Water Resources Engineering

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Lecture No. # 07

As we have seen in the hydrological cycle, the precipitation falling off the surface of the earth either runs off from land to the stream or some part of it infiltrates into the ground. The part which goes into the ground either gets transpired by the plants or goes back to the atmosphere. Some part of it percolates deep down and contributes to water already inside the earth. So today we will look at this water which is exists below the ground surface. This is commonly called ground water or sub surface water. In surface water we have already looked at various kinds of it. This may be pond, lake, streams or oceans in the sub surface. Let us look at a cross section of the ground.

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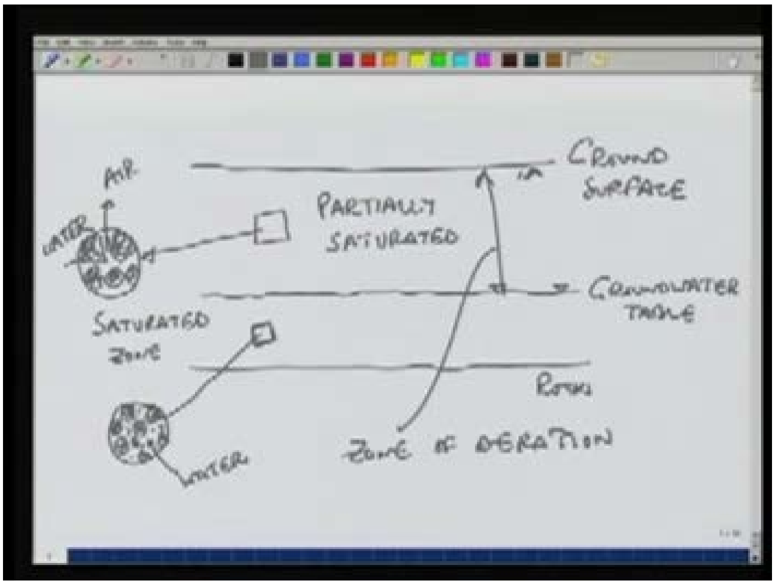

Let us say this is a ground surface and there may be bed rock which is impermeable. So water will be staying on top of this. This portion shown here by this line is the soil pores, filled with water therefore this is known as saturated zone. If we take soil samples from inside this portion the soil will consist of solid grains and the remaining portion will be filled with water. In other words there is no air inside this zone. If you go above the ground water table or sometimes simply called water table, and take a sample from here, it will have solid particles. A part of it will be filled with water and a part of it with air. So we may have a water flow around the grains and in the middle we may have air. So this portion will be partially saturated and it is also called zone of aeration because of the presence of air. This zone again can be sub divided into 3 parts. As we know that whenever water is in a tube it will have a capillary

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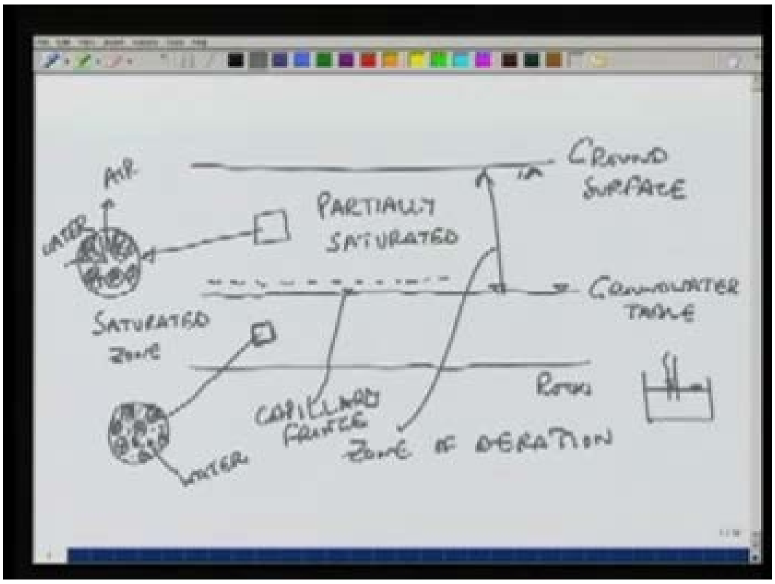

reaction because of which it will rise within the tube this phenomena is known as the capillary rise. This occurs because of the surface tension. Same thing happens below the ground level also. So in this partially saturated zone there is a thin layer which is known as capillary fringe. We know that the height of the capillary rise depends on the diameter of the tube therefore the soil diameter will decide the amount of capillary rise. So this thickness of this capillary fringe will depend on the type of soil. For small grained soil typically the rise is more, for large grain soils the rise is smaller.

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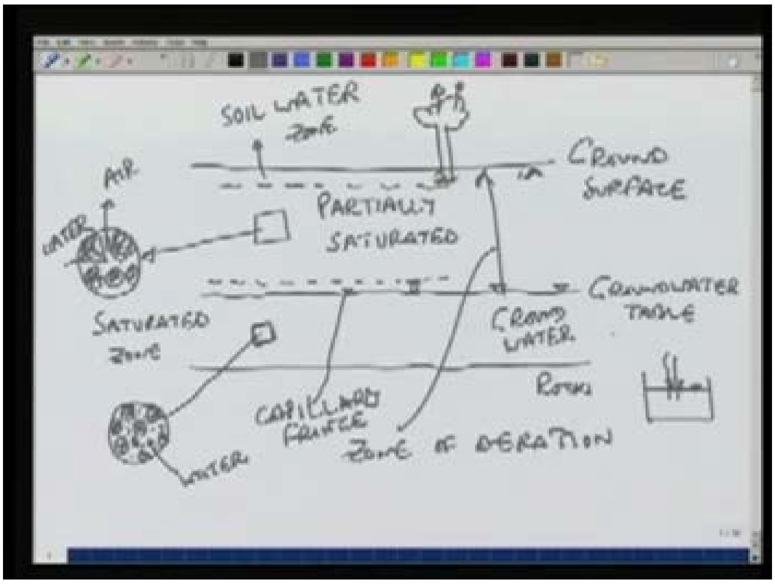

If we look near the ground surface, there would be a zone just below the ground surface from which the plants can take water and this is known as the soil water zone. The roots of the plants can take water from this zone and this goes back into the atmosphere through transpiration. This zone is important, more for an agricultural engineer but from water sources point of view, we would be mostly be concerned with the saturated zone or the ground water.

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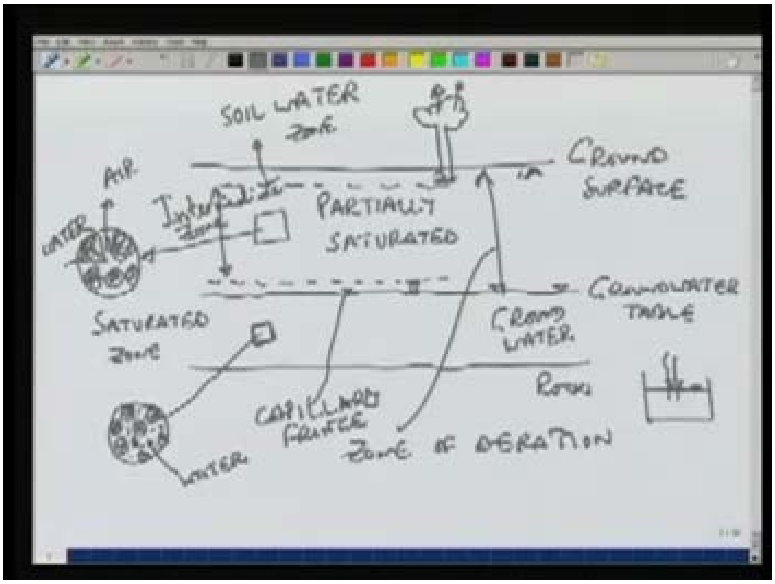

If we look at the zone inside between the soil water zone and capillary fringe, we can call it an intermediate zone.

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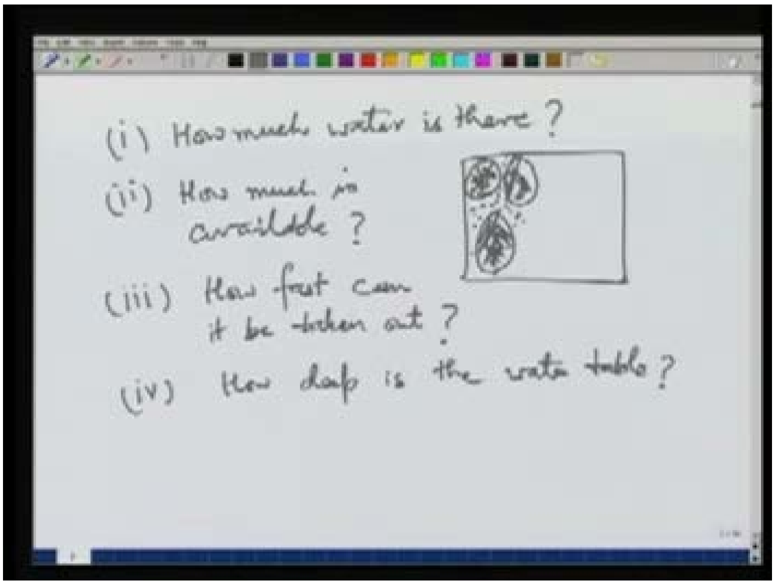

So this is how water is distributed below the ground. We have soil water or soil moisture, then we have intermediate zone, below that we have the capillary fringe and below that we have a saturated zone in which we are interested because this is the zone which will store and contribute to the water whenever we want to use it. So if we look at, let us assume this soil volume which has solid particles. The size of these grains will depend on again what kind of soil it is. If its sandy soil, the grains will be larger. If it is a clay soil, the grains will be smaller and then the surrounding area is filled completely with water. There are two things which we are interested in. One is the amount of water and the amount of water that can be taken out and speed at which it can be taken out. All the water which is present there may not be taken out because some of it will be attracted to the grains and will not be available. From a water sources engineer point of view we have to look at how much of this water is available for us and the third thing which is also equally important is how fast this can be taken out. Another thing which is important also is how deep the water table is because the deeper it is, the more pumping cost we need to use and therefore how deep is the water table. So the depth of the water table is also important.

These questions need to be answered before we try to utilise this water source which is available within the ground. If we try to compare surface water and subsurface water, we find some advantages in surface water. The advantage is in sub surface water. For example if we want to use surface water from a river, it has to be carried to the area where it is used. So we need to store the water somewhere, we need to carry it to the population which needs that water. So we need a storage system and we need some conveyance system like pipe, networks, but in ground water we really do not need the storage because everything is stored underground and the storage is already available to us. Similarly for conveyance too we do not need structures because if we store water inside the ground, it will diffuse because the head difference and will reach to the surrounding areas without laying any conveyance system and therefore the cost of the storage and conveyance system is not present. So it will be less expensive. On the other hand we need to pump it because typically it will be available at a very great depth.

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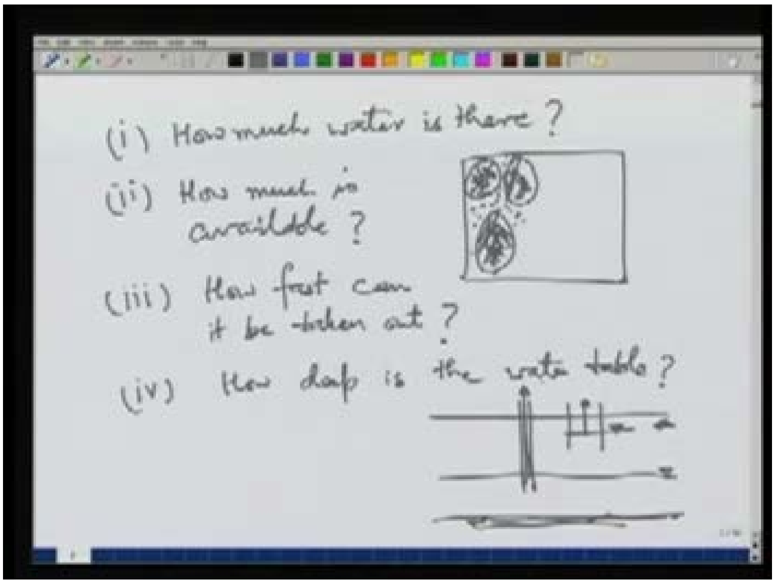

So at the ground surface, the water table will be somewhere here (Refer Slide Time: 10:38) and this bed rock. So if we need to take this water out, we need to install pumps which will be expensive and we need to constantly put in energy to take this water out. If the water table is close to the ground level then we can just dig a well and get water from the dug well. But if it is very deep then we have to have some kind of bore wells which will be able to go very deep and we have to install a pump to pump this water out. So let us look at these things one by one. Firstly, let us assume the amount of water.

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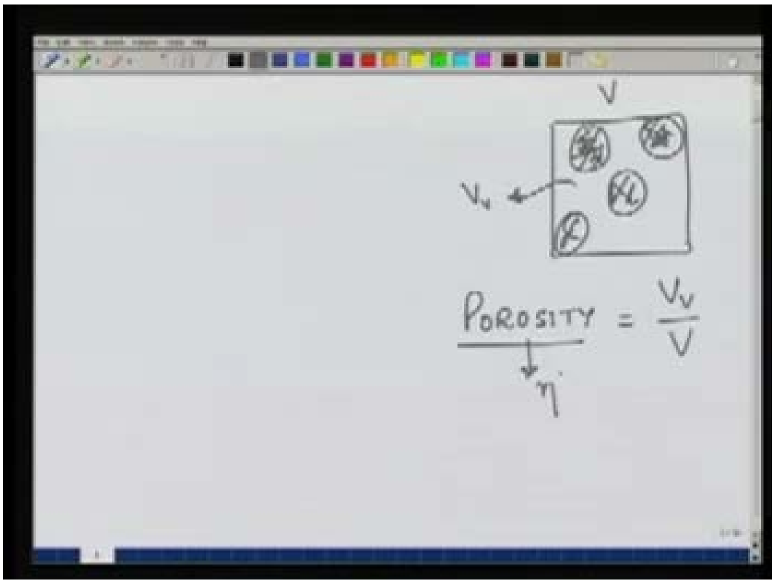

In soil mechanics we have seen a term called porosity which is defined as the ratio of volume of voids by the total volume of the soil sample, so if this (Refer Slide Time: 11:56) is the soil sample and the total volume of the sample is V, then we need to know what is the void space. We call that volume as V_V and the ratio of these two is known as the porosity. Per unit volume the amount of pore space is available is the porosity and if it saturated with water then that means that much water is present. We denote it by symbol eta. This amount of water is available, this is not available but it is present there. How much is available needs to be seen but this much water is present in the soil sample of a unit volume. Now all of this will not be available because some of the water which is very close to the grains.

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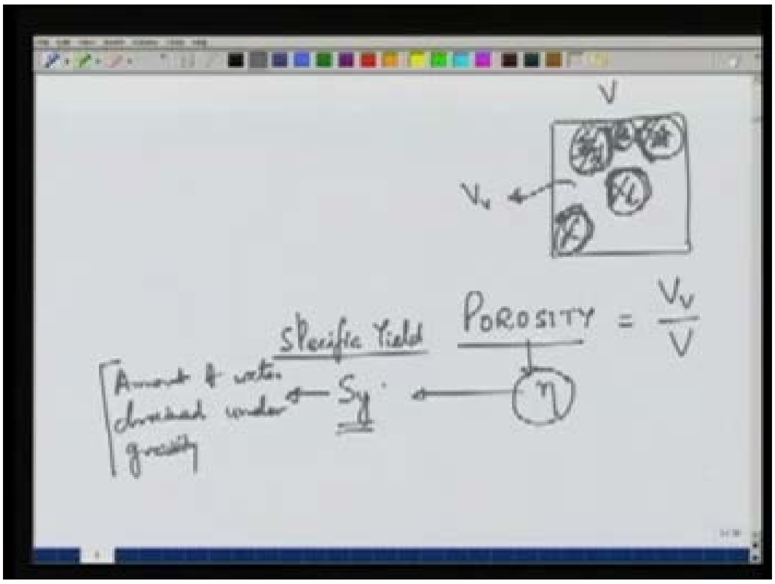

It is attached quite solidly to these particles and cannot be removed. So in order to look at the availability, we have a term which is known as specific yield. Now this specific yield which is denoted by S_y is the amount of water which can be drained under gravity. So you take a soil sample saturated with water and allow it to drain. After draining, there will be some water left inside the sample attached to the grains and may be sometimes between grains but the rest of the water can be taken out and this is known as the specific yield of the formation. So we can define it as the amount of water drained under gravity per unit volume of the formation. Specific yield is the term which is more important to us than porosity. Two soils may have the same porosity but they may have very different specific yields.

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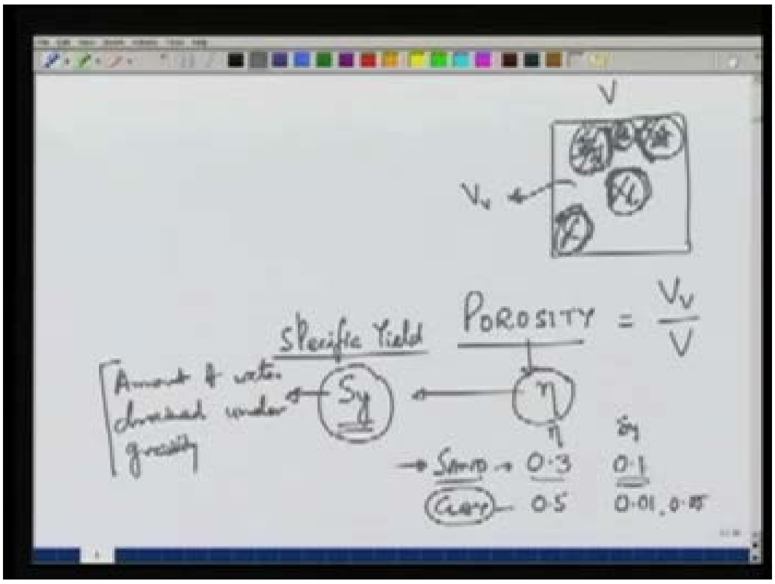

For example sand may have a porosity of about 0.3 and specific yield may be of the order 0.1 or 0.2 while clay can have a high porosity. Sometimes it may be a highest point, 5.6 or even higher but the specific yield is typically small. So it may be 1 percent or 0.055 percent. So though we can see that a clay formation stores a lot of water, the amount of available water to us will be small and therefore we would prefer to have a sandy formation in which there is storage and it can yield sufficient quantity of water too. A formation which stores water may not be able to yield water.

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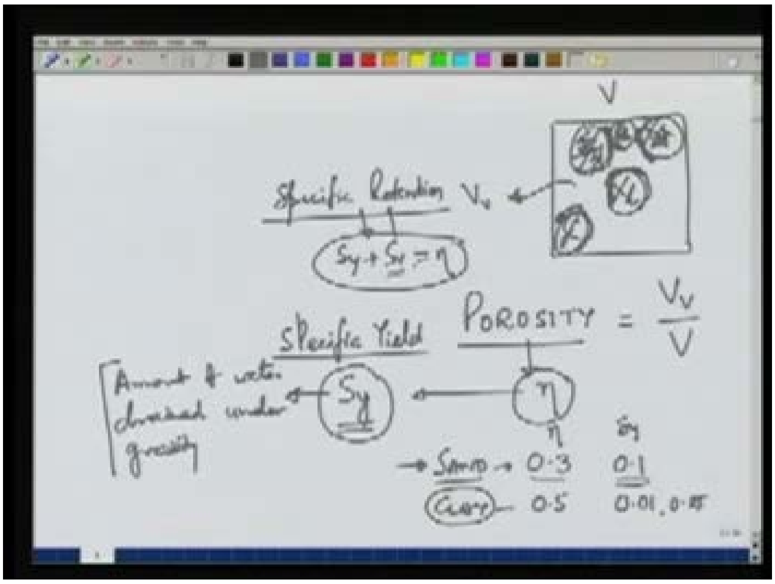

The other term which we sometimes use although, specific yield is more important to us and specific retention is the amount of water retained. Therefore S_y + S_r are the specific retention S_r, so out of total porosity, if we take out S_y then the amount retained by the soil will be S_r, so what we understand from this is the specific retention will be higher for and less for sand and we understood what I prefer or the formation should be able to store enough water and should be able yield enough water. So based on these two criteria, we classify the formations in four different categories.

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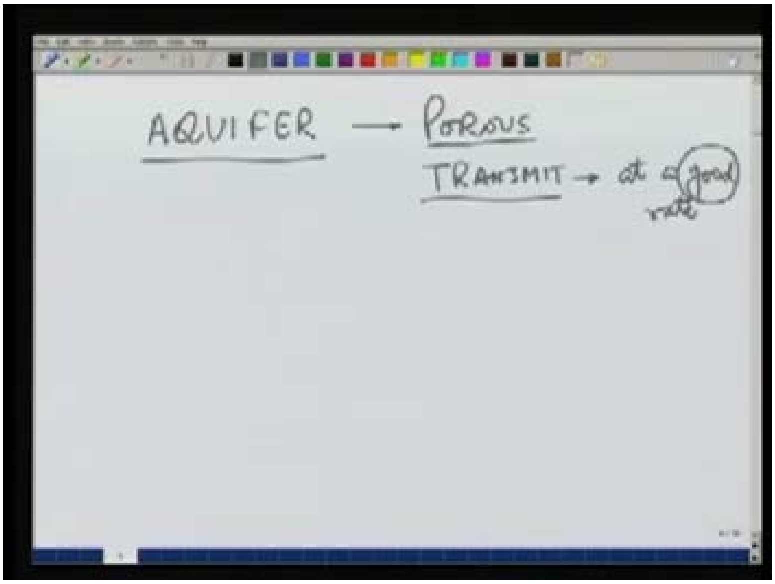

These categories are aquifer, which is the most important for us. Since it can also store water, we would call it as porous. So porous means that it has lot of pores and therefore it can store lot of water and it can also transmit water at a good rate. Now this term is qualitative. It may change from place to place another. Sometimes soil formation may be yielding a good rate for our purpose in some area. The same formation may be yielding water at the same rate but the yield may not be good for some other purpose. Therefore this is qualitative and will depend on the purpose of which we are using the water. We have already seen the case for porous.

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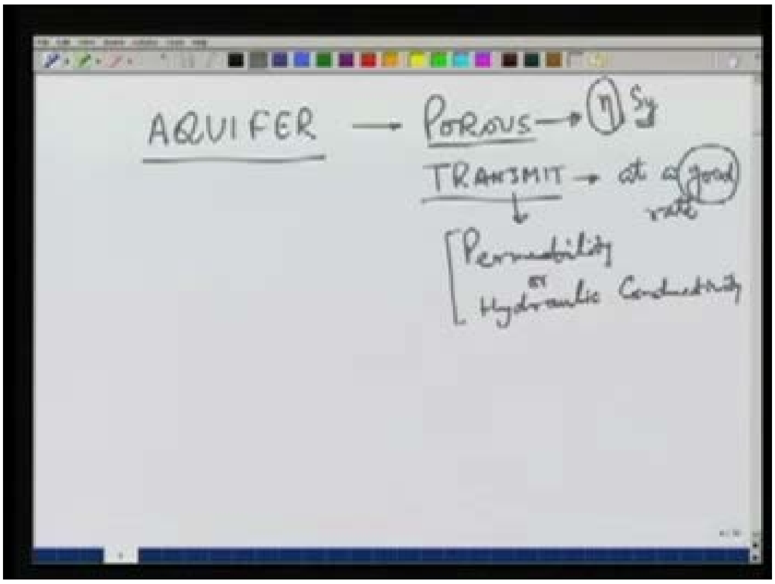

This depends on porosity and specific yield porosity of course is important but specific yield is more important in water resources engineering because this is the amount which is available to us for transmissibility or how fast the formation is able to transmit water. We have a term which is known as the permeability or hydraulic conductivity. We will look at these in detail later. But right now we can just think about these as the ability of the formation to transmit water. So if the hydraulic connectivity is larger that means the water can be transmitted at a faster rate for the same conditions.

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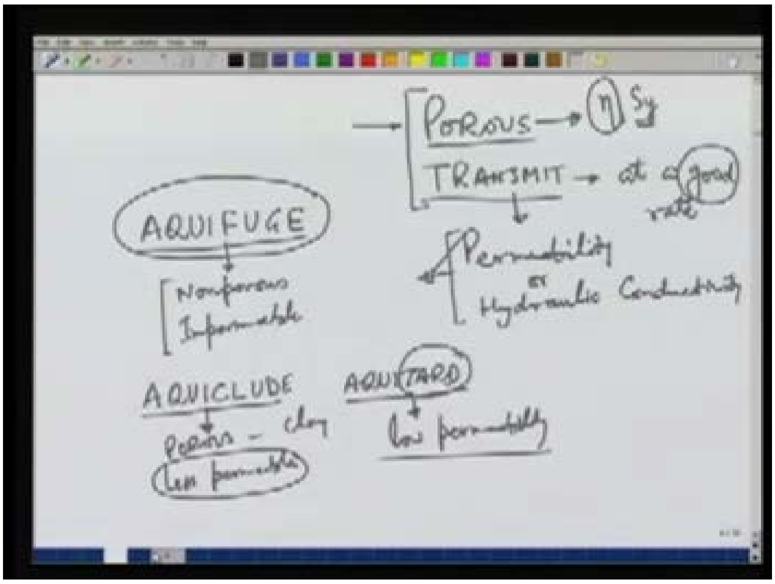

It has a porosity which is high or specific yield which is high and it has a high hydraulic conductivity. Also the example of an aquifer would be a sandy or gravel kind of formation. So the aquifer is able to store and transmit water at a good rate. The second kind of formation which we classify is known as aquifuge, which is just the opposite of the aquifer. It cannot store water and it cannot transmit also at a good rate. So it is non porous and we can say the transmissibility is very small or impermeable. So these are of course not good for our purpose because they do not have enough water and they are impermeable. Also so we cannot take whatever little water is available. We cannot take it out very easily. So examples of this aquifuge will be rock, which has very small porosity and very small conductivity. So this of course is not useful for our purpose. Aquifer is the one that we will be using most often. So this term aquifer will be used to refer to all soil formations and which are of use to us. The other two classifications are aquiclude and aquitard. Aquicludes are porous and less permeable so that they can store water. For example clay, but the conductivity is very small. The aquitards, as the name suggests retards the velocity. It has a very low velocity formation. So out of these as we discussed, aquifer is the one which we will be targeting for our purpose. So we have to answer the questions as to how much water can be taken out and how deep we will we have to go for pumping the water.

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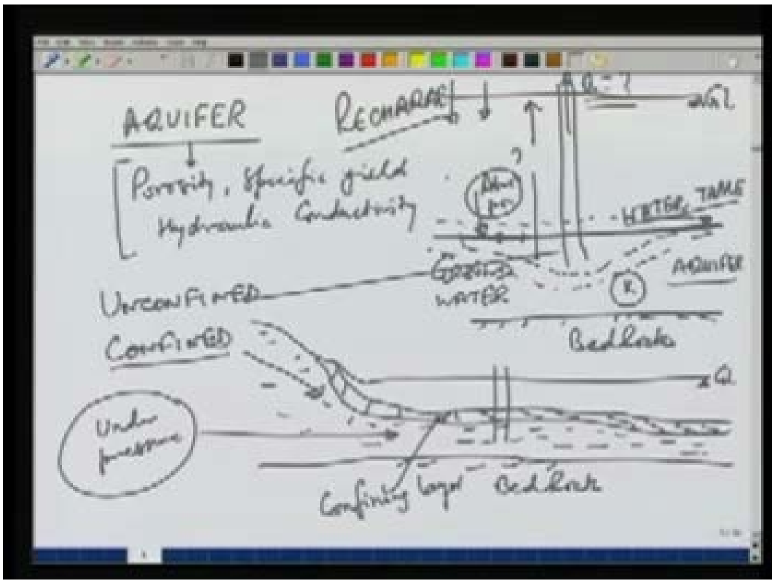

In other words for any aquifer if this a ground level water table and there is bed rock here, this is the ground level, we need to know that if we put a pump here, how deep do we have to install the pump because that will affect the cost of the well. Deeper the well, the more will be the cost. We need to know that when we pump water out, how much can be pumped now. Of course the pumping rate will depend on what the transmissitivity of the aquifer is. But if we pump more, the ground water level will go down. There will be some recharge to the aquifer which denotes how deep the percolation is from the amount precipitated in that area. So if we want to be on the safe side then our pumping should not exceed the recharge. But it does not happen because we need the pumping in areas where the rainfall is low or in arid zones and therefore the recharge is very small. Therefore the pumping rate is much higher than the recharge and slowly the ground water level starts to go down and with time we will see a lowering of the water table. So we need to be able to answer the question as to what is the safe value of Q. It will not result in excessive growth down of the water table so in order to analyse this behaviour of the aquifer, we have discussed earlier. We have this property of hydraulic connectivity for the aquifer which we find out because this will govern the hydraulic conductivity, denoted by K.

This will govern the rate at which the water can be taken out. So I prefer description can be thought of in terms of its porosity, its specific yield, hydraulic conductivity, or permeability. So these are some important parameters of the aquifer. For an aquifer which is shown here in which the water table is open, it means the pressure at the water table will be atmospheric. So if we look at this point or this point or at this point (Refer Slide Time: 25:24), the pressure will be atmospheric. We can call it 0 pressure. Of course, above this there will be F capillary fringe which will have negative pressure. But we will not be concerned about this capillary fringe. We will just assume that saturated zone is present and we will call it the water table and look at the behaviour of water flow in this. Now if the water table is open to the atmosphere, we say it is an unconfined aquifer and the behaviour of this unconfined aquifer is very different from the other kind of aquifer which we call confined. In confined aquifers if this is a ground level we may have a layer of impermeable material. So this is the bed rock or there may be another impermeable layer below this. But this impermeable layer confines the water. So this area is saturated but because of the presence of this confining layer, the aquifer water is under pressure. This water is under pressure compared to this which will open to atmosphere or it will not confine from the top. Therefore the pressure will be atmospheric at this point or we can say an unconfined aquifer on top of the water level will be subjected to 0 atmospheric pressure. In confined, the flow will occur under pressure and again depending on the pressure difference, the water will move from one location to the other. In terms of the movement of water we can define a head which is known as the piezometric head. So let us look at this new term which we have defined.

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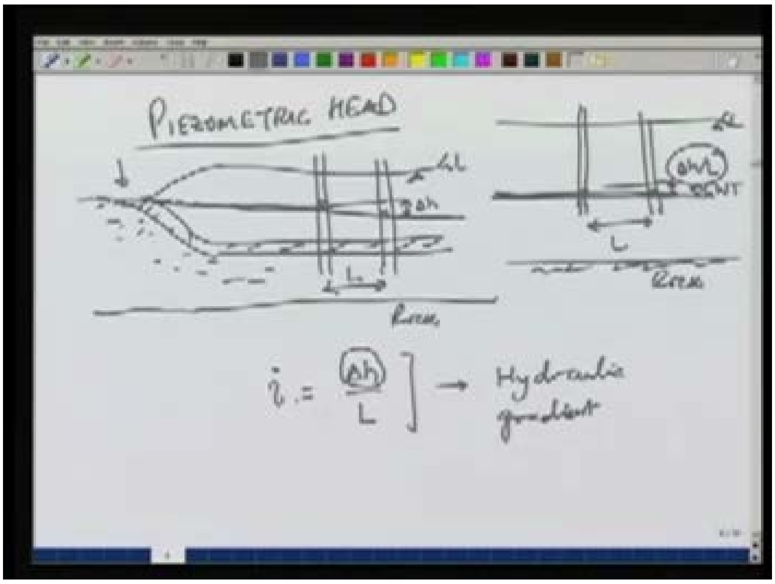

This just means the amount of much water that will rise in a piezometer which is placed in the aquifer. If we look at unconfined aquifer, ground level, water table, ground water table and bed rock. If we put a tube of water here, the water will rise in this tube up to the ground water table because the pressure is atmospheric there. But if we take a confined aquifer, a confining layer and then rock if we put a tube in this water, it will rise above the confining layer because this water is under pressure and it may be coming from some area recharged at this location. So this water is coming from let us say higher elevation, so the head of the water will correspond to a very simplistic way. We can show that this water will rise up to the level from which it is being recharged. So this is known as the piezometric head and it is the difference in the piezometric head which governs the flow of water. If there is no difference in the piezometric head then there will be no movement of water. So if we take another tube here, another piezometer here, the water may rise up to this point. So there will be a head difference which will cause the flow. If we plot the piezometric head it may look like this and the gradient of this is denoted by i, is called the hydraulic gradient. So in unconfined aquifers the hydraulic gradient will be nothing but the slope of the ground water table because if you put a piezometer here, water will rise up to the ground water table. So the slope of this ground water table will give the hydraulic gradient. But in confined aquifers the piezometric head difference, delta h and so this gradient is the driving force for the ground water flow.

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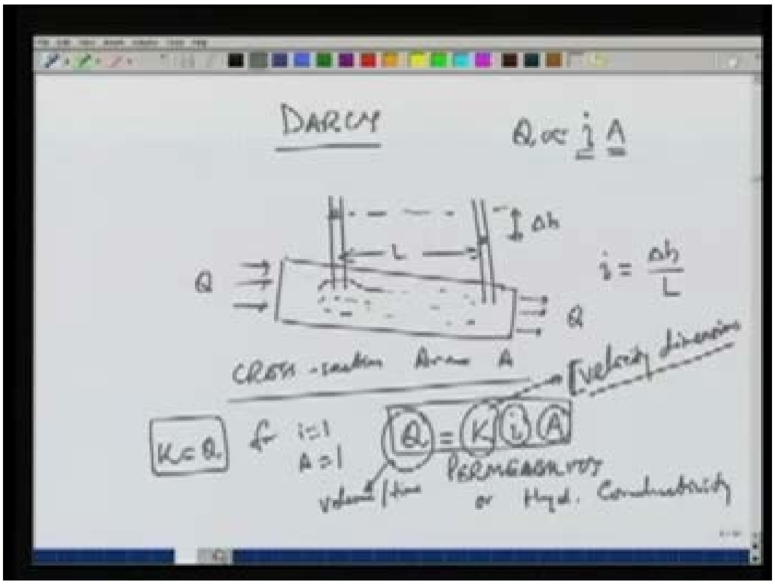

In a very famous experiment which was conducted almost 150 years ago by Darcy, in which a tube filled with soil was subjected to some water flow of let us say, amount Q in units of meter cube per second or feet cube per second. What the experiment looked at was, if this a tube of cross section area A, the head difference between these two piezometers is delta h and a length of L then what Darcy found was that the amount of water flowing would be proportional to i where i is the hydraulic gradient and the area of cross section. So if you take a different experiments with different hydraulic gradients, the amount of flow Q would be directly proportional to the hydraulic gradient i and area of cross section A. Therefore he introduced the constant of proportionality and called it permeability or hydraulic conductivity. So the dimension of this K will be the same as velocity that is meter per second or feet per second.

So if you look at this equation, we have a way of defining the hydraulic conductivity. For example if you say that there is a unit of cross section area tube subjected to unit hydraulic gradient then Q = K. So, hydraulic conductivity can be defined as the amount of flow passing through a unit cross sectional area of soil with a unit hydraulic gradient. We can write K = Q for i = 1 and A = 1 and what it tells is that, if hydraulic conductivity is higher, then we will have more amount of flow from the soil. For any given hydraulic gradient or given area, now if you look at the value of K, we say that it has a velocity dimension, the Q which is the amount of flow which is in terms of volume per unit time. So if we divide Q by the area, we would get a term which will be similar to velocity

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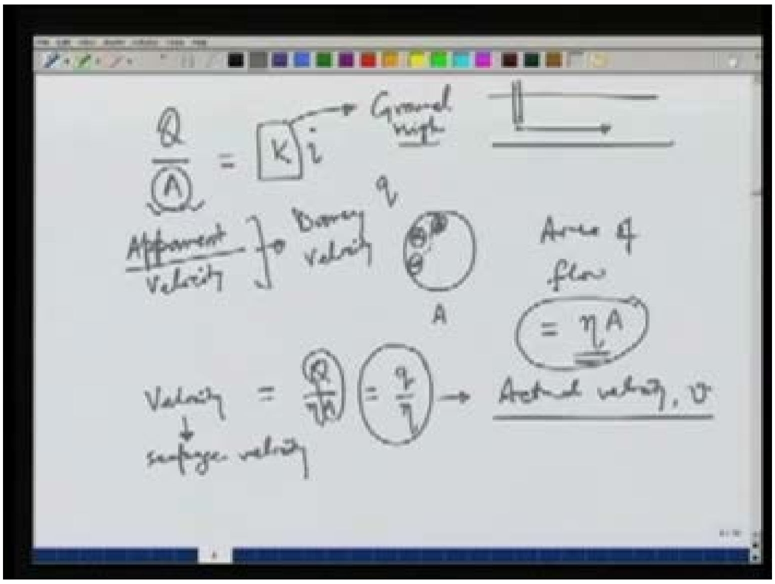

So we can write this term Q over A is an apparent velocity and why we call it apparent is because the whole cross section area of the tube, suppose this is the cross section area A of the tube, then this area consists of soil particles as well as the pore space filled with water. So when we divide it by area we are not accounting for the area of flow. The area of flow that is the area from which the flow is taking place will not be equal to A, but will be equal to the porosity times A. It can be shown that the volumetric porosity and the cross sectional area porosity are same values. Therefore the area of the flow, actually pore space is the amount which is occupied by water, is smaller than A by an amount which is equal to the porosity. So the real velocity which sometimes is also called seapage velocity will not be equal to Q over A but will be equal to Q over eta.

Generally, the term, apparent velocity is used. But sometimes we also call it Darcy velocity and it is denoted by small Q. The real velocity or sea page velocity is also written as Q over eta because Q over A is a Darcy velocity. So this is the actual velocity of flow and what it means is that if you take a soil sample and let us say we put some object here (Refer Slide Time: 34:48), we inject a die then the velocity at which this will move will be the actual velocity and we then use the notation V to denote the actual velocity. So if we put an object in the ground water its velocity of flow will be equal to Q over eta and not equal to the Darcy velocity. The hydraulic conductivity is therefore a very important parameter and there are various ways of determining the hydraulic conductivity for different soil formations. Gravel will have a very high conductivity. Sand will have a little smaller and clay will be very small conductivity. So in order to have formation which yields enough water and also very fast, we should have a high porosity, specific yield and hydraulic conductivity. So in order to compute the amount of flow through an aquifer, the Darcy’s law is used.

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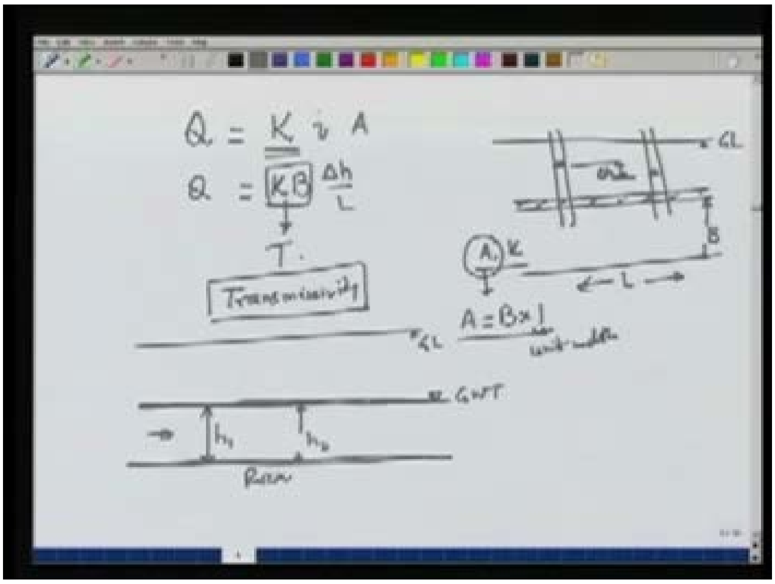

As we have seen Darcy's law tells that discharge Q will be proportional to the hydraulic gradient in the area and the constant of proportionality used is the hydraulic conductivity. So if you look at let us say confined aquifer, then we have these confining layers and if you look at the permeability of K for this and the area of A, let us say that these two piezometers are installed here which show a head difference of delta h in a length of L. let us say that thickness of the aquifer is B. Therefore if we consider unit area, we consider a two dimensional case in which we say that aquifer is extending for a very large distance perpendicular to this plane and consider unit width of aquifer, then the area will be B into 1. We can write then KB delta h over L. So this term K into B for confined aquifers occurs very commonly in these equations and therefore it has been given a symbol of T and called transmissivity. For unconfined aquifers, the thickness of aquifer h varies from point to point. So if there is a gradient here then we can say that we will have some head here h_1 or some height h_1 and a smaller height here h_2 depending on the location of the bed rock, the bed rock level is assumed horizontal then if there is a gradient like this h_2 will typically be smaller than h_1. But in confined aquifers assuming that this thickness B is constant K, B can be replaced by the transmissibility. So in order to find out the amount of flow which can occur through the aquifer, for a given difference of head, we use the Darcy’s and then we use the Darcy’s law to get the continuity equation which tells us a mass balance over a certain element.

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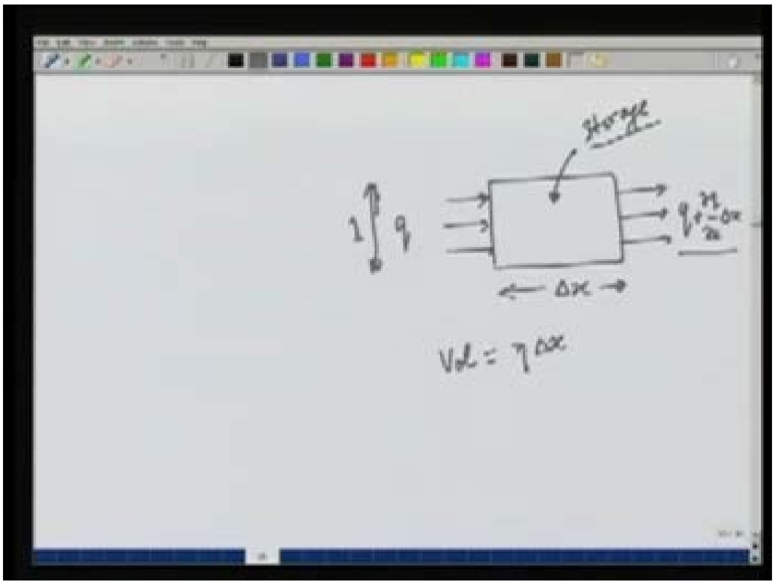

For example if we take an element like this which has let us say length of delta x, there is some flow coming in here from the left hand side. We can call it q and there is some flow which is leaving which based on the expansion can be written as q + del q/del x into delta x. So the continuity equation says that mass has to conserved. This means the net inflow into this volume should be equal to the change of storage.

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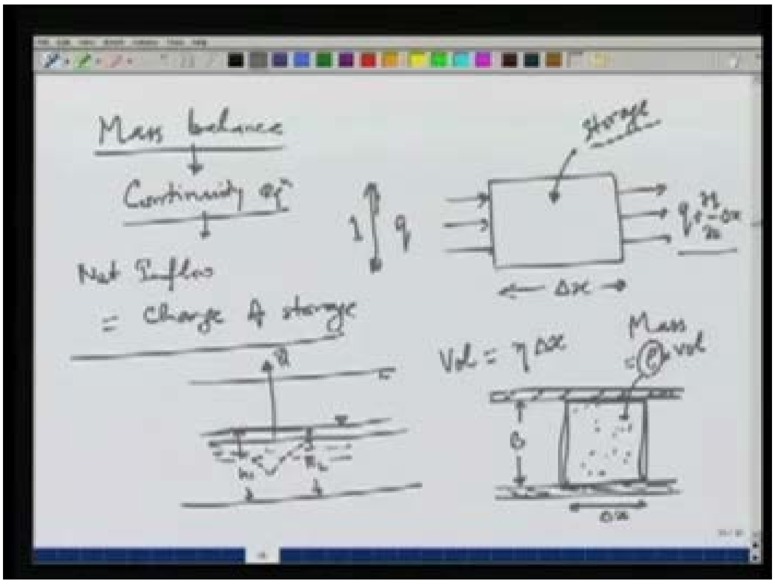

So there is some water stored in this element and if we assume that the porosity is data and consider unit width perpendicular to this length then the volume of water present inside this sample or inside this elementary volume can be given by, we take a unit width here, let us say that the width is 1 and also one perpendicular this length. So eta delta x will be the volume of water stored within this element now. If this mass balance has to be satisfied, it leads to the continuity equation which says that net inflow equal to change of the storage. So if we take this confined aquifer in which we are saying that there is no change in the height, what we are looking at is a constant height B. Let us assume a certain length delta x. So if we look at this volume, since there is no change in the volume, you can compare this case with unconfined aquifer in which case, suppose you are pumping water from this aquifer with time, the water level will go down or in case you have well here it may go down as this(Refer Slide Time: 47:58). But the area or the volume is changing with time but here in confined aquifers the area and therefore the volume is not changing with time therefore the mass can change with a change in the density. Here the compressibility of water as well as the soil will be important.

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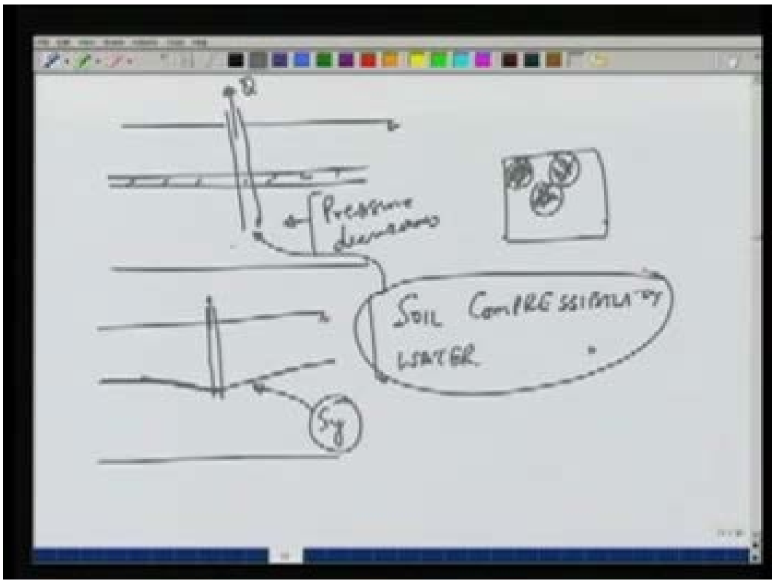

As we know the soil is compressible when you have a confined aquifer which is being pumped as water is released from the aquifer, the pressure goes down. So to this aquifer, some pressure will now be subjected to a lower pressure and therefore the density of water will change and the soil density will also change. So the soil metrics, compressibility and water compressibility will affect the release of water from this volume. Therefore when we write continuity equation for confined aquifer case, the compressibility of soil and water have to be taken into account. For unconfined case, since it is atmospheric pressure and water is incompressible under atmospheric or small pressure conditions therefore compressibility of water and soil does not enter into picture. Here the specific yield is more important. Specific yield will decide how much water will come out of an unconfined aquifer but soil compressibility and water compressibility will affect the yield or the release of water from the confined aquifer. So when we derive the continuity equation it is by nature different for confined and unconfined aquifers. We would look at the derivation of the continuity equation using Darcy's law and balancing the inflow and the rate of change of storage within the volume.

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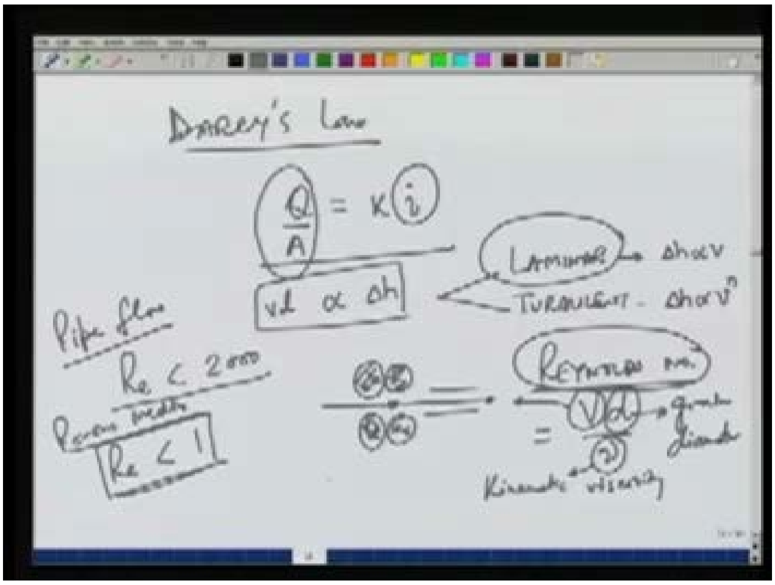

So if we write the Darcy's law, let us put the area on this side. This is the basic equation which we have to use in all our computations of continuity or mass balance. What it says is that there is a velocity which is proportional to head loss because this i is proportional to piezometric head loss. Now we have already seen in pipe flow cases that for laminar flow, the head loss is proportional to velocity and for turbulent there is nonlinear relationship where head loss is proportional to velocity to the power n. n is around 1.7 – 1.75. So if we look at Darcy's law, it tells us is that the flow has to be laminar in order that the Darcy's law is valid and velocity is proportional to delta h or the head loss is proportional to first power of velocity. We need to have some kind of laminar flow within the porous media. So let us look at flow through a pore and let us say that we have these kinds of soil particles and there is a tube, a porous tube through which water is flowing.

The diameter of this porous tube of course, will depend on the diameter of the grains. As w.r to pipe flow, we can define a Reynolds number as velocity, some length which typically will take as diameter and the kinematic viscosity. This diameter in pipe flow is the diameter of the pipe. So here since diameter of the pore will depend on the diameter of the grains, we can put the grain diameter here which may be let say d_{10} or d_{50} or d_{90} of the soil velocity. V can be put as the Darcy velocity and this new, is the kinematic viscosity of water. So when we look at the Darcy's law its applicability will depend on the Reynolds number in pipe flow. We know that the Reynolds number Re should be less than about 2000 for the flow to be laminar. In porous media, based on experiment, this has been found that Re should be lesser than 1. This is for pipe flow, circular pipe and for a porous media, using a grain size as the characteristic length, the diameter here d; Re should be less than 1 for the Darcy's law to be applicable. So the applicability of the Darcy's law will be limited to small velocities. In general, ground water flows at a very small velocity.

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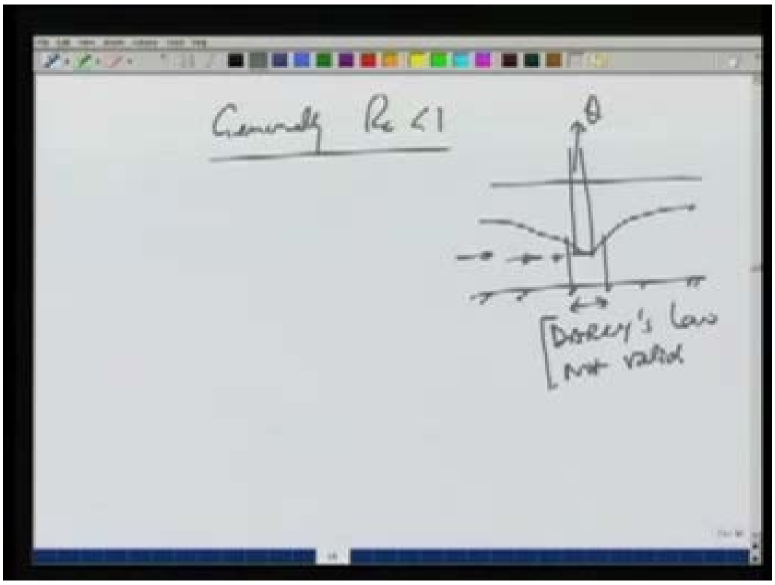

So generally Re is less than one and therefore Darcy's law will be applicable. But in some cases Darcy's law will not be applicable. For example if you are pumping water from a well, the velocity far away from the well may be small. But as water comes closer to the well, the velocity becomes very large. So it may not be valid in some portion here. For high pumping rates, very close to the well, Darcy's law may not be applicable. Similarly for flow through gravels sometimes we may get velocities which are very high and Darcy's law may not be valid. So when we apply Darcy's law in order to derive the continuity equation we should be aware of the limitation that the Reynolds number should be less than 1. So we have to check the Reynolds number and ensure that this is less than 1 and then apply the Darcy's law. The second thing which we notice in Darcy's law is this term K hydraulic conductivity.

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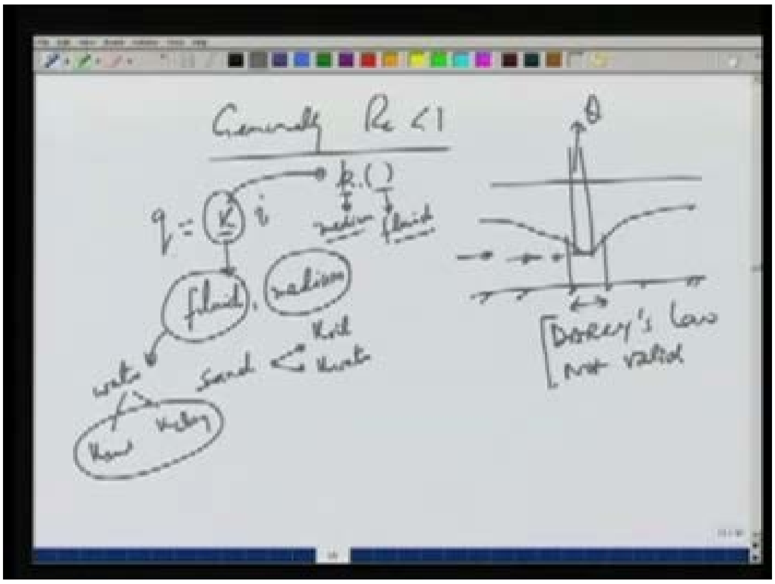

So if we write q = Ki, the term K will depend on both the fluid and also the medium. For example if you have a medium which is fixed, for example sand for different fluids, the hydraulic conductivity will be different. So suppose you have sand now. K for oil and K for water will be different for the same material; similarly if we have water, then K for sand and K for clay will be different. So the hydraulic conductivity term includes both the fluid property and the medium property. We will see little later that we can partition this into 2 parts and intrinsic permeability K into a term which will only depend on the fluid. So we will derive the continuity equation the next time using Darcy's law. So in today's lecture we have seen what is ground water, what is the basic Darcy's law that governs the flow to the ground water and what should be kept in mind while applying the Darcy's law. We have also seen different kinds of formations in terms of their water bearing capacities and water transmitting capacities and in the next lecture we will derive the continuity equation for different kinds of aquifers.