Groundwater hydrology and Management
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Lecture 19
Hydraulic Conductivity

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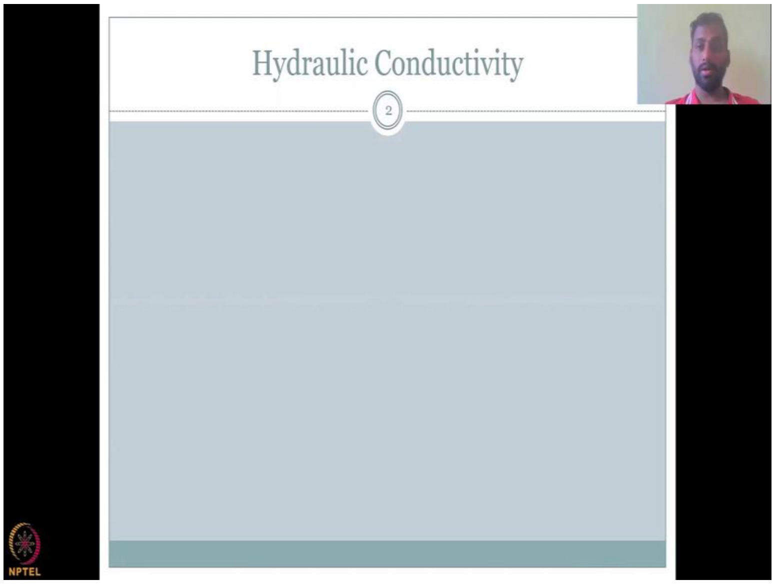

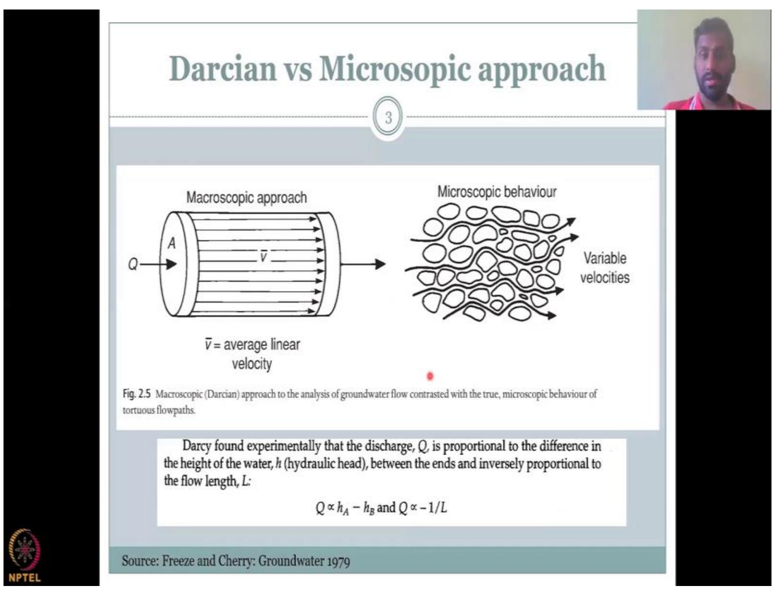

Hello, everyone. Welcome to the NPTEL course on Groundwater Hydrology and Management. This is week 4, lecture 4. In this week, we are continuing to discuss the important components of groundwater hydrology. And to continue our discussion, we will look at hydraulic conductivity, which is one of the most important parameters for groundwater hydrology.

In the previous lecture, we discussed about the macroscopic view and the microscopic view of groundwater flow. And how the water interacts and moves accordance to the material the soil or the rock material. So, in the macroscopic or which is called the Darcian view, you have a average linear velocity of the water particles, because in a discharge Q which goes around a cross section area A, the macroscopic view does not capture what is happening inside.

So, how does water move inside is not captured and not needed to be honest, because in a macroscopic view, it is averaged. So, you have an average linear velocity. So, the velocity is assumed the same on the top, middle and bottom portions of the soil. But in the real world, which is a microscopic view, you see on the right-hand side, you understand that the water does not go in a straight line as we see here, in the macroscopic view.

Where water would go in variable velocities along the soil medium. And this is because of the heterogeneous composition and arrangement of the soil particles. So, you need to understand that there are microscopic differences and variable velocities. However, when you want to describe them in a particular equation, you need a macroscopic view.

So, that is what Darcy took over. And he modeled this groundwater flow through a pipe. So, he did not want to do it on the land and ground because of the microscopic variations, he did it in a lab setting. So, Darcy found experimentally that the discharge Q which goes into the soil medium is proportional to the difference of the height of the water h which is the hydraulic head and the difference we also called as gradient between the ends and inversely proportional to the flow length, which is the length of a soil column through which the water flows.

So, you have Q is directly proportional to hA minus hB we will see what hA and hB is in the experimental setup. And Q is inversely proportional to the length of the soil column. Before that, just to introduce Darcy, Darcy was an engineer in France where he worked on fountains, water fountains and he had to supply water through underground to make sure that the water fountains were working properly, for that he did not have any equation, this was very very old times.

And so, what he did is he took the soil column to his lab and then did this equation. And till date, it is one of the most accurate, very simple, but most accurate description of the groundwater flow in a saturated system. The assumption is also that the soil inside is fully saturated, we need to understand Darcy's approach because Darcy was doing this to send water into the fountain and the fountain I needed a continuous supply of water for which the soil and everything was saturated and through a pipe column. So, we can look at the differences in his experimental setup and how he got it.

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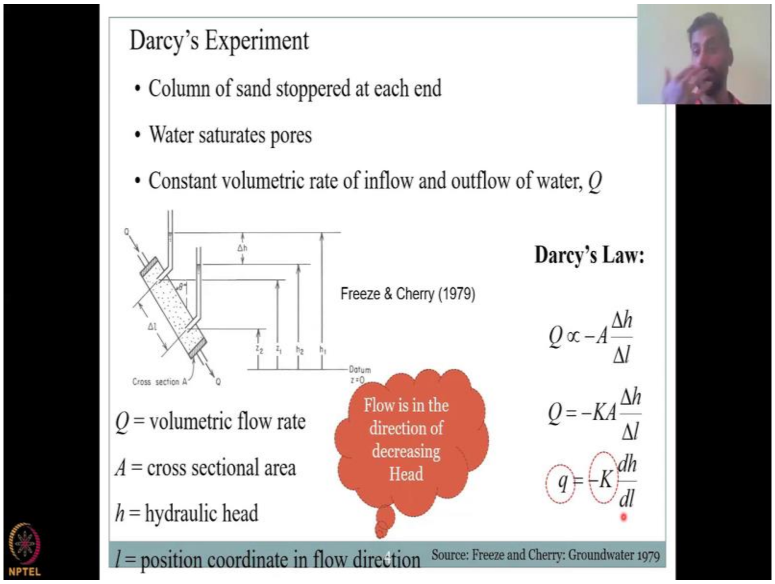

This slide, so, in the Darcy's experiment what we noticed is that the column of sand stoppered at each end so, either sand, soil, rocks materials, the material the matrix is kept in a tube and it is stoppered, a rubber stopper is put on the top and bottom. Water saturates the pores; water is fully saturated inside the pore space. Now apply yourself to the previous lectures, if we say porous space is fully filled with water that means it is a saturated system.

And also, it means there is no air inside the soil. So, this column of soil he took in a tube has full water inside along with the soil particles. How do you establish it? You just continue to pour water until for a long time until the water comes out in the same rate. So, Q is the input rate and if the Q water comes out, that means full it is saturated. Constant volumetric rate of inflow and outflow of water Q.

So, he also maintained Q to be constant, the flow coming in and coming out, and that is what was needed to operate the fountain systems. So, he would send a known volume of water which is Q, which is already measured and metered through a soil column of length del l which or just l. And then he had a stopper and Q coming out, the cross section of the tube was measured as A and he had two points of monitoring inside the tube and those can be visualized as wells.

So, he wanted to know, what is the flow inside the medium. So, to understand the flow, he put two monitoring points. And between the points he is going to calculate the well, hydraulics and the hydrology groundwater hydrology movement. So, what he did is the first well is called well A, let us say A and then the well B is in a lower elevation. And why does water move from top to bottom?

Because water flows from high potential to low potential. There is no other fancy instruments here just Q, he is sending in, he does not have to push it because gravity is pulling the water from high potential to low potential. So, when you put in the well, automatically the water level in the well will equilibrate based on the atmospheric pressure, the pressure inside should balance the pressure outside and it falls into a particular level after it equilibrates.

And that is hA, we saw in the previous equation, hB is the same water level measured in the well B. So, del h or hydraulic gradient, it would be your difference in the h and divided by the length, del l. So, what we have here is a distance between the wells and also a difference in the head. Also, what we need is the elevation of the well inlet from the data which is 0. So, here the table has 0 and from there how much is the elevation of hydraulic head 1, which is hA and hydraulic head B which is at hB.

So, he measured the elevation of the well z1 and z2 then he measured the total hydraulic head which is h2 and h1. So, h2 and h1 are going from the datum which is the 0 elevation. So, from the 0 elevation you go up to the water level, this includes the elevation of the well. The elevation of the well is the point at which the well opening is there from the ground from the ground which is 0.

And the hydraulic head is at on addition to that the water column height is added. So, now we have the total potential. So, h1 is higher than h2 and that is why groundwater will flow from h1 to h2 because high potential low potential. So, it was from high potential to low potential. So, Q is given as the volumetric flow rate. A is the cross-sectional area, h is the hydraulic head which is including the elevation, elevation of the well from the ground. And L is position coordinate in flow direction. So, how much in the flow direction at length.

So, Darcy's law has given us the first law what it says it is proportional to the hydraulic head difference which is del h, del h is the difference between h2, h1 and h2. And also proportional to the cross-sectional area directly proportional, it is inversely proportional to the length between the wells between the estimation points. So, now, any proportionality can be converted to an equation by introducing a proportionality constant. So, this proportionality symbol would go to an equal when we introduce A proportionality constant and that constant is called hydraulic conductivity.

So, the hydraulic conductivity is given as K and A is the area del h by del l. So, if you take the area out, I am not interested in the total volume but I want the velocity or the discharge. And that discharge Q is rated by the area. So, if you divide by area on both sides, you get small q which is equal to minus K dh by dl. So, this is a very simple equation but captures the flow of water between two wells and also the discharge rate.

Now, let us take a step backwards. Why do we have a minus? Where did the minus sign come? So, when we discussed it is like it is proportional and it is inversely proportional to the length. But where did the minus sign come? The minus sign is introduced by Darcy to document that the flow is in reducing direction of potential. So, the negative is a directional value not a value that you put on discharge, you cannot minus the discharge.

So, what do you mean by minus discharge? There is nothing as minus discharge, but the negative sign indicates that the flow is in the direction of reducing head. So, it flows from high head to low head and that capture, that needs to be captured otherwise, how do you know which side is the water flowing. So, to document that Darcy had introduced the minus sign, and it flows from high potential to low potential or towards the decreasing head, the head is decreasing. So, all of this is captured in a very, very simple equation.

And to be honest, working with groundwater systems for the last 10 to 15 years, I have noticed that this equation has been most powerful, even compared to the newer equations that come now and then. So, there is not much additions done to this equation. And all these groundwater models are based on this equation for saturated flow.

These equations and descriptions can be taken from Freeze and Cherry book 1979. As I said, it is one of the very important books that groundwater hydrologist would have and all these government schemes are also referring to these books. Flow is the direction of decreasing head. So, the negative side please understand it is a direction value, not a value that you put on the quantity, it is not a decreasing discharge, minus discharge plus discharge, it is the direction. Flow is the direction of decreasing head.

Also understand the difference between large Q and small q, large Q is the flow which is a volume and Q meter cube or l times three on the power but your small cube is a rate or velocity kind of thing. So, it is a discharge and l by t. So, the time would come in this equation, whereas in the discharge it is volume per unit time.

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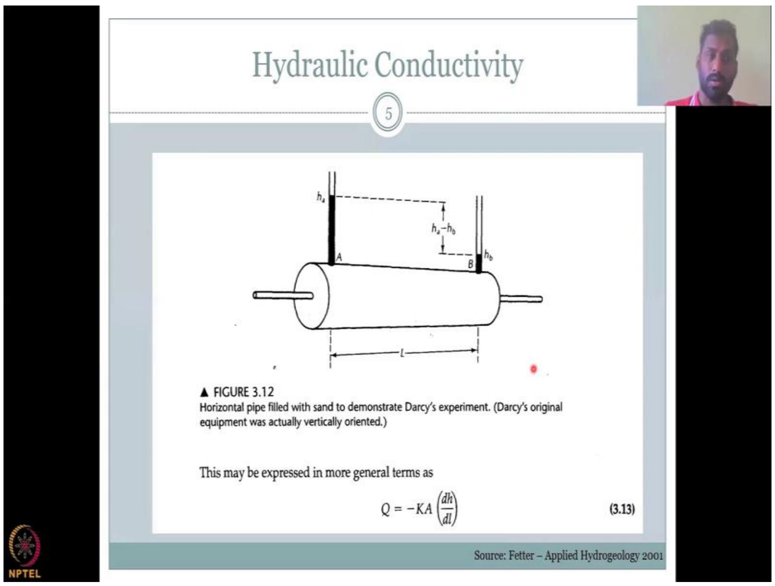

Moving on, we have a horizontal pipe filled with sand to demonstrate Darcy's experiment in a different book I have taken a different approach to just show the same explanation, but in a more different way, then the Darcy's book. So, horizontal pipe filled with sand, so, there it was slanting, but here it is an horizontal pipe to demonstrate Darcy's experiment. So, as the book says it is originally vertically or slanted position but we can also expend it in a horizontal way.

Why do we need to expend it in a horizontal way, is to capture the ground system, most of our ground is not going to be always like this in the field. So, for example, in a rural area, you want to monitor the groundwater flow between two blocks and the blocks are going to be straight, it is not going to be like tilted et cetera. But inside the ground it may be tilted and that is because of the layering, you remember the aquifers we talked about so, the layers might be tilted or different and that causes the head difference.

So, what this diagram says is that there are two wells and two wells have different head, hydraulic head. So, hA is the hydraulic head on well, A and hB is the hydraulic head on level B, well B. We cannot ask why is one higher than the other, it could be different aquifers, it could be different pumping regimes. So, even though it is horizontal, the levels are different.

Now, the L is taken as the difference between the wells. So, the basic equation is Q is equals to minus K hydraulic conductivity A, which is the cross-sectional area times dh by dl, dh is your change in the head or difference between the head from hA minus and hB and your dl is the distance between the wells. Now, this dh by dl is called the hydraulic gradient.

And what you also notice is that the K, the property K is the one which captures the property of the soil, because area A is basically the area of the cross section, h is the hydraulic head which is a water property and del l is the difference between the wells. So, where does the property of the soil or the solid come, it comes in K hydraulic conductivity. So, the conductivity as I mentioned in the previous class is a term given to the soil and how easy it conducts or lets the water to pass through. And so, we call it hydraulic conductivity, which is a property or a function of the solid.

Moving on, please understand, there are lots and lots of units for this values. It can be expressed as gallons per day per meter square or liters per day. It is all in a l by t dimension, which is length by time. So, if you divide gallons, which is a volumetric term by area, you get one length. And the day is your time.

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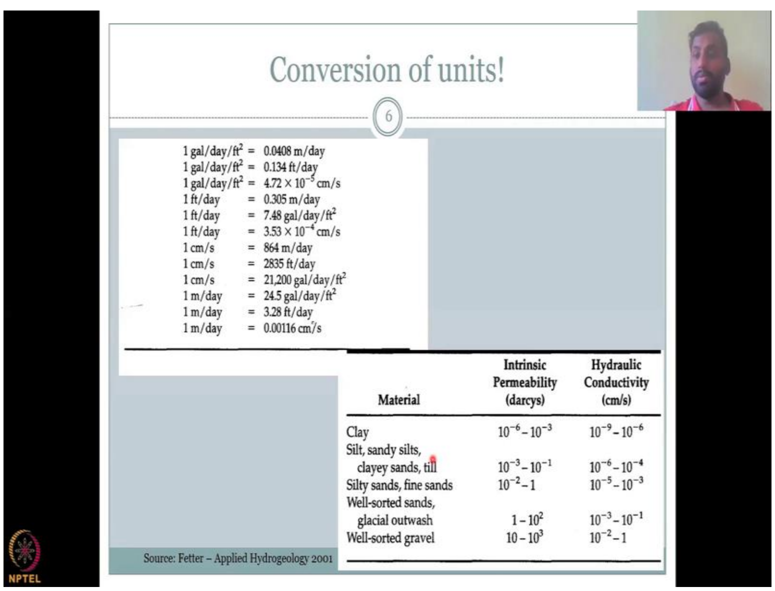

So, you can have multiple multiple units. So, please be careful with the units. I recently was in an examination where the student was trying to say no, it does not agree, the data does not agree. But then the simple thing was that the units were different. So, make sure the units are captured correctly. I am going to stress this again and again, please make sure what the unit is and see if it is agreeing when you compare.

So, let us look at some of the hydraulic conductivities. In the previous lectures, we looked at permeability, porosity differences and now hydraulic conductivity. If you look at it, hydraulic connectivity is a function or can be expressed as a permeability and along with the gravity constant and your viscosity and your density of the fluid. So, it is basically related variable. So, for clay it is very, very slow centimeters per second.

So, think about 10 minus 9 centimeters per second is the flow rate, kind of velocity of water in clay or how clay allows water to flow. So, it is very, very slow. So, when you go to a field, the first question you can ask is what type of soil it is. And if they say clay, then you would understand that groundwater recharge would take a long, long time. We will have some examples in the next class.

So, moving on silt and sandy soils, the mixture of clay, sand and particles have a slightly reduced hydraulic negativity or a higher hydraulic conductivity because sand actually can improve the hydraulic conductivity. When you go to silty sand and fine sand you have more hydraulic conductivity. So, we are going in increasing hydraulic conductivity. And then, when you go to well sorted sands, glacial outwash which is the deposit by snowmelt.

And well sorted is that the particles are well sorted, good space in between, then your hydraulic conductivity increases. So, the highest would be at least on this data set. It is the well sorted gravel; gravels are bigger in grain size. And they have well good built structure, because it is well sorted and it has space in between. So, when you start something, it will have have lot of space in between and that space can make the medium conductive. And that conductive will increase the hydraulic conductivity of the material.

So, you will see higher water flowing through recharge and groundwater discharge through well sorted gravel and least in clay, clay also swells, it also takes the water and holds on to it. So, all this is kind of captured by your hydraulic conductivity. We can also use a Freeze and Cherry's book that we used in the previous lectures for permeability.

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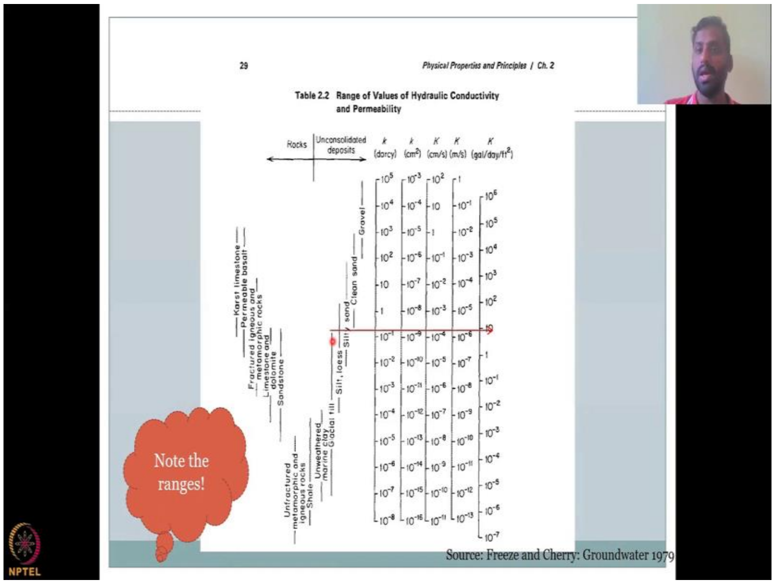

Let us take an example of again the silty sand, because that equates to your fracture igneous metamorphic rocks. If you go back to the class notes, you understand that is the dominant aquifer system in India, the hard rock aquifer covers more than 60 percent area. And so, if you take that, we are going to take that as an example to understand hydraulic conductivity. We will use a centimeter per second or meter per second to discuss the results.

So, you see that it is anywhere between 10 minus 4 to 10 minus 3 centimeters per second, it is very slow, whereas in your aquifers, alluvial aquifers, which is around 30 percent in the country, the Ganges, Indus, Brahmaputra, the Kaveri, Delta so, those regions will have a higher hydraulic conductivity.

So, those would be more on your permeable basalt or your clean sand, the sand, alluvial sand. And then you could see jumps up, the hydraulic conductivity can jump up from 10 power minus 4 to 10 power minus 1, if I draw a line here, it is 10 power minus 1 centimeters per second. So, it is moving at 1 millimeter per second, which is pretty fast.

So, you are thinking about per second, per day. So, then you convert it per hour, per day, per year. Always go in time in sequence. We will do some calculations in the next class to show what does these value mean. But before that, I would like to also introduce the hydraulic head concept in this lecture.

So, always note the ranges is, the range is big. And why is arranged big? For example, in silty sand, the range is from 10 power minus 5 to 10 power minus 1 so, minus 10 power minus 4 orders of difference and that is because of the mixture, the combination of your silty sand could be different. And also, the management of the land could be different. But either way it falls within this band.

Also note that when I just take one value, let us say 10 power minus 4, it could be a clean sand on the border of clean sand, it can be a silty sand it could be silt loess or glacial till. All these four, five different types can be within that one value. So, it is up to you to understand first what that material is by physical and lab estimations. And then you pick your hydraulic conductivity.

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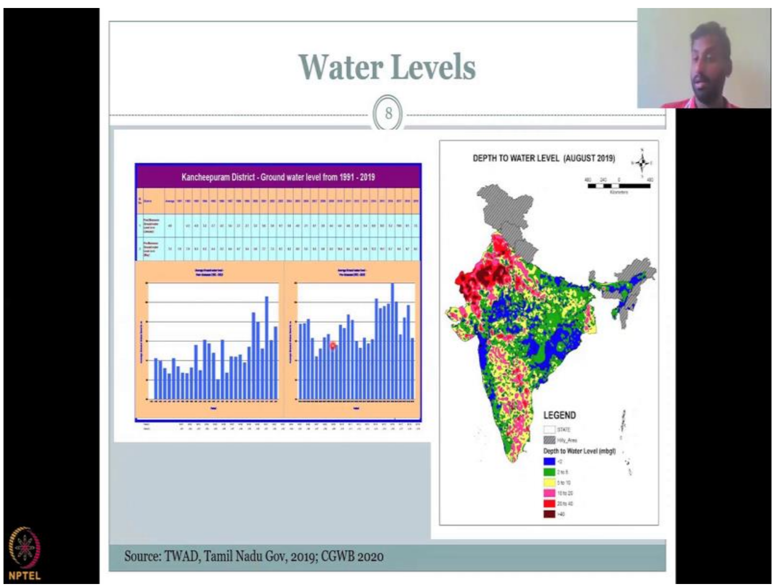

Water levels. This is a very, very important concept to understand the hydraulic conductivity and groundwater hydrology. Because that is what we are measuring. At the end of the day, the government and the system would measure water levels. And I am taking a small example just an introduction, we will jump into one lecture on this data to understand this. So, all this data would convert to a groundwater hydrology equation by the examples we showed in Darcy.

So, this is a picture of the groundwater data that is calculated and captured by the government of Tamil Nadu and on your right is the Central Groundwater Board. So, there are two agencies at least in Tamil Nadu collecting groundwater data. So, they collect the data and then they collect it in different years and months, and then they equate the difference to understand what is happening.

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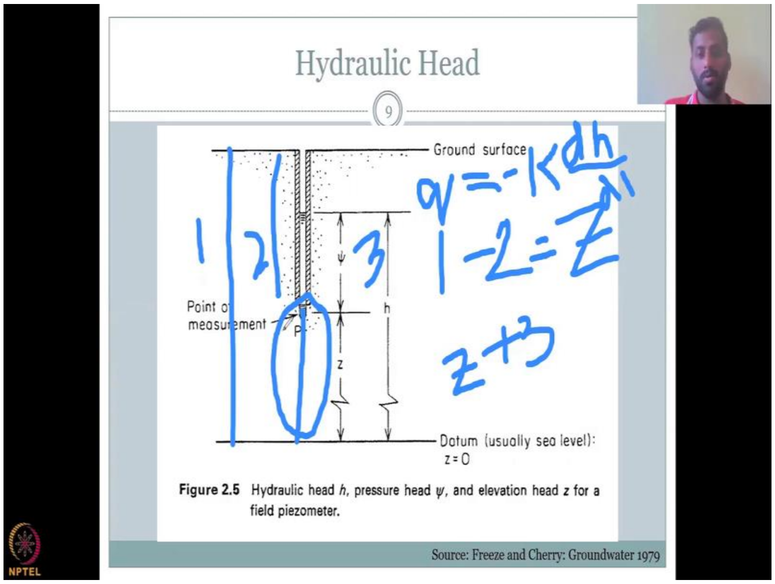


Figure 2.5 Hydraulic head h, pressure head ψ, and elevation head z for a field piezometer.

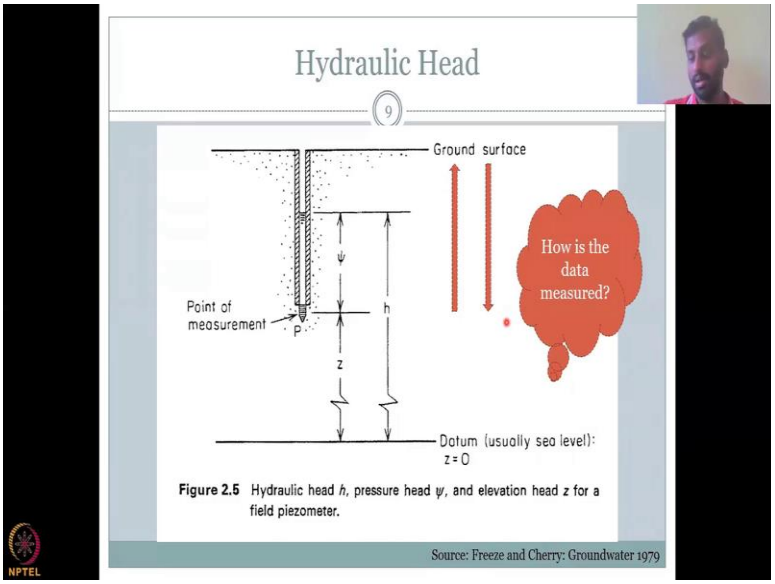
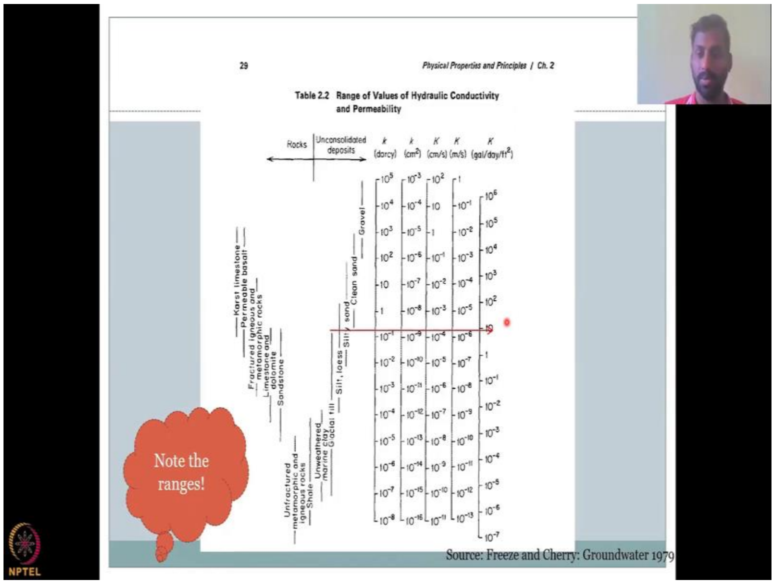


Figure 2.5 Hydraulic head h, pressure head ψ, and elevation head z for a field piezometer.



So, before that, let us get into the hydraulic head concept. I have already explained this in the Darcy equation, but let us take one well to show how do you calculate the elevation. Because in the real world, the 0 is not the table because the 0 is your center of your location where the level is 0. So, normally the 0 is taken as the sea level on the planet, the elevation 0 is taken as mean sea level. So, where the sea is starting that is called 0, and from there the elevation can go up or down.

So, let us take z as 0 which is your sea level, here we are somewhere in let us say, Chennai and I am on the beach, that level, the water level is 0. And I am moving inward into Chennai to measure the groundwater level. I need to measure the water level, the hydraulic head and from the hydraulic head, I will go to Q which is your Darcy's equation.

So, I go to a well and the first thing you would notice is that the elevation of the well is not there. You cannot have the elevation of the well readily, the hydraulic head readily calculated. So, you need to calculate. The first step you do is to ask what is the depth of the well? And where the well is actually open for measurement? So, here is the point of measurement. And as usual, as I showed in the previous slide, you would measure the water level or depth to the water.

So, you end up calculating this. So, you have one value which is the depth of the well and also you have your water level which is psi. And what is needed for your Q is h. How do you calculate h? You ask for the elevation of your ground surface at that point, which you can take from topographic maps or digital elevation maps. So, you have the elevation of this your ground which is 1.

Now, 2 you have this z which is your depth basically a depth of your wealth which is 2. And you know your psi, how much is your psi which is the water level which is 3. But how do you get that 2? How do you know how much is my elevation from the ground? You know, from the depth of the well which is this, you know this is your 2 and but you will not know this one because you have to calculate this indirectly.

So, you know, 1, you know, 2 and 3. How do you get at h? By subtracting 2 from 1, you get this area, this length. So, you get this length when you subtract 2 from 1. So, 1 minus 2 is going to give you your z. And you know psi which is your 3. So, z plus your 3 will give your, your z plus your 3 will give your h. And that is simple. Please understand that this is what we want. But if in order to get this, you have to subtract your elevation using your depth to the well.

So, now you get h, you do this to another well. So, I walk to another groundwater well, and I do another h. I know the distance between the wells, and then I would do the equation as Q is equal to your minus hydraulic conductivity. So, since I am in the field, I would ask what type of soil it is, and then I know the hydraulic conductivity from the values I showed from Freeze and Cherry book. I know the, let us not do the area of your wells.

So, let us do your q, small q. So, we do not need the area of cross section, we just need the discharge velocity. So, let us say q is equal to minus K times your dh, which is your distance, the difference between your hydraulic heads by the length, the distance between your wells. So, all this we have done just by calculating two values, which is your elevation of the well, and then the depth to the well to get at your z which is the elevation of the well from the measuring point.

Then we measured the groundwater level to get at 3, 1 minus 2 got we z and z plus 3 gives you h. So, with this, we would calculate the groundwater hydraulic heads for one well we do it for two wells and then we establish the equation, Darcy's equation. But remember we need the hydraulic conductivity which can be obtained from the previous values which are shown here.

So, always have this you can have this slide, I use this slide always to measure all the materials are there. So, to any system in the world, you want and take government report to understand what is that particular soil. And then, go to this slide and get the value and you can put it here by measuring the ground surface, the elevation of the z which you get by subtracting the groundwater well elevation or the depth of the well and you get Q. So, please note that we will also look at some Q values in the next lecture. Thank you.