Engineering Geology
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Lecture - 26
Groundwater Flow

Hello everyone, and welcome back. We are going talk about groundwater flow in today's lesson, but before we get on with groundwater flow, let us look at the question set of the previous lesson.

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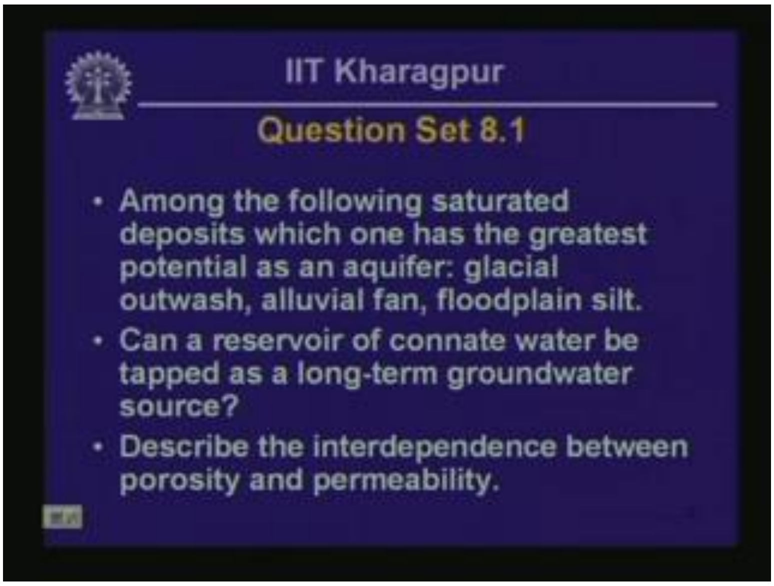

The first question that I gave you last time around was - among the following saturated deposits, which one has the greatest potential as an aquifer? The three deposits are glacial outwash, alluvial fan, and floodplain silt. Now, if you recall from our previous lesson, what I said was that in order for the geologic unit to qualify as an aquifer, we need to have a fairly coarse grain size structure of the of the geologic unit, and as result what we are going to get is, we are not going to prefer floodplain silt because that is going to have a relatively small permeability; it is not going to conduct groundwater quite that easily. So, we are left with the other two alternatives.

Now, the glacial outwash and the alluvial fan, among these two, alluvial fan is heterogeneous; it is going to have a distribution of grain sizes over a very wide range; it is going to have gravel size particles to silt size particles, and there might be, in fact, lenses of silts, within the mass of alluvial fan, which is going to impede drainage in the long run.

So, we are going to end up with selecting the first option in this case - that is the glacial outwash. In this case, we are going to have fairly coarse grain size distribution, and that is going to make it suitable as groundwater; it is going to qualify the deposit as a good source of groundwater or it is going to act as a good groundwater aquifer.

Now, the second question that I asked was - can a reservoir of connate water be tapped as a long-term groundwater source? Now, connate water is typically entrapped within isolated cavities within the formation of rock. As a result, what happens is that the supply of connate water is relatively limited. So if you start tapping connate water, it is not going to last over a very long time before depletion. And because of the fact, that the pore space within which the water is stored - connate water - is stored is isolated; it does not really have much option of getting recharged during wet seasons. So, connate water therefore, does not qualify as a groundwater source to be used over a relatively longer duration.

The third question that I asked was - in fact, I asked you to describe the interdependence between porosity and permeability. Now, what was apparent from the previous days discussion was that, if you have got a formation - subsurface formation - which has got large porosity that is likely to have large permeability as well, but what you need to also consider is that what you need is a distribution of pore space; you need to have a large proportion of pore space which is interconnected and not only that, the interconnected wide space should have a larger opening size.

In other words, if you have got a fine grain matrix, then the capillaries that are going to be formed by interconnected wide space are going to be very in small diameter. Indeed, as result the water that would like to flow through the tubes are going to resist the movement primarily because of capillary action, because of surface tension of water.

So, what we need is a larger porosity matrix, but that is not the only fact that you need to look at while selecting a potential groundwater aquifer. You also need to look at what is the grain size distribution of the formation as well. In addition to it, you need to ensure that the pore spaces are relatively interconnected. So, that takes care of the question set of the previous lesson.

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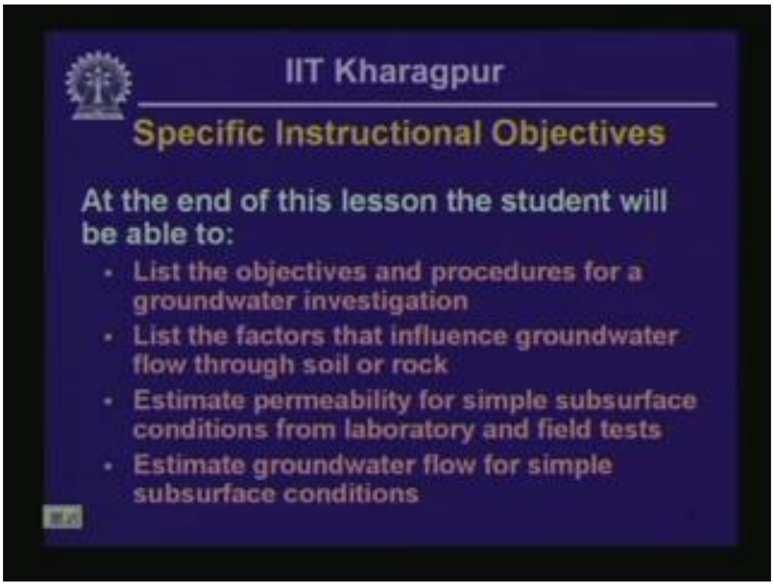

Now, we move on with today's subject matter. What do we want to learn in this particular lesson? At this at the end of this lesson, we would like to be able to list the objectives and procedures for groundwater investigation; we would like to be able to list the factors that influence groundwater flow through soil and rock; then, estimate permeability for simple subsurface conditions from laboratory and field tests; and finally, we would like to be able to estimate for very simple subsurface condition what is the volume of groundwater flow that is likely to take place.

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So, first of all, we look at the typical procedures - objectives and procedures - for groundwater investigation. Now, in order to assess groundwater potential, the first step is to carry out a groundwater investigation. That investigation should ideally give us some idea about the safe yield of an aquifer.

So, in order to do that, we not only need investigation of the groundwater condition - subsurface groundwater condition - we also need to have some handle on the meteorological aspects or weather pattern - some idea about the weather pattern, that is prevalent in the particular region of interest.

Then the second purpose is to identify groundwater related engineering problems. We are going to look at some time later, some of these problems - some of the groundwater related problems - that are handled by engineering geologists - that often needs to be handled by engineering geologists. And then, we need to identify also the groundwater chemistry in some problems.

In other words, whether the groundwater is going to be suitable for a particular use such as - used as drinking water or used as irrigation water or any such or for that matter used as construction water supply. So, we need to identify the potentially harmful chemical constituents in groundwater sources depending on the use of the groundwater source. Then, that actually gives us a list of parameters that might be of our interest and these parameters we would like to get from groundwater investigation.

First of all, we need to be able to assess the groundwater table contour or the artesian pressure depending on whether we are looking at a confined aquifer or rather an unconfined aquifer and a confined aquifer. Secondly, we would like to be able to estimate what is the natural recharge and discharge affecting a groundwater source. And thirdly we would like to get an estimate of the permeability of the underground geological formation that is used as groundwater source.

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Continuing with groundwater investigation the procedure - one of the procedures - in it is involves groundwater prospecting. So, what we need to do - what we attempt to do - in groundwater prospecting is to identify a source of groundwater. Typically resistivity survey is a very common procedure for identifying a potential source of groundwater or a zone of saturated soil underneath the ground surface.

We have looked at the main features or essential details of resistivity survey in one of our earlier lessons on subsurface exploration. So, I am not going to get once again into the detail of this particular procedure.

Then another type of investigation that is carried out is called groundwater survey. And that involves installation of monitoring wells, drawing water samples for assessing groundwater chemistry from the monitoring wells, and long term monitoring of the monitoring well to assess seasonal fluctuations in groundwater level within these wells or artesian pressures within these wells.

Now, what is also done in addition to all these things for groundwater survey is to pump out the wells at steady state in order to assess what is the potential yield from this particular well and that is called well testing. So, all these steps are carried out in groundwater survey and groundwater prospecting.

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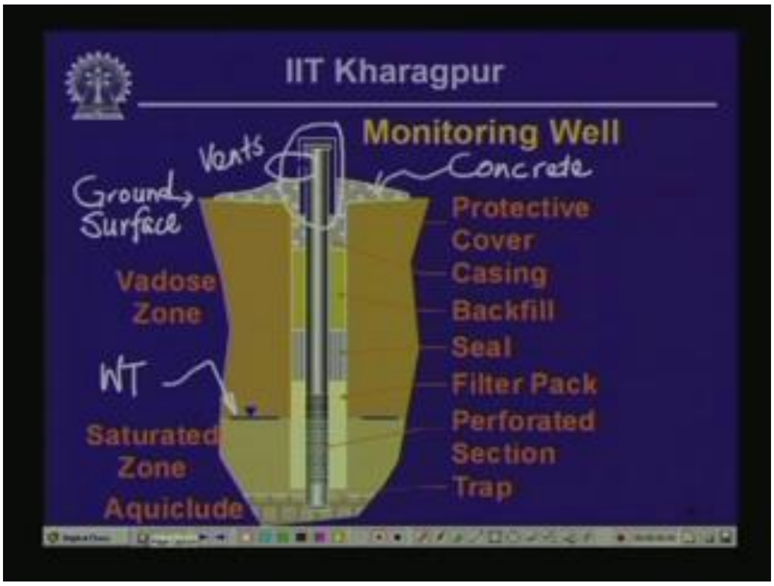

So, then you might ask - what is a monitoring well which is used in groundwater survey? A typical cross section of a monitoring well is shown on this particular sketch. So, it is essentially a casing, a tube - a casing tube - installed within a pre-board hole, inserted within the pre-board hole drilled or bored or excavated within the ground and the casing is shown at the center of the hole there, and you can see that there is a back fill around the casing.

Let us go from the top. At the top end of the casing, you can see a cap, and you can see that there are two vents on the left side of this particular sketch, and these vents are provided in order to give vent to any gases that might be present in groundwater.

And then, the well casing is protected by installing a protective cover - this is usually a lockable protective cover - encased within a concrete back fill at the top. So, this one here, this one here, is a concrete encasement in order to hold the protective casing, and then, underneath the protective… underneath the concrete within the annular space in between the casing tube and the borehole wall is a semi-pervious backfill. Typically, you can use silty clay or clay silt or glacial till or that kind of material which is not totally permeable.

And underneath the backfill there is a seal. This particular seal is constructed using very fine grain material such as bentonite, in order to seal the portion of the casing tube that actually is used in extracting groundwater, which is in turn encased within a filter pack;

filter pack is essentially a uniform sized filter sand, and you can see that encased within the filter pack is a perforated segment of the casing tube. And through the perforations, the groundwater enters the tube, and the portion of groundwater that enters the tube is used in groundwater monitoring or testing of the aquifer.

Now, you can also see at the bottom of the perforated section there is a trap or the solid portion of the casing tube extends a little bit below the perforated segment of the casing tube. And this particular portion is normally installed in order to ensure if there is any fine grain debris that move into the casing tube, with groundwater entering the casing tube through perforations, get trapped at the bottom of the casing tube without clogging the pipe casing tube itself.

What you see here is that there is a vadose zone or unsaturated, partially saturated zone near the surface. So, ground surface in this case is here. Underneath the ground surface is a partially saturated vadose zone; underneath the vadose zone is a saturated zone; and on the interface between the saturated and unsaturated zone, as we know from previous lesson, is the entity called the water table.

What we also have shown here is that the casing tube, in this particular case, penetrates the entire depth of the saturated zone and it is encased within an underlying aquiclude near the bottom of the tube there. So, that in a nutshell is a very simple simply constructed monitoring well that is used that is normally used in groundwater survey.

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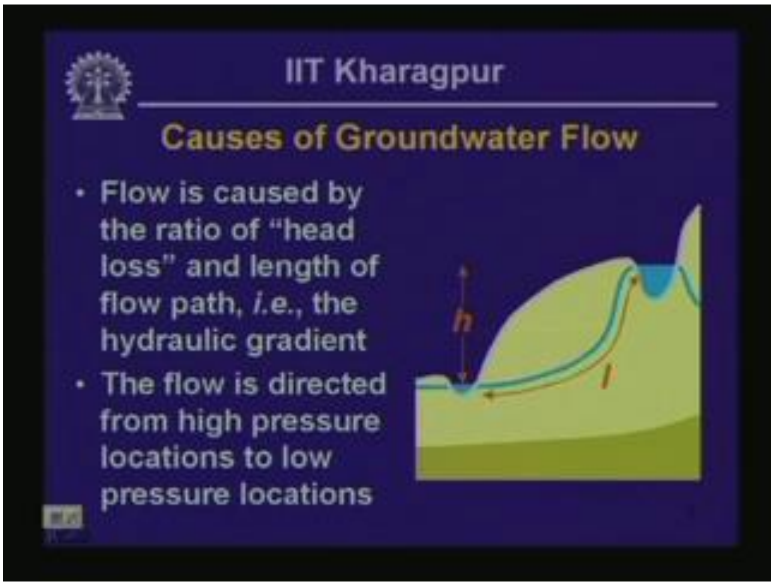

So, then, we would like to know what are the causes or what are the driving factors that trigger groundwater flow. First of all, flow is caused by head loss and flow is caused by the ratio of the head loss to the length of the flow path and this particular term is called the hydraulic gradient.

Simply stated, what is meant here is, that if you have got the water table existing at a higher elevation at some location - within the general geographic region that you are interested in - in comparison with another location within the area where the groundwater table is at a lower elevation, then what we are going to see there, is that usually the water – groundwater - is going to move from the location where water table is at a higher elevation to the location where the water table is at a lower elevation.

And that is because water is going to flow - we have already stated that in the previous lesson, that groundwater is that portion of soil moisture, which is free flowing or which can move, which can be mobilized by the action of gravity - so, it is going to move from a location where it has got a higher potential energy to a location where it has got a lower potential energy. And the elevation of water table is a measure of the potential energy of an unconfined aquifer. So, in that situation, water is going to move from a location where the water table is at a greater elevation to a location where the water table is at a lower elevation.

Then, the second thing that actually triggers groundwater flow is - groundwater flow is directed from a location of higher pressure to a location where the pressure is comparatively smaller. So this one here is applicable incase of both artesian groundwater flow as well as non artesian or water table type groundwater flow.

Let us look at the details. Let us say we have got a section where we have got a mountain stream that is running - we are showing a cross section here actually; we have got a mountain stream that is towards the right of this particular sketch and we have got another stream running parallel to the previous one, but at a lower elevation towards the left of this particular sketch. So, the location of the water table - this is a situation involving an unconfined aquifer. So, here the location of the water table is shown by the thick cyan line at the near the top of this particular sketch.

So, here what we are going to expect is that because of the fact that the elevation of the water table is much higher towards the right of this particular sketch, the flow here is going to take place from the right to the left.

So, what is the definition? Let us look at what is meant by a hydraulic gradient using this particular configuration here. So, here the flow length is going to be l shown by the orange arrow there along the water table, and the head loss, in this particular case, is going to be h indicated towards the left of this sketch. So, the hydraulic gradient that is going to trigger the flow of groundwater from the right side of this sketch to the left side of this sketch is going to be h over l. And that is the hydraulic gradient under which the flow is going to take place in this particular case.

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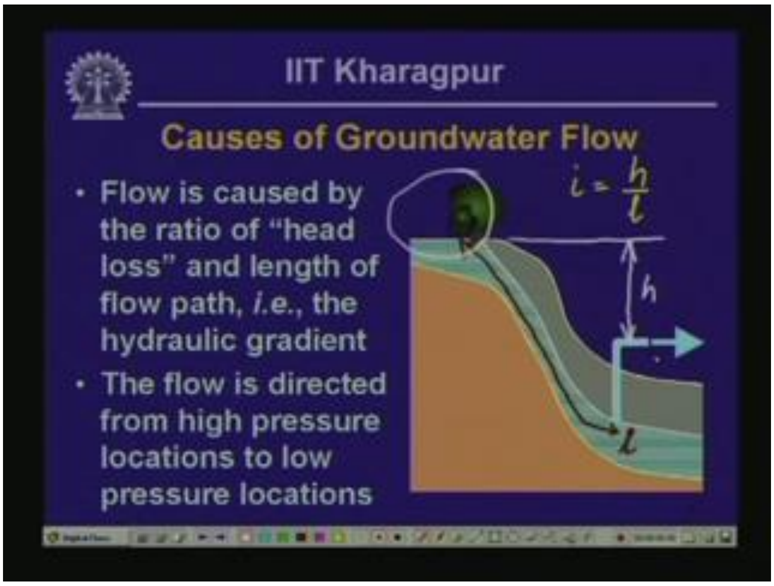

Let us look at the flow in case of an artesian groundwater condition which is shown on the sketch of this particular slide here. Now here, again the flow is going to be caused by head loss divided by the length of the flow path, but in this case the head loss is going to be slightly different and that is going to be given by these quantities. Actually it is going to be given by the difference in elevation between the recharged area and the elevation of the outlet of the artesian well. So in this case, the head loss is going to be this one and the length of the flow path - in this particular case - is going to be this much. So, hydraulic gradient is normally expressed using the symbol i. So, i, in this case, is going to be equal to h over l.

Now, here also the flow is going to take place between the recharged zone - which is towards the top left of this particular sketch - towards the artesian well and this is the out flow direction, which is shown by the thick arrow within near the outlet of the artesian well in the sketch. So, h and l I have explained already.

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So, we have already looked at what is the driving mechanism of groundwater flow. So, groundwater flow is driven by the hydraulic gradient, essentially. So, what is hydraulic gradient? Hydraulic gradient is the ratio of the head loss between the inlet and the outlet divided by the length of the flow path - that is the hydraulic gradient. So, that is going to drive the groundwater flow.

Now the question comes - what are the factors that are going to inhibit or going to discourage the movement of groundwater flow. We know some of these concepts already from the previous lesson. So, inhibitors of groundwater flow include, first of all, capillary tension. So, we need to have relatively larger void space in order to get a reasonably good groundwater flow as we have already discussed.

Second inhibitor of groundwater flow is when we have got highly bent interconnected pore spaces; if you have got relatively straight flow path or the interconnected pore spaces are relatively straight, then the flow through the soil - flow of groundwater through the soil - is going to be relatively easy. So, tortuosity is another inhibitor. Tortuosity is a measure of how bent individual flow paths are - shown by yellow arrows there - in comparison with straight flow paths. So tortuosity is another inhibitor of groundwater flow.

And the third inhibitor of groundwater flow is fluid viscosity. So, if you have got less viscous pore fluid that is going to flow through the interstitial wide space - interconnected interstitial wide space - within the subsurface formation relatively easily in comparison with another fluid that has got a much larger viscosity. So, these are the factors that inhibit groundwater movement.

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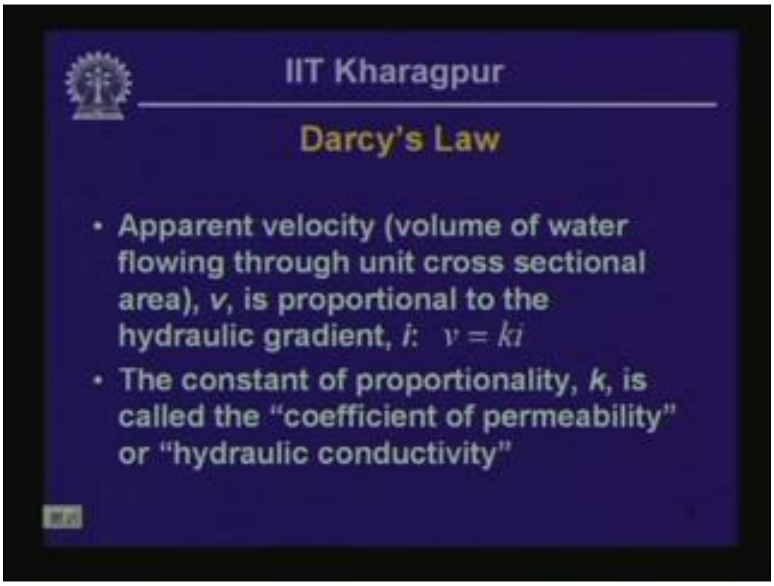

Now, we need to formalize the concept a little bit. Darcy's law is the law that governs groundwater flow. And what it states really is that apparent velocity - v - is proportional to the hydraulic gradient. In other words, v is equal to a constant of proportionality times the hydraulic gradient and this particular constant of proportionality is called the coefficient of permeability or hydraulic conductivity. And that is, in fact, a measure of the factors that inhibit the groundwater flow through a subsurface formation.

Now, what we need to stress here is that v - the quantity v - is not the actual velocity; rather it is the apparent velocity; and apparent velocity is actually defined as the volume of water flowing through a unit cross sectional area of the aquifer and that is going to be different from the actual velocity.

Why that is going to be different? It is because the amount of length or the length of the route travelled by groundwater, through the aquifer, is going to be different from the straight-line distance from the inlet to the outlet within the aquifer, because of the tortuosity of the interconnected void space.

So the velocity - apparent velocity - is typically is going to be much smaller than the actual velocity with which the groundwater is going to travel through the interstitial wide space within the subsurface formation. You need to really understand the difference between apparent velocity and the actual velocity of groundwater flow in this respect.

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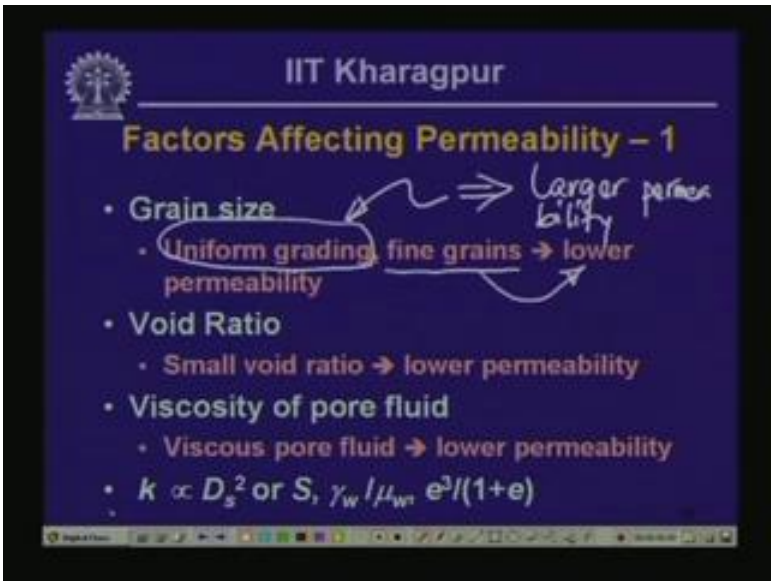

Factors affecting permeability. We know some of these things already, because what I have indicated in the previous slide is that the constant or proportionality or the coefficient or permeability or hydraulic conductivity - we are going to use the term permeability in this particular lesson - but you need to understand that the term is in fact interchangeable with hydraulic conductivity.

Now, first of all, we mentioned in the previous lesson is that the permeability is a measure of those factors that inhibit groundwater flow - we know that already from what we have learned so far. So now, the factors that inhibit groundwater flow are those same factors which are also going to be affecting permeability in the long run. So, what are those factors?

First of all grain size is an important factor. We have already seen that if you have got uniformly graded subsurface formation, then you are going to have a relatively easy groundwater movement through the formation. So, the permeability is going to be relatively high. If you have got fine-grained soils - so, here actually I need to make a correction - in fact, uniformly graded soil will have larger permeability. And if we have got fine-grained soils on the other hand, the void space are going to be a very fine; so, the water is going to be held, the movement of the water within the interstitial pore space is going to be inhibited by the capillary tension. So, that in fact, is going to lead to a smaller permeability.

Second aspect is void ratio. If you have got a much tighter packing or small void ratio, then you are going to have a lower permeability.

If you have got viscosity or if you have got a highly viscous pore fluid, then you are going to have a smaller permeability. So you need to note the correction as far as grain size is concerned, which I have already noted at the top there.

So, if you have got uniformly graded subsurface formation that is going to have a larger permeability not lower permeability as indicated on this particular slide here. So you need to take a note of that one.

So to summarize all these things that we mentioned: permeability k is going to be proportional to the square in fact of the representative grain size or the surface or the surface area of the particles. So, if you have got a very large surface area, you are going to have a smaller permeability. Then permeability k is going to be proportional to the unit plate of the pore fluid divided by the viscosity of the pore fluid. And permeability k, is also proportional to a term equal to e cube divided by 1 plus e where e is the void ratio.

So all these factors are going to affect permeability. It is going to depend on the representative value of the grain size; it is going to depend on the specific surface or s; it is going to be proportional to the specific surface in fact, and proportional to the square of the representative value of the grain size; it is going to be proportional to gamma w over mu w; and it is going to be proportional to e cube over 1 plus e. So, these are all experimentally observed parameters that are known to affect permeability.

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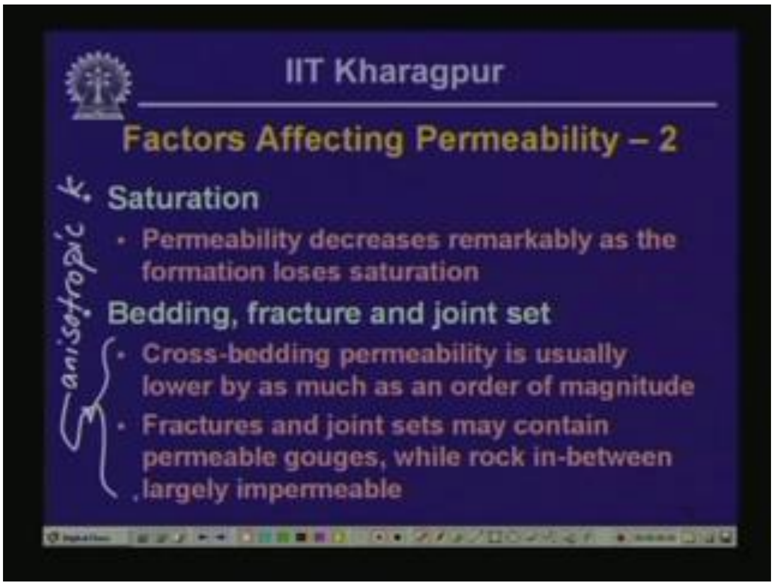

So, some more factors that affect permeability. Saturation ratio is another factor that is going to affect permeability. And in fact, permeability decreases remarkably as the formation loses saturation. It is because the pore space becomes occupied by non-interconnected volumes of water and these non-interconnected volumes of water are relatively difficult to mobilize through the interstitial void space; as a result, saturation goes down drastically as the formation becomes partially saturated in comparison with a completely saturated formation of identical characteristics. Then the second aspect you need to consider are the existence of imperfections such as bedding planes, fractures, and joint sets.

Cross-bedding permeability is usually smaller by almost an order of magnitude in many cases. And fractures and joint sets, since they are more permeable in comparison with the rock that is in between the fracture or joint sets, and this also affects the distribution or permeability and the cross anisotropic or anisotropic, or in other words actually this leads - both these aspects - they lead to the development of cross anisotropy in permeability properties; not cross anisotropy actually anisotropic permeability behavior. So, anisotropy and anisotropic k. So both these aspects lead to anisotropic k. In other words, k is going to be different along the fracture sets rather than in comparison with the value of k in a direction which is perpendicular to the fracture sets; and same is true in case of bedding planes.

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You also need to consider time dependent changes in permeability. Permeability - although in Darcy's law permeability was treated as a constant - if you recall, v or the apparent velocity is given by permeability times the hydraulic gradient, and we considered in that particular case k is a constant, but in fact k might actually change with time, because of several different reasons, because of mechanical reasons or because of chemical reasons as we are going to see in the next little bit.

What could happen? Actually, with time over which the groundwater flows through a particular aquifer, clogging may take place or opening of pore spaces may take place; these are two opposite effects. If the pore spaces get clogged because of migration of solids or because of chemical precipitation, then the permeability of that particular formation is going to decrease as the time passes.

On the other hand, if the pore space becomes larger, then the permeability is going to increase as the time passes. And this also can happen in case of hydro fracturing. We looked at it very briefly - we looked at the details of hydro fracturing very briefly, some time back, in one of the earlier lessons regarding in situ stress within a subsurface formation. So, if you get hydro fracturing triggered within a formation, then permeability is going to increase for that particular formation.

Second thing is changes in void ratio. Void ratio in fact might change as time passes and that is particularly true in case of fine grained soils; in case of fine grained soils, depending on pore water movement, the stress may increase - in situ total stress might increase - and as soon as that stress increases, initially the stress gets transferred to the pore water. And because of the increase of pore water, there could be a decrease in sigma v prime initially or the effective stress might decrease. And this particular process ends up in draining of the interstitial pore water from the matrix of fine grained soils. And that process, leads to the reduction of void ratio. And finally, the initial increment of the total stress gets transferred to the inter-particulate contact stress or the effective stress, and the initial increment of the pore water pressure goes down to zero. And this particular process, because of the fact that it leads to a decrease of void ratio, this process is going to lead also to a substantial reduction in the permeability of the strata.

Third thing that you need to consider in order to account for time dependent changes in permeability is rise and fall of water table. When the water table rises, the amount of vadose zone or the thickness of vadose zone is going to decrease; as a result, the flow in the lateral direction is going to likely to increase as the water table rises. And opposite is the case when the water table - lower water table - settles to a lower elevation after the wet season is over.

Fourth point is changes in proportion of dissolved gases in pore water - that also might actually lead to a time dependent change in permeability, because dissolved gases tend to alter the viscosity property of the pore fluid; as a result permeability changes depending on the amount of dissolved gases in pore water. So these are essentially the set of factors that affect permeability.

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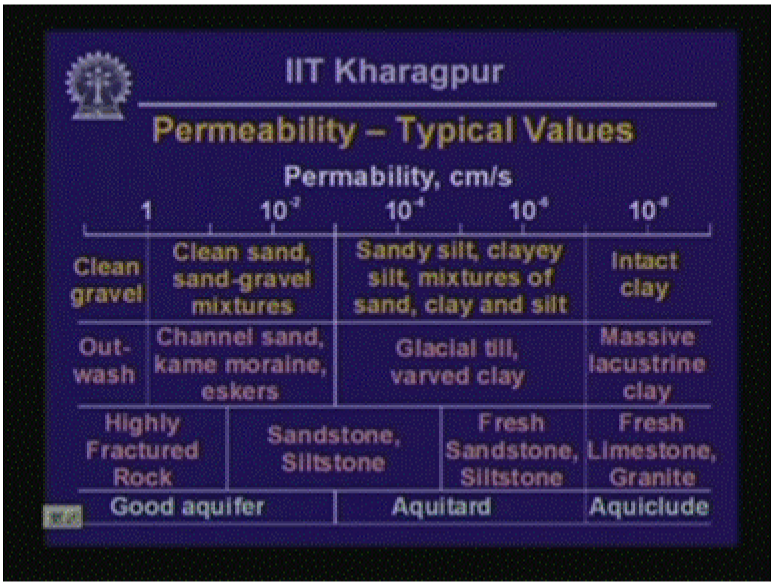

And now, we look at the typical values of permeability of different types of aquifers, and we are going to look at different types of soils, and different types of rocks - typical values of permeability of different type of rocks and soils - and how permeability depends on the geomorphologic character or geomorphology of the particular deposit. So, we look at all those things.

From this particular table here, it is obvious that if you have got clean gravel, the permeability is going to be much larger in comparison with an intact clay deposit. Clean gravels have got permeability in excess of 1 centimeter per second where as intact clay might have permeability as low as 10 to the power of minus 9 centimeter per second.

So outwash deposits are towards the left end of this particular permeability scale. Then, we might have channel sand, kame moraine, and eskers; kame moraine and eskers are two different types of glacio fluvial deposits. If you recall from our previous lessons, channel sand, kame moraine, and eskers have got typically permeability in between 1 centimeter per second to 10 to the power minus 3 centimeter per second.

Glacial tills, varved clay are of even smaller permeability; range in between 10 to the power of minus 3 to 10 to the power of minus 7. And massive lacustrine clay are on the lowest scale or they are the most impermeable of all these different geologic units that we looked at here and they have got permeability between 10 to the power of minus 7 and 10 to the power of by minus or smaller than 10 of minus 7.

Consider some rocks. If you have got highly fractured rock, then you are going to have permeability of 1 centimeter per second or more. Sandstone and siltstones typically have got permeability of 10 to the power of 1 centimeter per second to about 10 to the power of minus 5 centimeter per second. Fresh sandstone, siltstone - well compacted fresh sandstone and siltstone - they have got permeability on the order of 10 to the power of minus 6 centimeter per second; whereas, limestone and granite - they are the most impermeable of all; we are talking about compact limestone in this particular case – fresh, compact, unjointed limestone - they might have permeability on the order of 10 to the power of minus 8 centimeter per second. Then at the bottom row there, we indicate what qualifies a particular geologic unit as a good aquifer, aquitard, or aquiclude.

Now, good aquifer is if you have got a permeability greater than 10 to the power of minus 3 centimeter per second typically. So, clean sand, sand gravel mixtures, some sandstone, siltstone, highly fractured rock, channel sand, kame moraine, eskers, and outwash deposits typically are within this category. Aquitards comprise typically of clay silt, sandy silt. From the consideration of geomorphology, glacial tills and varved clay are often classified aquitards.

On the other hand, if you have got intact clay, massive or lacustrine clay, fresh limestone and granite, then those geologic units are not likely to conduct any groundwater movement at all for any practical purpose. So they qualify as aquicludes. Just have a look at these value, because there is lot of information presented on this particular slide before we move on to the next topic.

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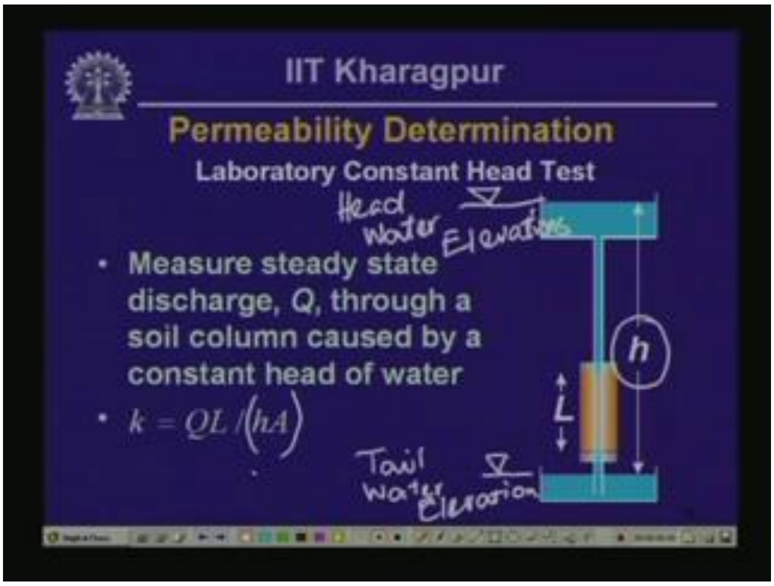

The question comes - how we are going to determine permeability? So there could be laboratory methods or there could be field methods that might be used in order to determine permeability.

So, two simple methods - two simple laboratory methods - are first taken up. I am go to describe them to begin with, and then, I am going to describe one simple field method for determination of permeability.

The first method that we look at is shown schematically on this particular slide. It is called constant head laboratory permeability test. So, what is done here is that a soil or rock sample is placed under constant head difference. So, at the bottom end of the cylindrical sample, you have got a lower head elevation, lower groundwater pressure corresponding to the tail water elevation. So, this one here is the tail water elevation.

And at the other end of the of the sample we have got a much larger, much higher elevation. And the difference between these elevations are going to run, going to trigger groundwater flow and the difference is in fact h. So, in this particular case, the permeability is simply given by the flow that takes place through the specimen in meter cube per second multiplied by the length of the specimen over the head loss multiplied by the cross sectional area of the specimen. So, h multiplied by a is in the denominator of this particular expression.

So, q is in the unit of volume per second; l is in length unit; h is in length unit; and a is in the units of square of length. So, what you end up with is permeability k is going to be in the unit of 1 over length.

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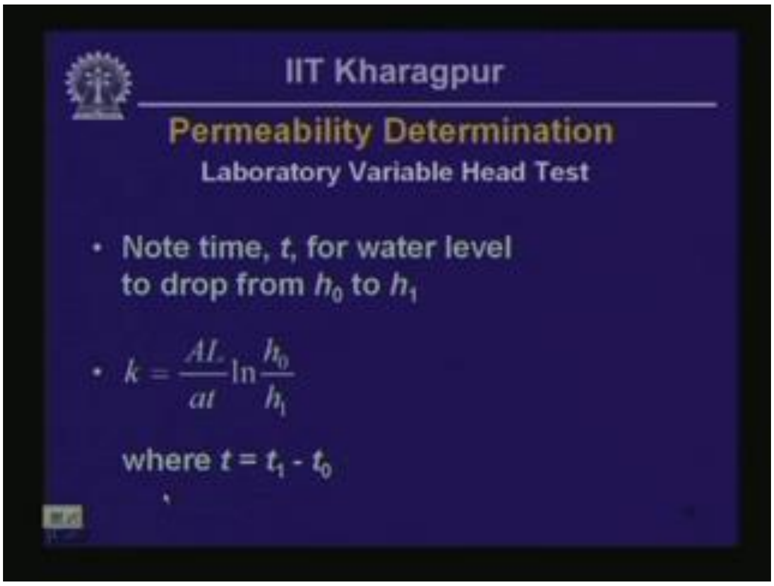

Another method involves variable head test. In this particular case, what we do is, we again use a cylindrical sample of soil or rock, and we allow a flow to take place under variable head through the specimen, and we note the time for water level to drop from h naught to h 1 as will be shown in the next animation. And from these two measurements, we get permeability using the equation shown at the bottom left of this particular slide.

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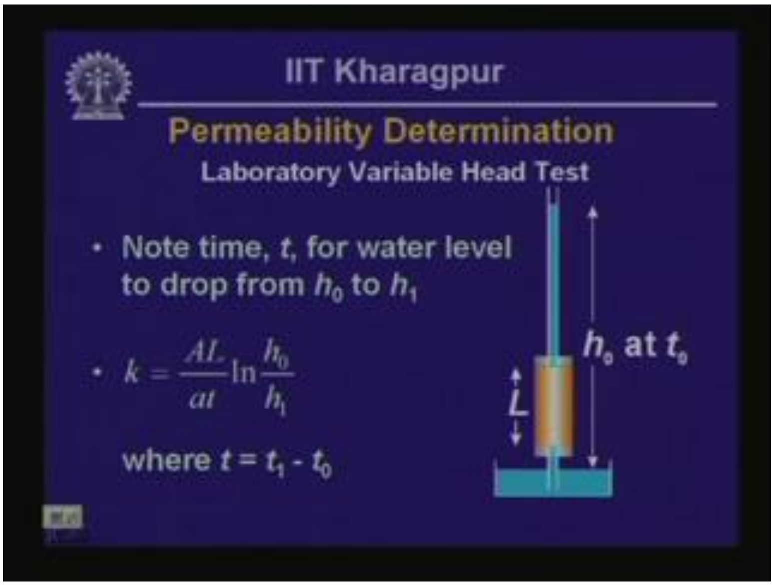

Now let us look at the animation of the experimental procedure. So, first of all we place the cylindrical specimen at that particular configuration shown on the right, and then, we let the water table to drop to a smaller elevation. We find the time difference between these two elevations - the time difference between when the water within the stand pipe at the top end of the cylinder was at h naught, and that at the height of water of h 1. And from these data we can calculate the permeability using the expression which is given on the bottom left of this particular slide.

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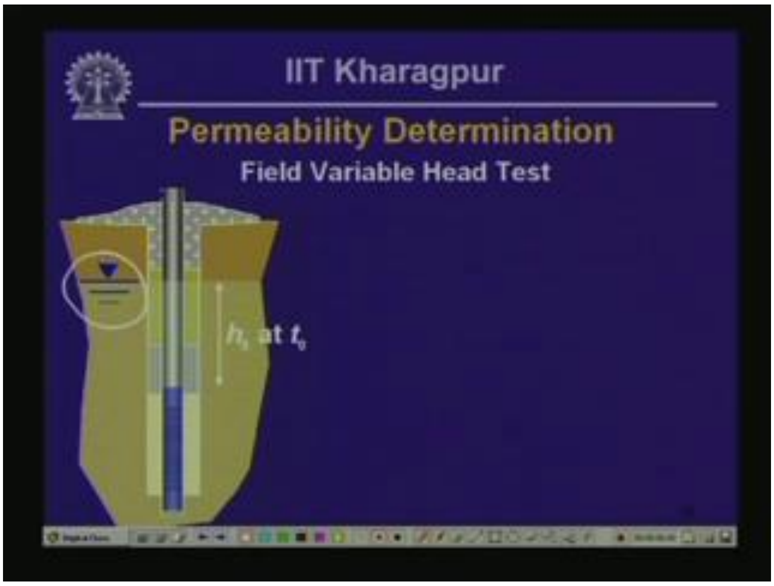

Now, laboratory methods are not representative of in many cases of the general nature of a large mass of aquifer that might have to be encountered in the field. So, many engineering geologists prefer in fact field variable head test as opposed to a laboratory test.

Now, a field variable head test is conducted within a monitoring well and what is done, in this particular case is, say you have got a monitoring well like this, and the water table location is as shown on the left of this particular slide here. So water table is as shown here. So here what we are going to first do is to bail out the water from within the casing tube, so that the elevation of the water level within the tube goes down to a depth of h naught below the existing water table.

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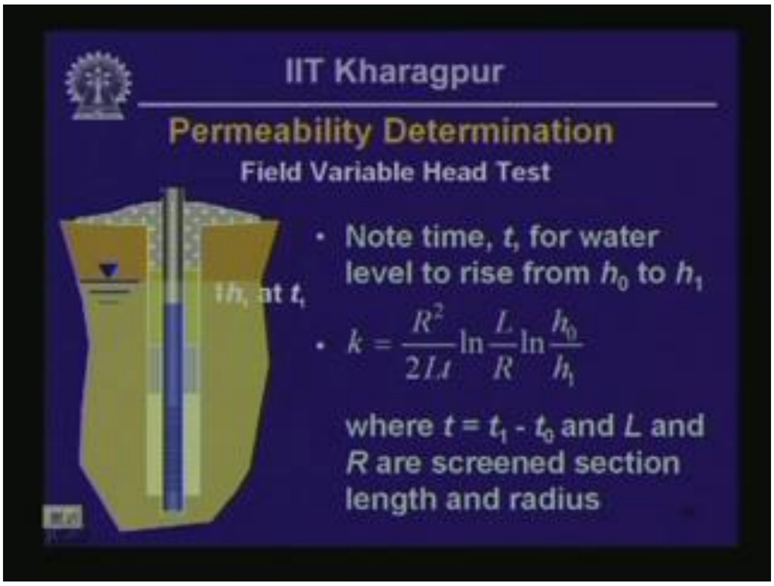

And then, the water table is allowed to rise to another depth h 1, and what we do in this case, we find out the time difference between when the water table was at h naught depth below the existing water table or the water within the casing tube was at a depth of h naught, from the water table, and that when the water is at a depth of h 1 below the existing water table, and from these two measurements, we can compute the permeability using the expression on the right of this particular slide. Now, this test - this particular equation - represents an aquifer which is unconfined and extends to a great depth below the water table.

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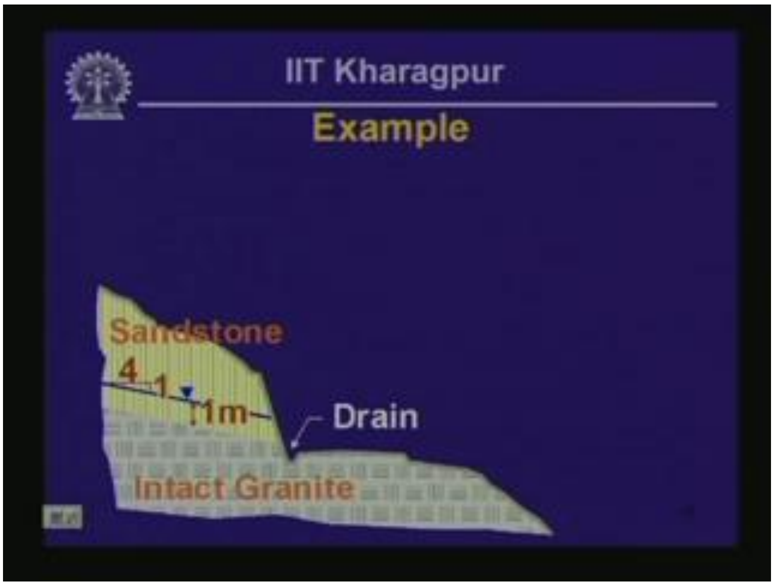

Now, I want to give you an example of flow of groundwater and in this example in which there is a road cut, and there is an aquifer - unconfined aquifer - within sandstone that actually discharges water into the road cut, and there is an interceptor drain parallel to the road cut as shown on this particular sketch. What you should try to find - from this particular configuration, you should try to find the amount of water that is going to flow into the drain, or in other words how much of flow that the interceptor drain needs to be designed for. Now, try to answer this particular question in your leisure time and we are going to look at this calculation when we meet with the next presentation next time around. So, until then bye for now.

Thank you very much.