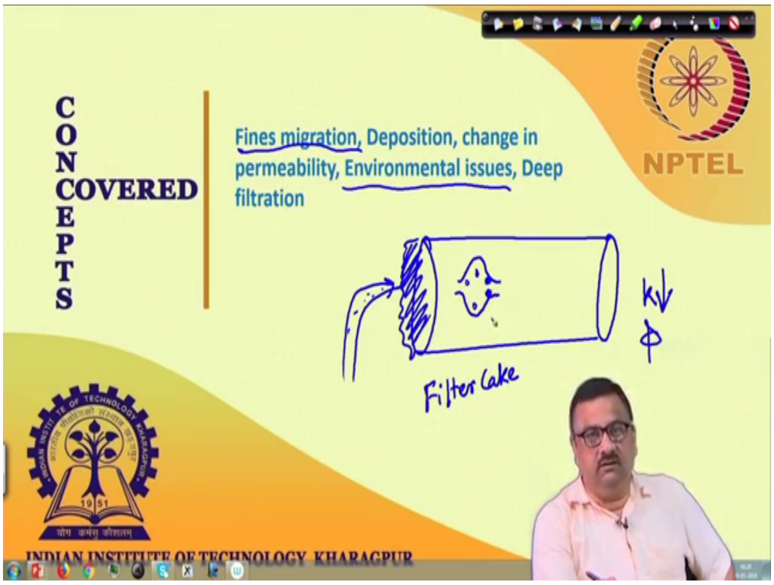

CONCEPTS COVERED

Fines migration, Deposition, change in permeability, Environmental issues, Deep filtration

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So, we would be talking about in this section fines migration, deposition, change in permeability and there are some issues environmental issues with regard to this permeability, with regard to this particulate matter getting held up in porous medium and then this process known as deep filtration which is based on this interception process.

So, what do we what I mentioned just now if I look at it quickly if this is the porous medium if this is the porous medium and then this has let us say I have pores which is of the order of say 1 micrometer and then I have I am having a flow when this flow I have some suspended matters are there. So, now, suppose I have the suspended matters which are larger than this pore throat, in that case they will be all accumulating here and it will produce a so called filter cake.

One see this kind of one can we see this kind of filter cake in when they go for this hydraulic fracturing in a reservoir. For example, they put this they put a suspension into this porous medium there the aim was that the fluid that is used that is going to fracture the medium by application of very high pressure, but it will not enter much into the matrix.

So, they intentionally they put such constituents in the in that in that fluid so that the this that will form a filter cake and that will carries the flow into the porous medium because if it goes if that suspension goes into the porous medium it will damage. So, they intentionally they put constituents that will form a filter cake. So, we are not discussing about this filter cake.

What we are saying is suppose inside this now let us say I look at a pore here I amplify the size of the pore obviously. So, let us say this is a pore. So, there would be these small particles. The small particles they are traveling small particles, they are traveling and then these small particles that enter into a pore they will tend to accumulate near the pore throat ok.

So, it is not changing much the pore volume or it is not changing much the porosity, but it is clogging. It is occupying this poor mouth and so; thereby it is restricting the flow. So, what essentially we I am talking about is that the permeability is decreasing, but porosity is not changing much ok. Permeability is decreasing because these suspended particles they are getting lodged at the pore mouth and thereby the flow becomes difficult.

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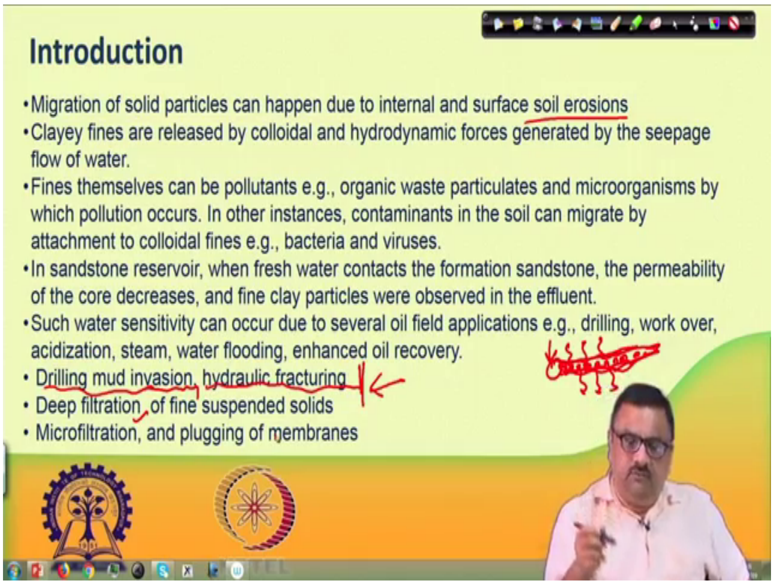

Introduction

- Migration of solid particles can happen due to internal and surface soil erosions
- Clayey fines are released by colloidal and hydrodynamic forces generated by the seepage flow of water.
- Fines themselves can be pollutants e.g., organic waste particulates and microorganisms by which pollution occurs. In other instances, contaminants in the soil can migrate by attachment to colloidal fines e.g., bacteria and viruses.
- In sandstone reservoir, when fresh water contacts the formation sandstone, the permeability of the core decreases, and fine clay particles were observed in the effluent.
- Such water sensitivity can occur due to several oil field applications e.g., drilling, work over, acidization, steam, water flooding, enhanced oil recovery.
- Drilling mud invasion, hydraulic fracturing
- Deep filtration of fine suspended solids
- Microfiltration, and plugging of membranes

So, now first of all where all we have this kind of applications migration of solid particles can happen and due to internal and surface soil erosions. Soil erosions are something which is very common soil erosions. Soil erosions: so, me eroded particles will be carried downstream as the flow is taking place, soil itself is a porous medium. So, as it is as the fluid will be carrying some eroded particles to downstream and they may plug the pores in the downstream.

Now, these clayey fines are released by colloidal and hydrodynamic forces generated by the seepage flow of water. Clayey fines are released clayey fines I mean basically clay, clay material and this fine particles made of clay these are released by colloidal and hydrodynamic forces generated by the seepage flow of water. Why they happen I mean I will discuss it in a moment.

Fines themselves can be pollutants such as organic waste particulates and microorganisms. Here the fines themselves are pollutants and so, the these fines traveling into porous media. I mean So, it is not this pollution is not confined, pollution goes elsewhere and that that is more dangerous. So, that is why we said that micro organic waste particles and micro organisms they may travel and because of which pollution may occur.

In other instances, contaminants in the soil can migrate by attachment to colloidal fines. Such as bacteria and viruses they will get attached to the colloidal fines and travel downstream. So, these so these this is this is very much there and this is something which they have researchers who are in environmental or soil science they are very much concerned with that how this particulates will travel and what will happen to the downstream.

In sandstone reservoir sandstone reservoir, is the reservoir petroleum engineers they are much interested because major part of oil are mostly in sandstone and some are in carbonate. So, in sandstone reservoirs when freshwater contacts a formation sandstone, the permeability of the code decreases and fine clay particles were observed in the effluent. That means, when a freshwater is injected into the formation sandstone one notices that permeability of the core decreases and fine clay particles are observed in the effluent; that means, fine clay particles got dislodged from the inner wall of the pore and they are carried downstream at the effluent.

So, this is called water sensitivity in sandstone reservoirs. Such water sensitivity can occur due to several oilfield applications such as drilling, work over, acidization, acidization steam, water flooding, enhanced oil. So, these are some of the processes which are where externally fluid has to be injected into the reservoir. And, since water is the cheapest source so, mostly it would be aqueous phase being entered entering into the porous medium. And, so, this problem always remains that water sensitivity to this there. So, this will always be there.

Further it is basically when water is injected fine clay particles they are coming from inner source. So, these particles were originally in the porous medium itself. They were tucked into the when inside the pore, but for some reason when you injected water I mean originally in place what was there was brine. So, now the salt concentration has changed and so, you find that these particles are getting dislodged from the inner wall of the pore and they are carried downstream.

And, they are a potential you know plugging agents because they as they go downstream they will plug some other force. So, that is the reason why permeability decreases when fresh water is injected into sandstone instead of saline water that is what the point has been made already. Now, these particles very inside the porous medium it is not injected from outside. However, one injects particles from outside when it comes to drilling or hydraulic fracturing because there were there were reasons to inject particles. You may you may you may know that this it is it cannot be done by simple water. These drilling has to be done by one has to form drilling mud ok. Similarly, for hydraulic fracturing there would be proppants, there would be other suspended solids.

One reason is I told you at the very outset that you want this filter cake to form on the surface, so that water does not the aqueous phase is not penetrated into the porous matrix when a fracturing takes place. By that what I mean is suppose this is the well and one has to create this fracture. So, they are injecting aqueous phase at a very high pressure and because that pressure that water pressure will ensure that this rock gets fractured and they there is there is a channel forms channel gets formed.

So, now, here it is this fluid when it is when it fractures if this is a simple water, then it will start penetrating into the matrix and this cannot be a simple water. This water has to have some amount of polymer, some amount of because there are there are several issues. For example, when this hydraulic fracturing is done it carries proppant with it. Proppant are small you can think of something very similar to sand particles. So, they will go and they will go and sit there.

The idea is that when the sand particles when you release the pressure when the pressure is withdrawn then these two sides they will come back they will come back and they will there will not be any void anymore because they this because of pressure they parted. Now, they will they will come back. So , to avoid that inside you have to put something which is which can withstand that kind of stress.

So, these particles the small particles they are they are called proppants they are then acting against this force by which these two these two parted portions they are coming close to each other, they are they are trying to merge. So, these will leave this place open. So, for that one has to have these proppants. Now, the proppants if one wants to have this proppants suspended inside as the fluid is flowing into this porous medium so, this for that one has to have some kind of thickening agent and because otherwise this proppants will all precipitate immediately. So, one needs to have this proppants suspended as it travels.

So, there are so, there are a lot of other chemicals that needs to be injected and would if one does not want that chemical to go into this matrix because it will be lost and it will also would damage this matrix around which is not at all wanted. So, you may you may intentionally add something in this in this formulation that is used for fracturing so that it forms a filter cake around this wall, so that this lose into this porous medium can be minimized.

So, so these are these are some of the some of the reasons people have it during hydraulic fracturing you have suspended solids during drilling mud. This drilling mud for drilling a well so, that mud may invade into the porous medium and that time that drilling mud will have suspended solid. So, how the feature how they fare when it goes into the porous medium how much damage they will cause because there is there is a subject by itself which known as formation damage so, in petroleum reservoir studies. So, this is so, these are some of the areas some of the applications where one needs to think about this interception of solids.

Similarly, deep filtration of fine suspended solids are required in many chemical engineering applications. In many applications one has the suspended solids and you want to remove them remove the suspended solid because of environmental reasons because of chemicals of the need for the chemical process itself. So, there these deep filter for this deep filtration one use this one use this filter where this interception happens deep inside the porous medium not just as a filter cake.

And, similarly there are this process is known as micro filtration where in these micro filtration there is a plugging of membrane ok. So, there also the suspended solids very fine solids of course, this size of the pore in case of a membrane is much smaller particularly in micro filtration applications, but there also these kind of plugging issues are important.

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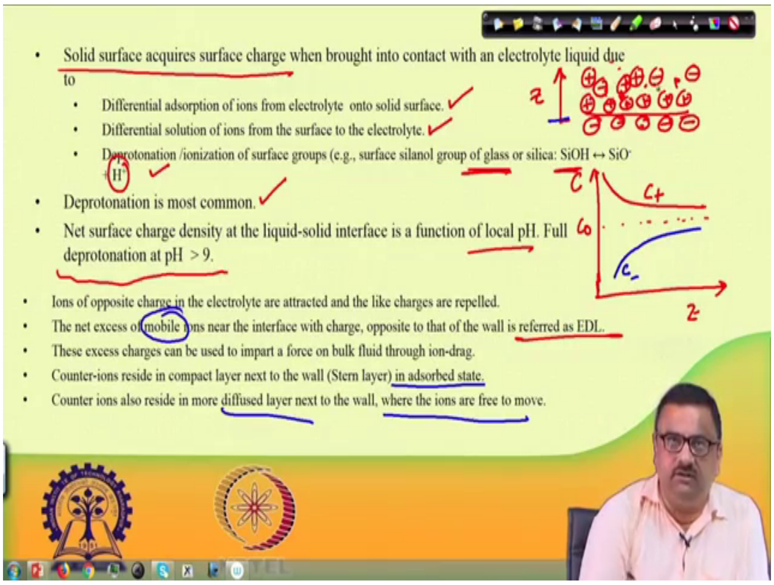

- Solid surface acquires surface charge when brought into contact with an electrolyte liquid due to
  - Differential adsorption of ions from electrolyte onto solid surface.
  - Differential solution of ions from the surface to the electrolyte.
  - Deprotonation /ionization of surface groups (e.g., surface silanol group of glass or silica: SiOH ↔ SiO^- + H^+
- Deprotonation is most common.
- Net surface charge density at the liquid-solid interface is a function of local pH. Full deprotonation at pH > 9.
- Ions of opposite charge in the electrolyte are attracted and the like charges are repelled.
- The net excess of mobile ions near the interface with charge, opposite to that of the wall is referred as EDL.
- These excess charges can be used to impart a force on bulk fluid through ion-drag.
- Counter-ions reside in compact layer next to the wall (Stern layer) in adsorbed state.
- Counter ions also reside in more diffused layer next to the wall, where the ions are free to move.

So, now, with this background, let us see why these particles they will get dislodged? I said that when water is injected there is a tendency that some particles they get dislodged from the inner wall of the pore. So, why this dislodging? This is this comes under the title under the heading migration of fines. So, why such migration at all?

So, in this regard first we need to understand very quickly what is zeta potential. We already you might have studied what is it zeta potential, but just a very quick look to it this what is it zeta potential. We see here that when solid surfaces solid surface acquire surface charge when brought into contact with an electrolyte liquid and that happens due to many reasons one could be this differential adsorption of ions from electrolyte onto solid surface; differential solution of ions from the surface to the electrolyte and deprotonation or deionization of surface groups.

What that means, is suppose I have a solid surface and I bring in an electrolyte; electrolyte means brine, let us say NaCl in a 1 percent NaCl, rest is water. I have Na plus and Cl minus. They are present and they are flowing. Now, if I focus on a very small layer next to the wall, I will find that some such the solid surface has acquired some surface charge this will happen. So, you will find possibly this surface has developed as a negative charge or we are looking at deprotonation.

So, deprotonation means proton is leaving the surface. So, Si say for example, it is the glass, glass silanol surface, silanol group breaks down into SiO minus plus H plus; so, this is the proton which is leaving. So, if proton leaves to the leaves to the electrolyte then it is leaving SiO minus. So, the surface has become minus surface is left with SiO minus because H plus is gone because there is this dissociation has taken place.

So, this is of course, at a very small level; I mean it will not be it will not be a big charge here and this will be felt only at this near the wall and since this porous medium is this dimension of these conduit is 1 micrometer or less so, that is why we are concerned with this. If it is 1 millimeter or if it is we are talking about a tube obviously, this aspect is insignificant.

So, now, when it is 1 micrometer scale these minus charge would be attracting the opposite charge; opposite charge means Na plus because you have Na plus and Cl minus. So, Na plus will be attracted here and it will form something called a double layer ok. It will form a double layer minus charge within the wall and it is attracting the plus charges. So, now here so, that is what it is referring to.

Deprotonation is most common. Net surface charge density at the liquid surface solid interface is a function of local pH. So, net surface charge density at the liquid solid interface. So, how much would be the surface charge density that depends on the local pH; full deprotonation at pH greater than 9. Now, in this regard I must note that ions of opposite charge in the electrolyte are attracted and the light charges are repealed. So, that means, plus charges are attracted and minus charges are repelled because of this charge net charge of SiO minus that has been or net charge that has developed at the wall.

So, the net excess of mobile ion near the interface with charge opposite to that of the wall is referred as electric double layer. So, it is not just a single layer it is basically it is you have one layer and then. You will see that gradually this layer is somewhat diffused you will see one or two minus charges here and there 1 or 2 minus changes here and there I mean beyond some level the first one is referred as turned layer that is a one can assume that it will be all positive charge.

Of course, this at this time this is all hypothesis, but gradually we will show that yes there is there is these are these parameters can be measured how much charge has been stored there, how much charge has been accumulated at the wall. So, now if you move away from the wall it is one or two minus signs you will see, but it is predominantly plus signs. So, that means, if I what I mean to say is if somebody plots the concentration here of these suppose somebody plots concentration versus distance, concentration versus distance.

So, let us say our original that NaCl that I placed that has C 0 concentration. So, C 0 Na plus and C 0 Cl minus was there and let us say this is that C 0 this is the C 0. So, this is the concentration versus distance Z where Z it is from the wall away that is Z. So, this is this is the distance. And so, now, if somebody plots the C plus ion concentration and C minus ion concentration in this case, one can see that there is an accumulation of C plus concentration. So, this is going to be the C plus concentration and there going to be this is going to be the C minus concentration.

So, these are C plus there is an accumulation of C plus at Z tending to 0 and then gradually as you go away from the wall as Z increases as Z increases from the wall you can see C plus and decreases and coming to the bulk concentration. So, add the bulk it is all neutral C plus is equal to C minus and so, C minus ion concentration is less at the wall and then gradually it goes and in the bulk it is all C plus and C minus they are equal to C 0, but near the wall there is an accumulation.

So now, so, ions over-recharged are repelled. So, net excess of mobile ions near the interface we charge opposite to that of wall is referred as EDL. There is this qualification mobile because one layer which is next to the wall is considered immobile that is called the stern layer. But, beyond this one layer of charge there would be accumulation of positive charge primarily, but there would be it is more of a diffused layer and it is considered that this layer can move. So, that is why this one mobile.

The excess charge can be used to impart a force on bulk fluid through ion drag. This I will discuss in a moment. Counter ions reside in compact layer next to the wall is stern layer in adsorbed state basically the first layer is considered in adsorbed state and counter ions also reside in more diffuse layer as I said beyond the first layer it is existing in a more diffused layer next to the wall, where the ions are free to move. And, these ions are not fixed like it is not in adsorbed state and they can move, but still there is an accumulation. So, this is something which happens when an electrolyte is brought to the surface.

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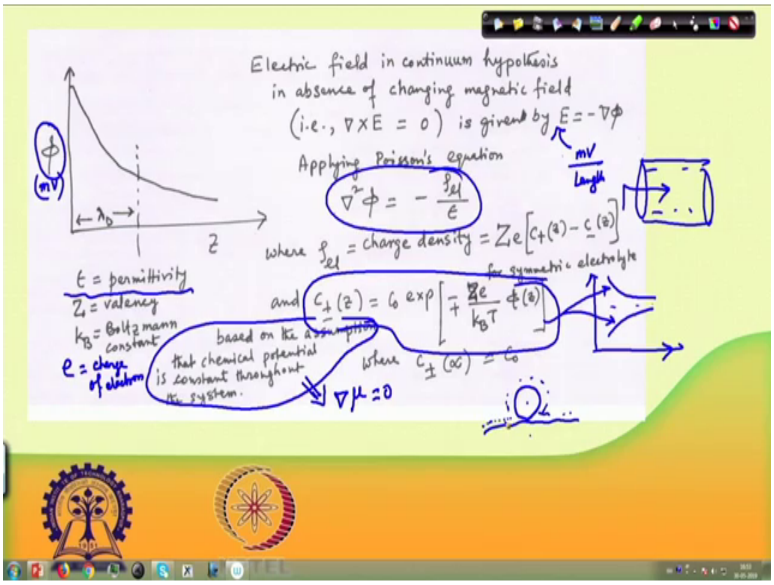

Electric field in continuum hypothesis in absence of changing magnetic field (i.e., $\nabla \times E = 0$) is given by $E = -\nabla\phi$

Applying Poisson's equation

$$\nabla^2 \phi = -\frac{\rho_{el}}{\epsilon}$$

where ρ_{el} = charge density $= Ze\left[c_+(z) - c_-(z)\right]$ for symmetric electrolyte

and $c_\pm(z) = c_0 \exp\left[\mp \frac{Ze}{k_B T}\phi(z)\right]$

where $c_\pm(\infty) = c_0$

based on the assumption that chemical potential is constant throughout the system. $\nabla\mu = 0$

ϵ = permittivity

Z = valency

k_B = Boltzmann constant

e = charge of electron

So, now if one tries to put together these exercise that if because of the accumulation of charge there would be something called a potential developing near the wall and as you go away from the wall as Z increases Z is the distance from the wall. So, as Z increases the potential goes down and potential becomes 0 when it is all neutral. So, near the wall there is an accumulation of charge and because of that some potential develops.

And, then one can write in this context these electric field in continuum hypothesis this under this condition one can use Poisson's equation and this is the form where rho e l is called the charge density; rho e l is the charge density in this context which is Z multiplied by e into C plus minus C minus. The idea here is what I have done here is I have written first of all electric field; this is unit of this is in volt. Generally, if you are plotting this for a surface charge it is of the order of milli volt. Let us say this is in milli volt. So this is in milli volt.

So, electric field e is defined as grad of potential grad of potential means del phi del Z. So, del phi del Z means if this is in volt or this is in milli volt then this should be milli volt per some length unit. So, probably volt per centimeter this could be the unit of e; e is the electric field in this case. So, now, one can apply Poisson's equation where this can be written as this is more of this is arising more out of continuity. You can think of electric field continuity that we have been talking about fluid continuity in porous medium this is an electric field continuity.

I can see a density term coming there also we had a density term and this epsa is more of a this epsa is known as permittivity this follows from electro of theories of electrostatics one can refer. This is this is a standard equation for electrostatics. So, and this charge density is basically one can see Z is the valency. So, if you are looking at NaCl the valency would be 1, if you are looking at calcium chloride valency would be 2. So, Z is the valency number and e is the charge of 1 electron that is fixed charge of an electron. e is charge of an electron and C plus is the concentration that I mentioned just now plus ion concentration and C minus is the minus ion concentration and the variation of C plus with Z we discussed in the previous slide.

So, if one based on this assumption or that the chemical potential is constant throughout the system throughout the system, chemical potential is constant. So, one offshoot is that grad of mu that has to be equal to 0 and with those with those understanding those assumption one can solve this concentration profile and this is typically the concentration profile where this is C plus minus Z I should not confuse this C here. C plus minus Z C plus minus Z is equal to C 0 exponential of minus plus.

So, when you are considering plus here it would be minus there minus plus Z e divided by k B T, k B is the Boltzmann constant that is a very standard parameter. In this regard Z is the valency we have already mentioned, e is charge of 1 electron already specified and this phi is the potential as a function of Z. So, wherever whichever Z I am talking about the concentration at that Z I mentioned just now right the concentration changes like this these and this, this is C 0. So, C was coming down and C minus is going up as Z increases right, this I discussed.

So, now, these equation essentially give you this profile or C plus and C minus. So, this equation can give this profile. We are we need to build on this further we need to we need to build on this further. So, because of this because the point that we are trying to make out of this exercise at this time is we will show that because of this charge accumulation there are a couple of issues that will happen in porous medium for. One issue could be that I have an inner wall of the porous medium and a grain.

And by virtue of London van Der Waals interaction this grain is attached to the inner wall of the pore. Now, I am talking about this electric double layer and this electric double layer will start forming here and electric double layer will start forming around the grain and then there will be interaction of this electric double layer ok. So, this is this is something which we are heading to that if there is an interaction with an electric double layer what kind of repulsion that can generate that can be generated here, one thing.

Second thing is if you have such kind of this kind of charges developing and all kinds of you know potential developing at the wall and then do you think I have a porous medium where at the wall I have developed this kind of charges here and here and there. And, now when I start having a flow will there not be a potential gradient developing within this porous medium? What is that potential gradient? That is known as streaming potential. We will discuss this.

So, these are couple of issues since inside I am discussing this anyway so, I thought I will mention this streaming potential also because that is an important concept when it comes to flow through porous medium. But, primarily we are trying to find out why there would be a dislodge of particle ok. Why there is what is a the essential reason for this migration of fines. So, that is all that is where I am heading to and this is what I have as far as this introduction module to the intersection of fines section of this lecture is concerned.

Thank you very much.