Engineering Geology
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Lecture - 27
Groundwater Flow - Part II

Hello everyone and welcome back. We are going to continue our discussion on groundwater flow in this lesson as well. And we are going to begin with the example or the question or the problem that I had asked near the end of the last lesson. We are going to try to find out the solution for this one. Now, this was the problem here; that we have got a road cut basically, which intercepts an unconfined aquifer within a sandstone bedrock, the underlying intact granite is relatively impervious.

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So, the question that I asked was - how much of flow will be intercepted on the drain that runs parallelly along the left edge of the highway shown on the cross section in the sketch there, and the problem was - the statement of the problem was - like this: the permeability of the sandstone aquifer was 10 to the power of minus 4 centimeter per second and what I have asked was, for you to find the design discharge for the interceptor drain. Now let us get on with the solution first.

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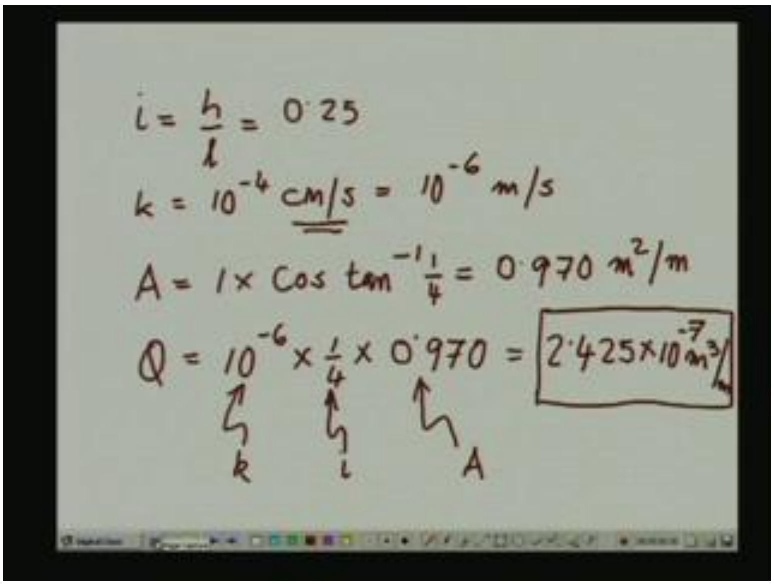

In this particular configuration, what we have is the hydraulic gradient is equal to the amount of head loss over the length of flow and this particular thing will be same in this case as the slope of the of the water table. So, in this particular case it is going to be one-fourth; what we also have is the permeability is equal to 10 to the power of minus 4 centimeter per second; that is in turn going to be equal to 10 to the power of minus 6 meter per second.

I should actually draw your attention to my usage of centimeter per second as the unit of permeability. Although, we are in general, sticking to SI units in this particular series of lessons, but in this case we are using centimeter per second as the unit of permeability - that is because, that is more commonly used in the profession, and so, many of the practitioners are used to seeing magnitudes of permeability in that particular unit.

So, they have got a feel for the general magnitude of the property once it is expressed in centimeter per second unit rather than meter per second unit, although meter per second is the actual unit - is the more appropriate SI unit - in this particular case. So, anyway, let us revert back to SI unit because we are going to get the volumetric flow in that case in SI units.

So, we also know that the cross sectional area of flow in this case is equal to 1 multiplied by cosine of 10 inverse of one-fourth and that is equal to approximately 0.970 meter square per meter length of the highway. So, we are going to get the discharge, in this case, by unit length of the highway perpendicular to the direction of the cross section shown on the sketch - original sketch - that accompanied the problem statement.

So, then the problem is simple. The volumetric flow is going to be given by or q is going to be given by 10 to the power of minus 6 meter per second multiplied by permeability or rather the hydraulic gradient times the area of the flow - cross sectional area of flow. So, this one here is permeability k; that one is the hydraulic gradient I; and this one here is the cross sectional area of flow. So, once we complete the calculations, then we get this is approximately equal to 2.425 multiplied by 10 to the power of minus 7 meter cube of water flowing into the interceptor drain per unit length of the highway. So, that is your answer in this particular case. So, you have to design the interceptor drain cross section for that particular flow in this case. That is the solution for the example that I or the question that I asked at the end of the last day's lesson.

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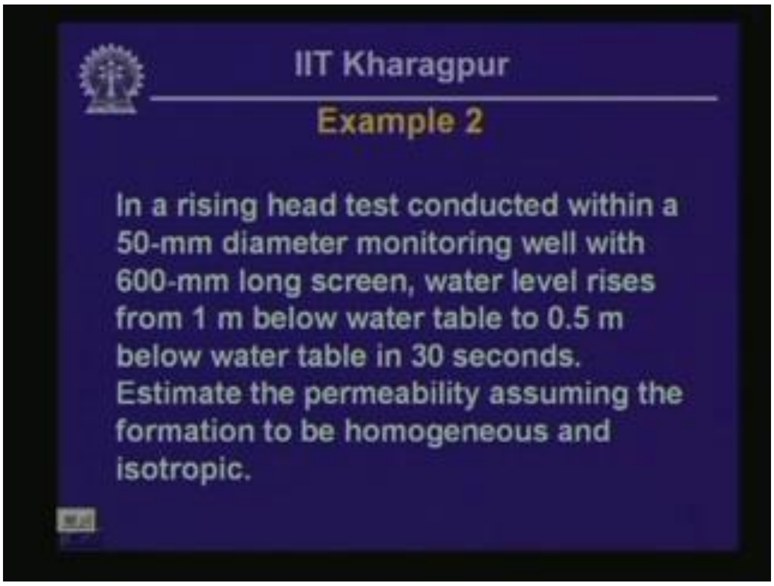

Now I also - in order to illustrate the procedures of estimating permeability from field testing - have got another example and we are going to work through this example before we get on with today's lesson. So, the problem statement in this case is - in a rising head test conducted within a 50 millimeter diameter monitoring well, with 600 millimeter long screen, water level rises from 1 meter below the original water table or the equilibrium value to 0.5 meter below the original water table in 30 seconds. And I asked, in this case, for an estimation of permeability assuming that the formation is homogenous and isotropic. So, in this case the governing equation becomes this one. And you should look back to your earlier notes in this particular case. So, the governing equation as mentioned is this - one that is this here.

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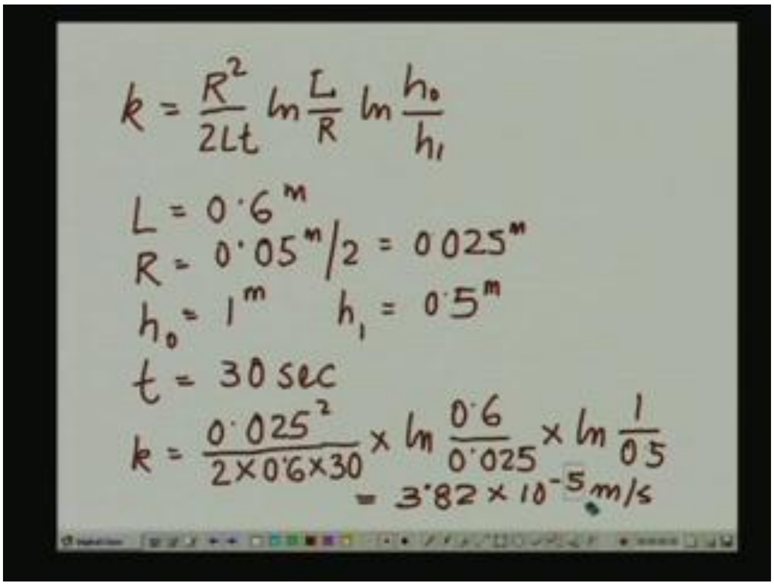

So, what is R? R is the radius of the screen section of the monitoring well; l is the length of the screen section of the monitoring well; t is the time taken by water to rise from h 1 distance below the equilibrium position to h naught below the equilibrium position. So, h 1 in this case is going to be a …. The water table rises in this case from h naught to h 1. So, h naught is going to be a larger number, in this case, and h 1 is going to be a smaller number. We have explained all the terms.

So, now we can start calculating, noting that l in our case is going to be equal to 0.6 meter; R in our case is going to be 0.05 meter over 2, that is equal to 0.025 meter; then h naught is going to be 1 meter in our case because the water table or the level of water inside the water well was initially lowered to a depth of 1 meter below the original water table by bailing out the water from inside the monitoring well. And h 1 is 0.5 meter and time taken for the water to rise from h naught to h 1 is 30 seconds.

So then, the problem becomes simple, becomes that way simple substitution into the governing equation, and what we get in the process is k is equal to 0.025 square divided by 2 times 0.6 times 30 multiplied by natural logarithm of 0.6 over 0.025 times the natural logarithm of 1 over 0.5.

And once you work through the calculations, then what you get is permeability of 3.82 multiplied by 10 to the power of minus 5 meter per second or this is equal to 3.82 multiplied by 10 to the power of minus 3 centimeter per second. So, that is actually the answer in this case; it is a simple problem.

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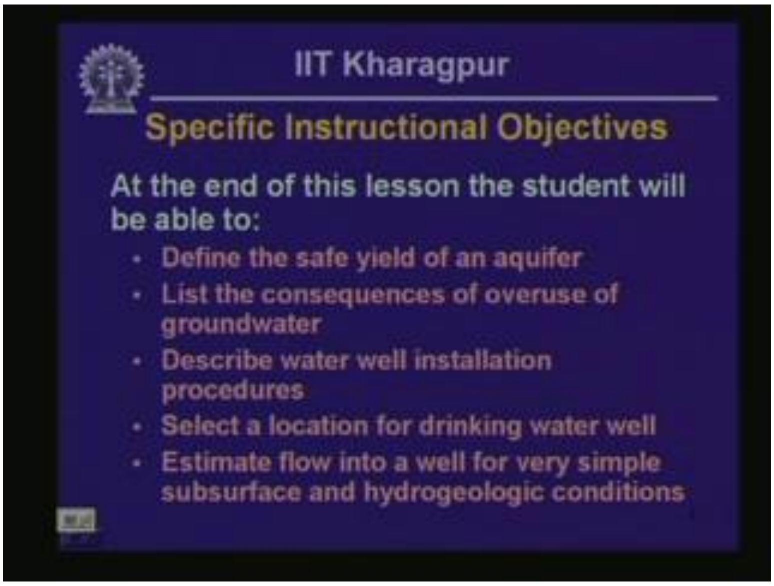

And now we get back to the topic that we are going to discuss in today's lesson. So, what are the objectives? What are the things that we want to accomplish at the end of this particular lesson? They are: we would like to be able to define the term denoted as safe yield of an aquifer; we would like to be able to list the consequences of overuse of ground water; we would like to be able to describe water well installation procedures; then we would like to be able to select a location for drinking water well; and finally, we would like to be able to estimate flow into a well for very simple subsurface hydrogeologic condition. Now, these are the objectives of this particular lesson. And first of all, we begin with a few definitions that we are going to get us through to the end of this particular lesson.

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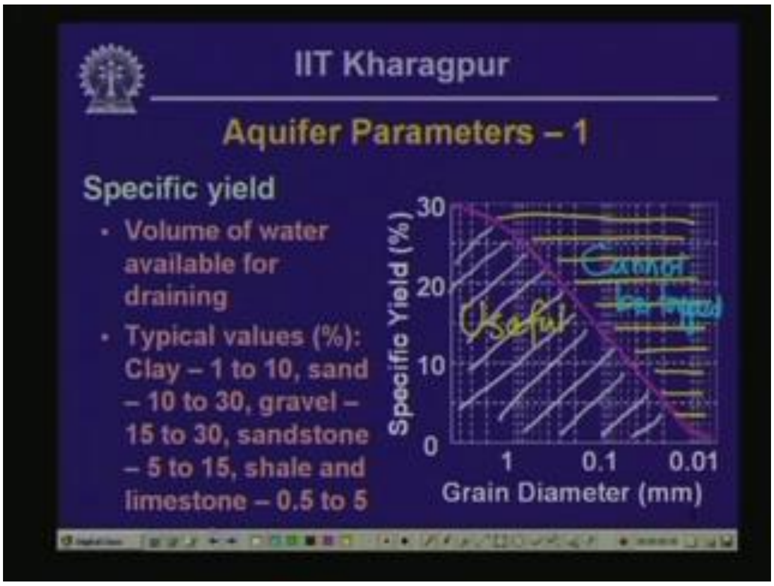

The first concept that I want to introduce is that of specific yield. What is meant by specific yield? It is the volume of water available for draining. So, in a sense, it is a measure of the groundwater that can be tapped from an aquifer. So, it is equal to the total amount of moisture that is present in the underground formation minus the amount of moisture that is held within non-interconnected pore space as well as that which cannot be tapped because of excessive capillary tension plus those amount of water which are absorbed on the surface, and tightly held in fact, on the surfaces of individual grains that make the formation. So, typical values of specific yield: for clay, we have got typically between 1 percent to 10 percent; for sand, we have got between 10 percent to 30 percent; for gravel, we have got between 15 percent to 30 percent.

Now for some rocks: sandstone between 5 percent and 15 percent; shale and limestone, on the other hand, we have got only between 0.5 to 5 percent. So, from the point of view it becomes very clear… it is becoming very clear now that from the point of view of the usefulness of the formation as an aquifer, we would like to have a larger value of specific yield. And also it is clear from the second point, noted on the left side of this particular slide, that specific yield becomes smaller and smaller as the individual grain size becomes smaller and smaller, particularly because of capillary action of the matrix - of the solid matrix.

So, a very rough, a very approximate correlation between specific yield and grain - representative grain - diameter is shown on the plot that is on the right side of this particular slide. So, in this one, you can see that for very coarse grained soils or rocks, you can have specific yield of up to 30 percent; whereas, as the grain diameter - representative grain diameter - goes down approximately to 0.01 millimeter or actually 0.005 millimeters, you are going to virtually have zero yield from that particular type of soil. So, this is a very approximate, very approximate correlation between specific yield and grain diameter.

So, you can differentiate the plot of the area within the graph in two zones - basically one above the correlation and the other one underneath the correlation. So, the area that is below the correlation presented on the plot, that actually represents useful water - useful groundwater - and the portion which is on the top side - top and right - of this particular correlation, that on the other hand represents groundwater which cannot be tapped. So, that is the concept of specific yield.

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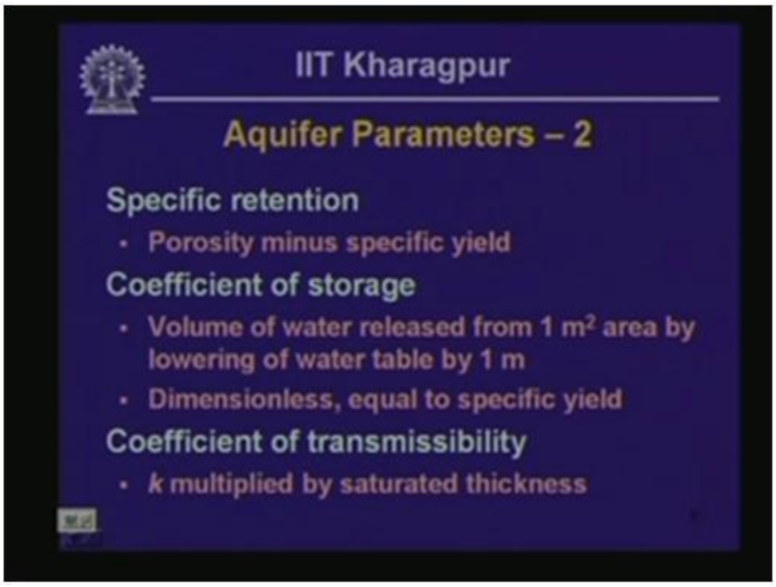

Now let us move on with some more concepts. The complimentary function of the specific yield is specific retention. So, the portion of groundwater which is on the top right of the plot that I have shown just now, that actually is the representation of a thing called specific retention. So, specific retention is basically porosity of the matrix or the solid matrix minus the specific yield.

So, this the water trapped or held tightly within the matrix that cannot be used or that cannot flow from within the soil mass - soil or rock mass - by the action of gravity. The other concept - the second one - here on this slide is coefficient of storage. Coefficient of storage is essentially equal to the volume of water released from 1 square meter area of the aquifer when the water table is lowered by 1 meter. So, since it is volume divided by an area divided by a length, what you are going to get as the unit of this particular term is nothing. So, coefficient of storage is a unit-less quantity. The coefficient of storage is going to be equal to specific yield in case of a phreatic aquifer or an aquifer, which is unconfined, and not under artesian pressure.

Then another term we need to define at this stage is the coefficient of transmissibility. Coefficient of transmissibility of an aquifer is equal to the permeability multiplied by the saturated stiffness of the aquifer. So, these are the definitions that you need to keep in mind while considering the characteristics of an aquifer.

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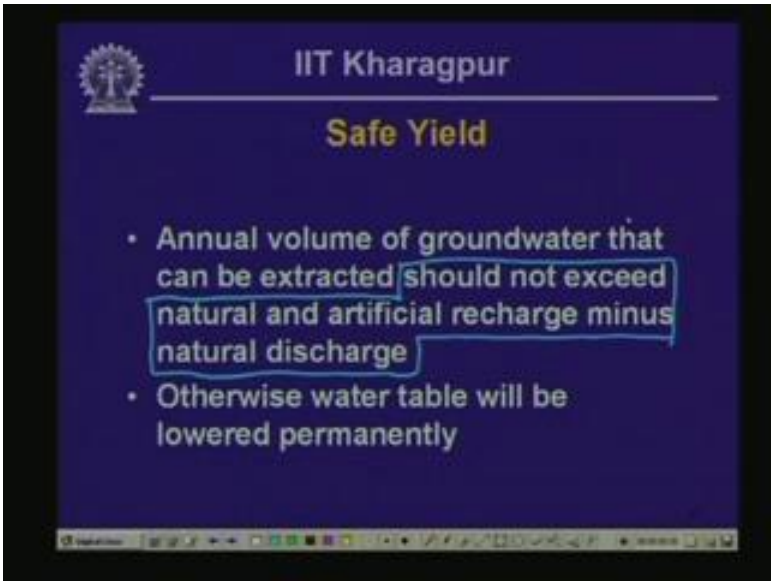

Now, the concept that is of interest - that is of primary interest - in many problems associated with extraction of groundwater is that of safe yield. Safe yield is equal to the annual volume of ground water that can be extracted without causing any long-term detrimental consequence. In other words, safe yield is that much of volume of ground water, which can be extracted without permanently lowering the water table. And so, the quantity should not exceed the natural and artificial recharge that the aquifer can have over the year minus the natural discharge from the aquifer.

So, this is very important - you should you should note this thing; this particular portion should be noted very carefully while trying to come up with a scheme of tapping a particular aquifer is that yield or the extraction of the groundwater should not exceed the natural and artificial recharge minus the natural discharge, because in that case you are going to cause a permanent lowering of groundwater table and it can have some long-term detrimental effect as we are going to see in the next little bit.

Now the question comes - if you lower the water table, then what are the consequences? The first consequence of permanent lowering of water table is uneven subsidence and many cities around the world are affected by this particular problem because of tapping of local aquifers to an excessive extent. Now, why this thing happens, let us look at this in a little bit more detail.

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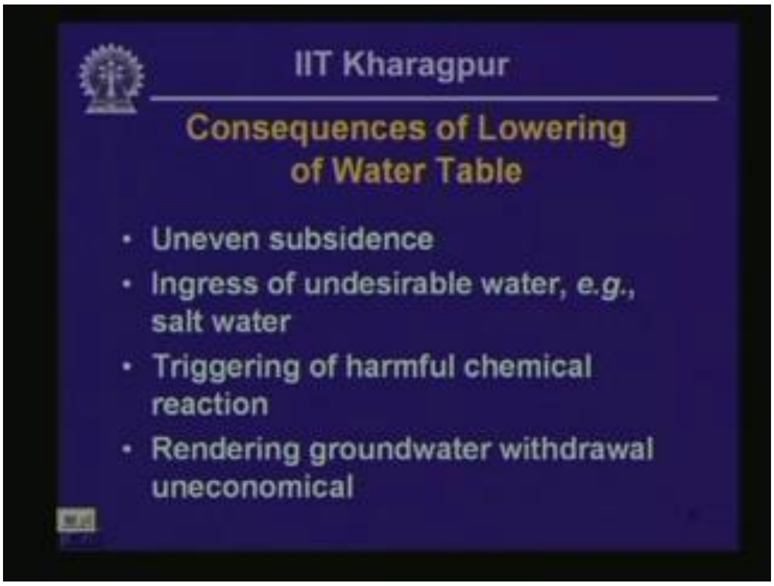

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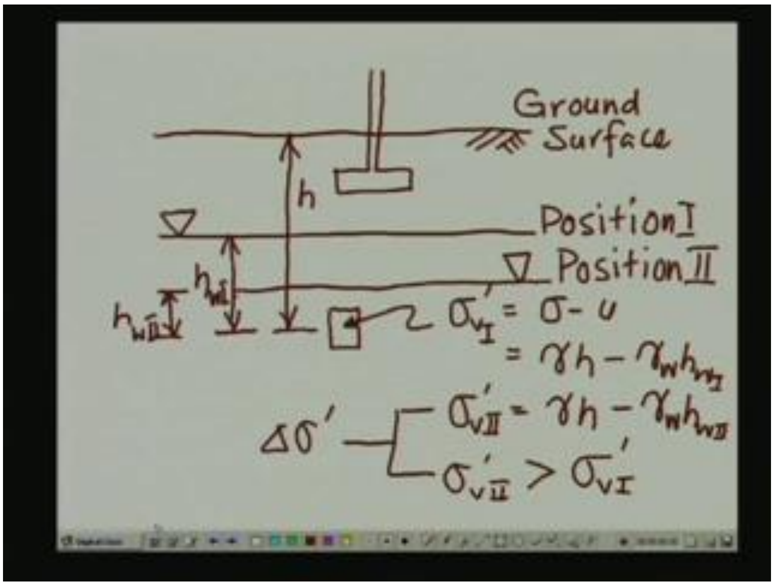

Let us say we have got a phreatic aquifer - flat phreatic aquifer - without an appreciable slope. In this particular case, if we consider an element of soil underneath the groundwater table, then for this particular soil we are going to have the effective stress as equal to sigma v prime is equal to sigma minus u where sigma is equal to the bulk unit rate of the soil. For simplicity, we are considering here that the soil is homogenous and isotropic. So, in this case, the entire volume of soil underneath the ground surface is characterized with an unit rate of gamma. So, gamma times h, where h is this height minus u, that is going to be equal to gamma w times hw.

Now, let us say we have got the water table lowered because of excessive tapping of local groundwater. So, this is position one of the water table - original position of the water table - and what we do in the process of tapping the groundwater to an excessive extent is to lower the water table to position two.

So, in this case, what is going to happen? Let us drop another subscript here. So, sigma v prime 1 will be the original effective stress within the element shown there and the effective stress, finally is going to be sigma v 2 and that is going to be equal to gamma h minus gamma w times hw 2; let us call the first depth of water table as hw 1 and the second depth of water table as hw 2. So, let me actually clarify this sketch a little bit.

So, this one here, we originally called it as hw; let us call it as hw 1 and since hw 2 is much smaller than hw 1, sigma v prime 2 will be larger than sigma v prime one. So, in that process, what we are having here is to load the element by the difference of these two quantities.

That is going to be delta sigma prime - this is going to be the vertical load that is going to be felt by the element of soil there, because of lowering of the water table and what is going to happen in the process is that the soil is going to try to deform or compress in the vertical direction, because of this increase.

And this increase of stress causes generally an uneven response in different areas within the affected zone. So, what you are going to have is the compression of the soil layers such as those shown by the element on this particular cross sectional sketch is going to be quite uneven. And as a result, you are going to have uneven settlement or uneven vertical sinking of the ground surface within different parts of the zone that is going to be affected by permanent lowering of the water table.

Now, you can also imagine that, if you have got a building foundation placed within the soil that is trying to sink, then those building foundations are also going to settle with the soil, and because of the fact that the settlement is going to be non-uniform, different parts of the building is going to settle by different amounts and that is going to lead to a severe distress - that could actually lead to a severe distress - or functional difficulty of the building or its different facilities, and even some structural problems such as cracking of walls and plaster and so on and so forth. So, this is the problem that you might actually end up having, if you have got permanent lowering of the water table.

Another problem associated with permanent lowering of water table is ingress of undesirable chemical constituents. A very typical example in this case is intrusion of salt water and we have looked at salt water intrusion in one of the earliest presentations of this series of lessons, and we are going to look at all these things later on in more detail as well.

So, particularly in coastal areas such as the coastal areas of Tamil Nadu, coastal areas of Gujarat, and many other places internationally in fact as well, because of excessive lowering of water table, salt water has entered the originally non-blackish or sweet water aquifers, and they are in fact displaced the sweet water aquifer further inland, and that has lead to great difficulty in water use problem associated with the use of the irrigation water wells within the affected area.

The fourth problem that you could have because of permanent lowering of water table is rendering groundwater withdrawal uneconomical, and that is very simple to explain - if you lower the water table - and let me draw a sketch to explain what I mean by this.

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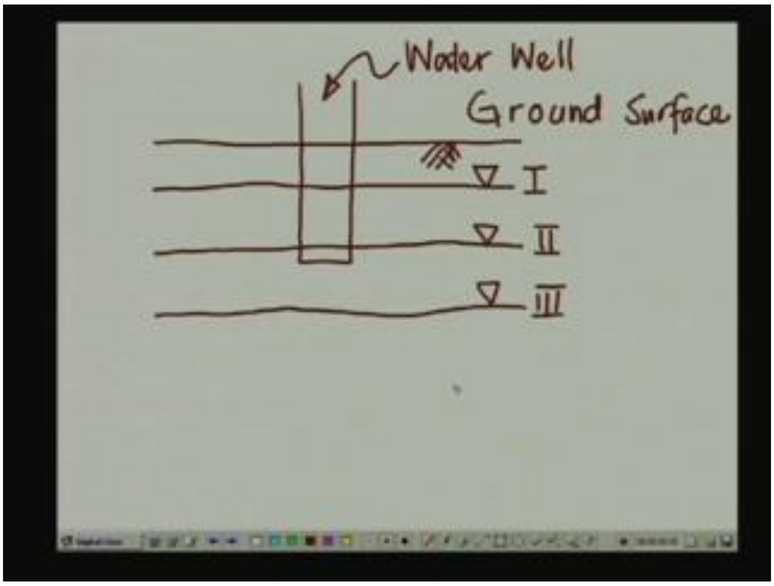

Let us say you have got a water well - a shallow water well - penetrating the aquifer which was originally at this position; we are going to call this position as I, and the position goes down to a lower elevation and this is a permanent lowering in fact; so this one here is our ground surface in this case. So, you can see the amount of yield that you are going to be able to tap from the water well. So, this is the water well; it is going to drastically reduce because of this lowering of water table.

So much so, that if the water table goes down below the base of the water well, then we might even have the situation when the well is going to totally dry up. And this particular type of phenomenon is being observed in several different parts of India because of excessive use of groundwater.

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So, we begin; actually at this stage it is perhaps appropriate that you know what is the typical use of groundwater in India. Groundwater, in fact, is a very significant source of drinking water and agricultural water requirement. In fact, ground water supplies 80 percent of the rural drinking water supply in India and 60 percent of the total agricultural requirement also is met by tapping groundwater.

Some more statistics. Mechanized wells across the country increased from one million in 1960 to 19 million in 2000. So, this one is a very significant increase. And, if you estimate, what is the typical cost associated with installation of so many wells, then you can calculate that the investment for installation of these many water wells - 19 million water wells - approximately could be US dollar 12 billion roughly over 50 years. And you can compare this number with the approximately 20 billion US dollars invested by the government in irrigation sector. And we are calling the investment in the mechanized water well as private investment, because most of the mechanized wells are installed by private farmers or other bodies local bodies - actually private individuals.

So, you can see that the private investment, in this case, is a very significant proportion of the of the total expenditure that the government incurred over the last 50 years in irrigation purpose.

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Now, we need to look at some of the constructional details of water wells. We have seen the typical components that are required in case of water well, when we considered the section of a typical monitoring well earlier.

Now, you can install the system by simple digging, and by far this is how an overwhelming majority of water wells are still constructed in India. So, most of the water wells are still constructed in the rural parts in India by hand digging and installation of a liner within the hole that is dug in the ground. This particular method cannot be used for installing a water well to depths - to very large depths. In fact, you cannot typically use this method for installing a water well going down beyond typically 10 meter or 15 meter. The diameter of the water well installed by digging can vary anywhere between 1 meter to 10 meter.

Then, the second process of installing water well is by hammering or jetting a thing called well point and what is a well point I should draw it here. So, well point is essentially a perforated section of well casing with a tip - a conical tip - like that and this particular segment has got perforations. And then, this well point is connected via adopters to casing tubes, and this entire assembly is hammered into the ground. So, this one here is the cross section over the well point. So, this particular assembly is hammered into the ground or it can be installed into the ground by jetting water at high pressure through the perforations. Usually well points are less than 75 millimeter or 3 inches in diameter, and this particular method is very common especially in North America for installing residential water wells within shallow sand and gravel aquifers.

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You could install the water well by the process of wash boring as well. In India, this is a very common method for installing tube wells that are shallower than say 100 meter depth below the ground surface. And what is involved here is to install a string of casing tubes with a perforated section at the tip of the string of casing tubes by the procedure of wash boring that we discussed sometime back.

There is also another method in which a well casing is installed by drilling a hole in the ground and the drilling can involve the use of rotary drilling procedure - air rotary or mud rotary or there could be auger boring to open up a hole for advancing the well casing.

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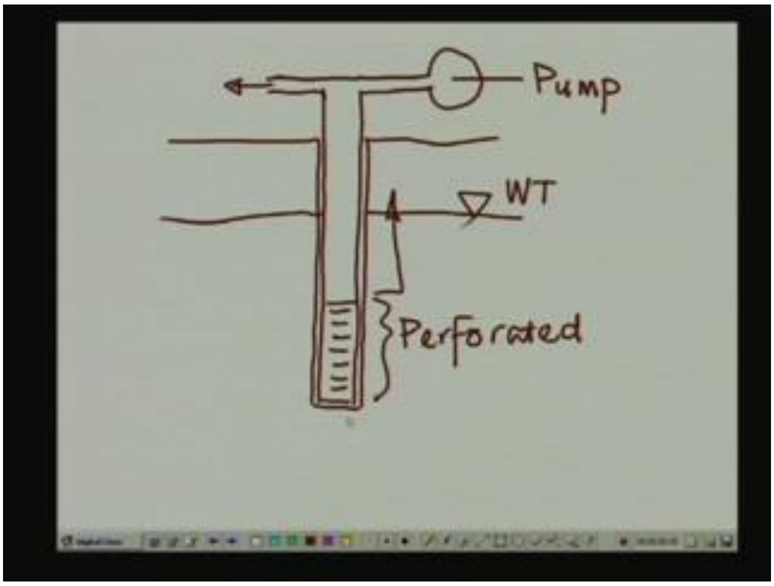

So, the essential component of the well casing is very simple. What are you going to have here? You are going to have a hole in the ground, and that hole could be hand dug, and then, you are going to have a casing tube inserted within the hole, appropriately sealed. A portion of the casing tube is going to be perforated, and the remaining portion is a solid tube through which you are going to pump out the water. So, you essentially put a pump near the top of the casing and that actually is going to allow the water to be withdrawn from the aquifer.

And in our case, the water table was perhaps at this elevation. So, this is the configuration in general; this is the configuration in general for any water well installed by drilling or jetting or by hammering in a well point. So, that is a typical section.

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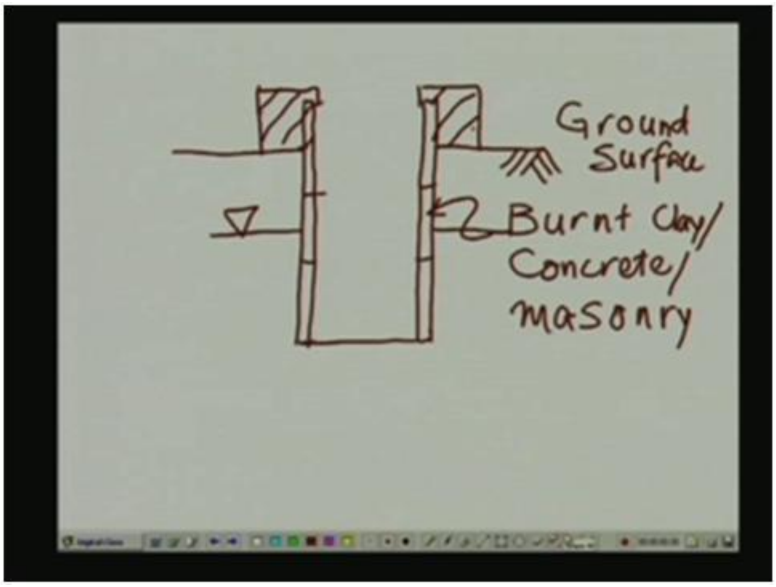

Whereas, in case of hand-dug water well, what you are going to have and many of you must be aware of this configuration yourself. So, you are going to have a hole and within the hole, there will be a series of liners, and these are typically segmented, and these liners they can be constructed out of burnt clay or concrete, and basically, they allow the water to be tapped into the well or even you can use masonry liners as well; that is also quite common across the country. This is the typical cross section of a hand dug water well. So, let us move back.

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Now, drinking water well needs to be separated from a potential source of contamination. There are some guidance available in many jurisdiction. And the Indian standard codes of practice are also available for this purpose. Typically, you should not install a drinking water well within 3 meters of building sewer, 8 meters of septic tank, 15 meters from a municipal sewer line, 30 meters from underground petroleum tank or within 400 meters of a landfill site, because that is going to let contaminated water into the drinking water supply which could cause health hazard.

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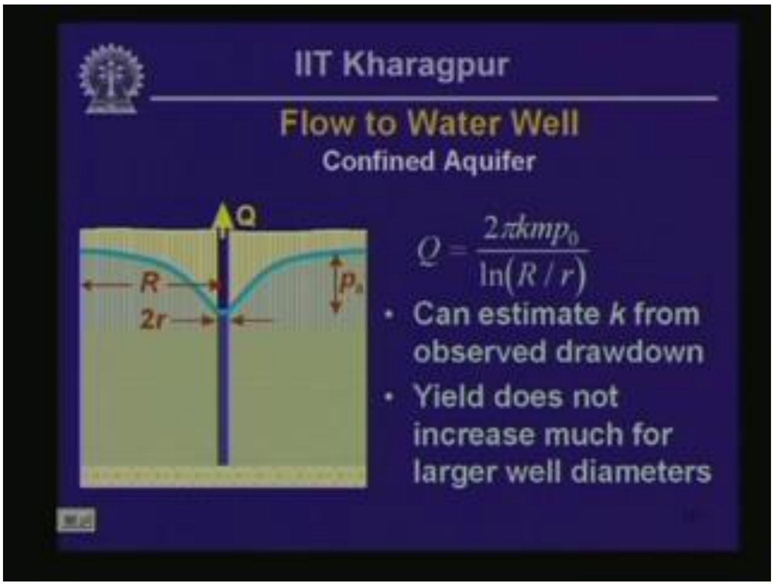

Now we look at the flow of water flow - groundwater - into water well. First we consider the flow into a confined aquifer. The confined aquifer, in this particular case, is like that; we have shown the position of the water table by thick blue line near the top of this particular cross section, and the hatched layer near the top of the sketch - of the cross section - represents a layer of aquiclude. So, groundwater is not free to move within this particular layer.

And the aquifer, in this case, is the solid shaded portion, underneath the hatched portion, near the top of this particular section. And at the bottom, is another impervious layer where the water well has terminated. Now, if we install a water well in this particular sequence of different layers, then initially when there is no flow, you are not tapping the ground water, then the water level within the water well is going to be the same as the phreatic surface or the surface to which the water level is going to rise within the open casing.

So, if it is a sub-artesian confined aquifer, then the water level is going to rise to a level which is going to be below the ground surface, as is the case on this particular section shown here. If it is on the other hand, an artesian water well, then the water table is going to rise above the ground surface. In any case, the treatment - the mathematical treatment - is going to be the same irrespective of whether it is sub-artesian or artesian groundwater. And you can show by theoretical calculation for a homogenous aquifer, what you are going to have is a definite relationship between the quantity q - that you are going to pump out or the discharge that you are going to pump out of the water well - and the reservoir or the aquifer properties and aquifer geometry, as we are going to see in next little bit.

Now, let us first see what happens when we try to tap this particular water well by installing a pump and trying to pump out a uniform quantity of water of q meter cube per second from within the aquifer. If you do that, then the water table is going to drop like that, and a cone of depression is going to form as shown - on the picture - on the cross section there.

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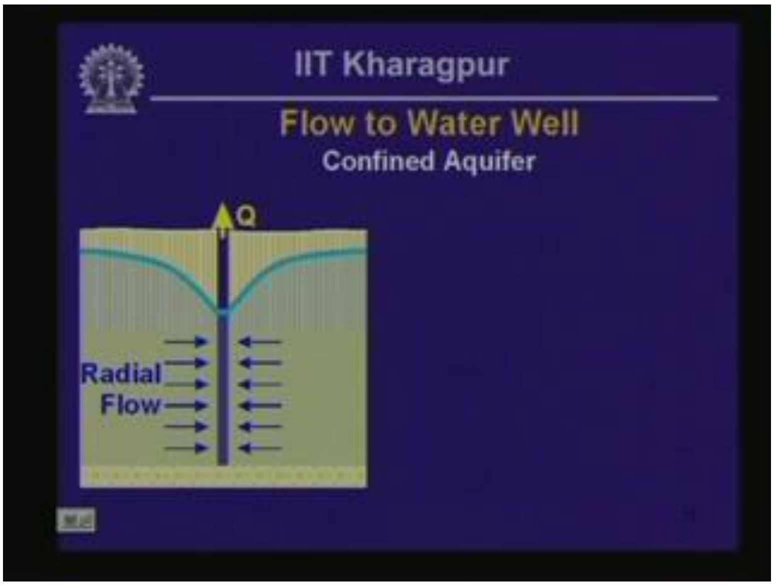

And let us put a few dimensions there, and actually you should notice here is that the water is flowing within the confined aquifer. So, in this case, because of the fact that the water well penetrates the entire depth of the confined aquifer, you are going to have a flow which is going to take place in the radial direction inward towards the well.

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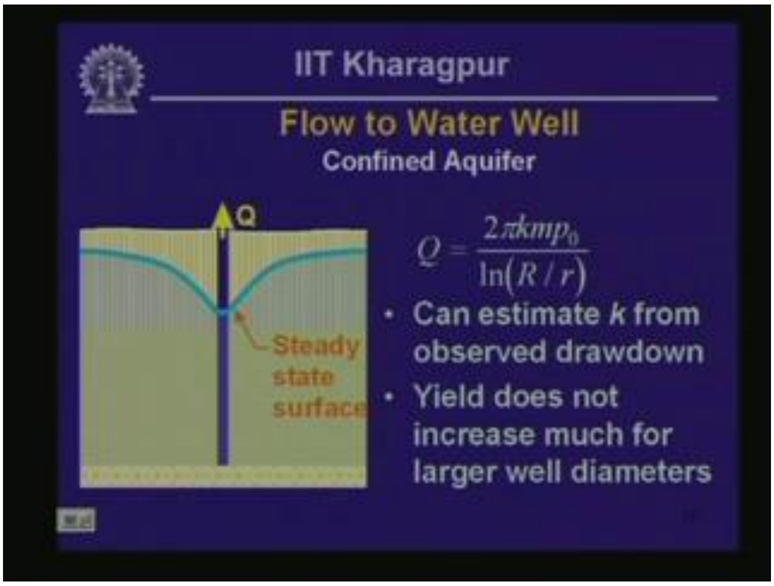

Also you are going to get a steady state water table at which if you do not change the pump out rate of q meter cube per second, then this particular water surface is going to remain unaltered with time. And once, if you actually stop the pumping, then eventually the water table is going to start rising and get back to the equilibrium value after the recharge has taken place over sufficiently long duration. Now q, as I was stating a few minutes back, it relates to the geometry of the aquifer and the permeability k and the expression for q is as shown near the top right of this particular slide.

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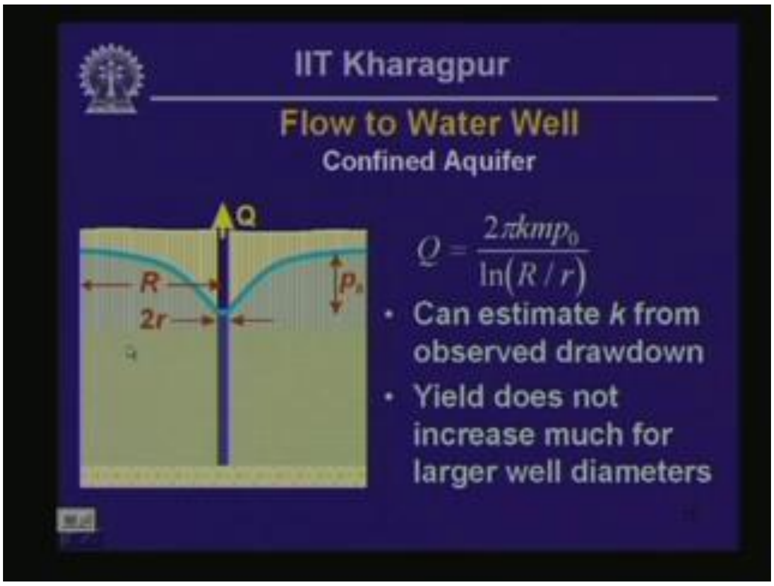

Now, we have to show also what are the different dimensions that we talk about in this particular case. So, p naught, in this case, is the amount of pressure drop because of the pumping out of groundwater or in this case is the outer periphery, is the radius from the centre of the water well to the outer edge of the cone of depression.

And small r, this is the capital R that we are talking about or upper case R, and the lower case r in this case represents the radius of the cross section of the water well itself. So here, what we get is the capital R, in this case, is the radius of the cone of depression; p naught is the pressure drop because of pumping out; and small r is the radius of the cross section of the water well.

So, you should notice, that we can also estimate k from the observed drawdown in a water well, and average value of k from the observed drawdown in a water well, and you should also notice here that the yield does not increase much if you start using a larger and larger well diameter. You should use the expression here - this particular expression; you should try to use this particular expression to satisfy yourself that yield does not increase by much if you start using progressively larger well diameter. So, it is relatively insensitive, in fact, to the diameter of the well. Now, we have defined all the terms required here. Now we can move on to the case of flow into an water well installed within an unconfined aquifer.

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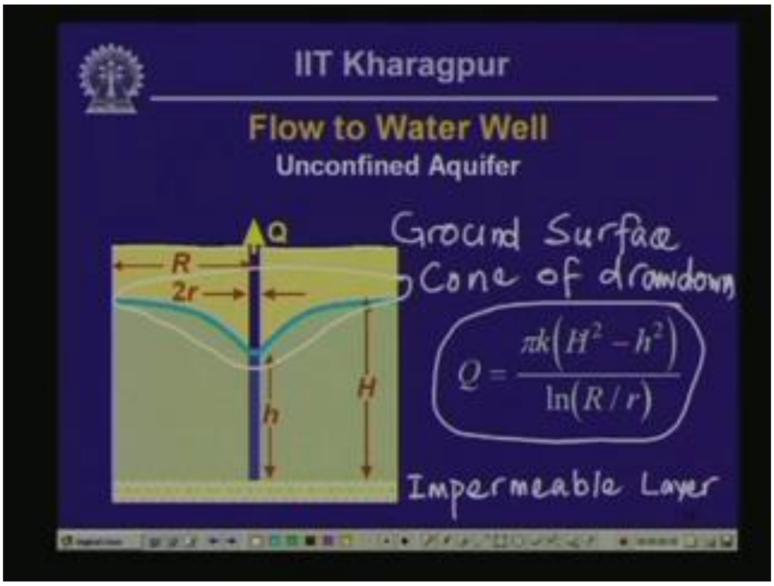

So here, what we are going to have is a very similar situation compared to the previous one. Here also the water table, after drawdown, is represented by thick cyan line as in the previous case. But here what you should notice is that near the top of the sequence of the geologic units, you do not have the cross hatched layer. So, the water table in this particular case is unconfined - represents an unconfined aquifer - and the aquifer unit extends all the way down from the ground surface to the contact between the unit and the underlying impermeable units.

So, this the impermeable layer like what we had in the previous case, and like in the previous case, this is our ground surface; and this one here, is the cone of depression - cone of drawdown actually - cone of drawdown, and then the symbols - capital R or the upper case and lower case r both of them represent the same thing as before. And here what we have is the height of the water table above the impermeable layer originally before drawdown was upper case H and that at the well itself is represented by lower case h.

So, if you measure all those quantities, then you are going to be able to calculate the flow rate q that is given by pi times the permeability times capital H square minus small h square over natural logarithm of the ratio of between capital R and small r.

So that is the case of flow into a water well installed in an unconfined aquifer. You should notice here as well that we did not consider any sloping water table in this case, but there are solutions of similar type available for sloping aquifers as well.

And also another thing you should note here is that we considered that the permeability in all cases are isotropic, and that is not going to be in case of a fractured rock because of the explanations that I provided in one of the previous lessons. So, these expressions are strictly not going to be applicable if you have got jointed or fractured rock with a joint set oriented in a preferred direction.

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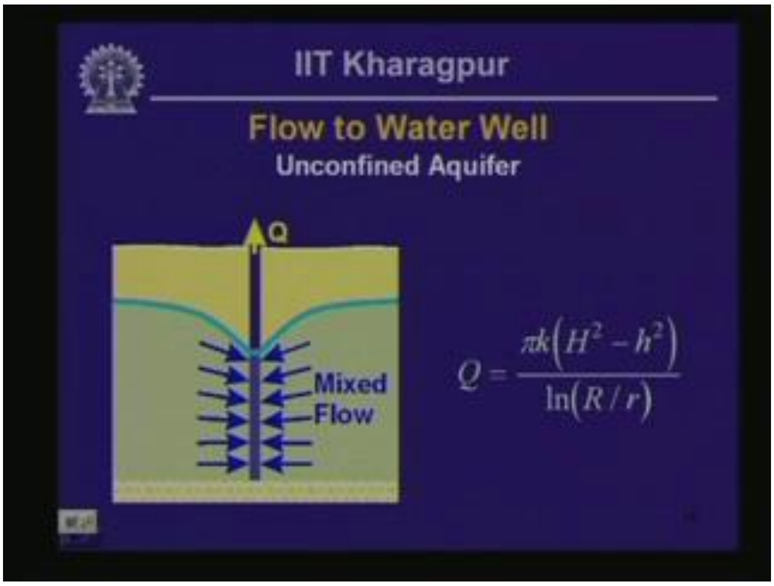

Now, in this case also, you should notice that the flow is going to be a mixed flow condition; it is not going to be a purely radial flow, is because of the sloped nature of the flow near the top portion immediately underneath the cone of depression.

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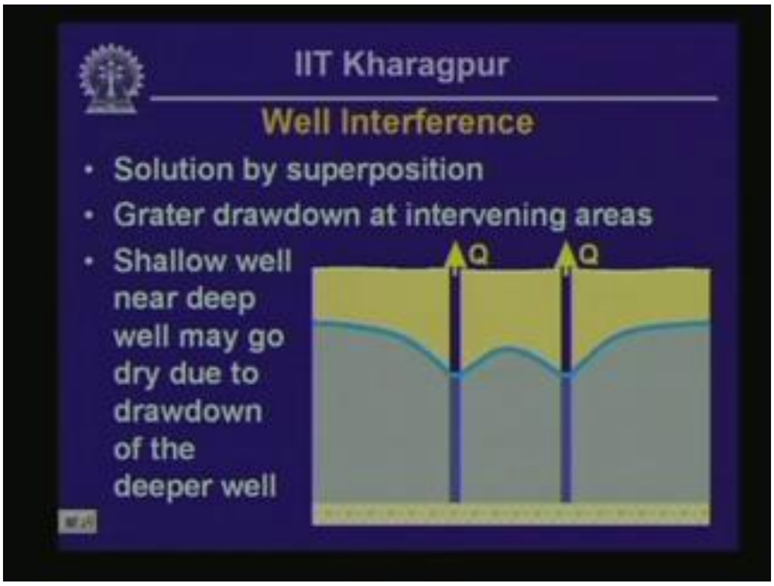

Now, you should also be aware that there is thing called well interference; that is if you have got a well already working in the vicinity of another well to be installed, the combined drawdown is going to be much larger as shown by the sketch near the bottom right of this particular slide. And, in fact, because you can you can get the solution of q in terms of the permeability and aquifer geometries, in this case, by superposing the solutions of the individual wells. And you should also note that if you have got this kind of well interference, if you have got a smaller well working originally at a location where a larger well was installed at a later date because of the drawdown of the larger well the smaller well, in fact, can go dry and that type of problem is encountered in many different locations of our country.

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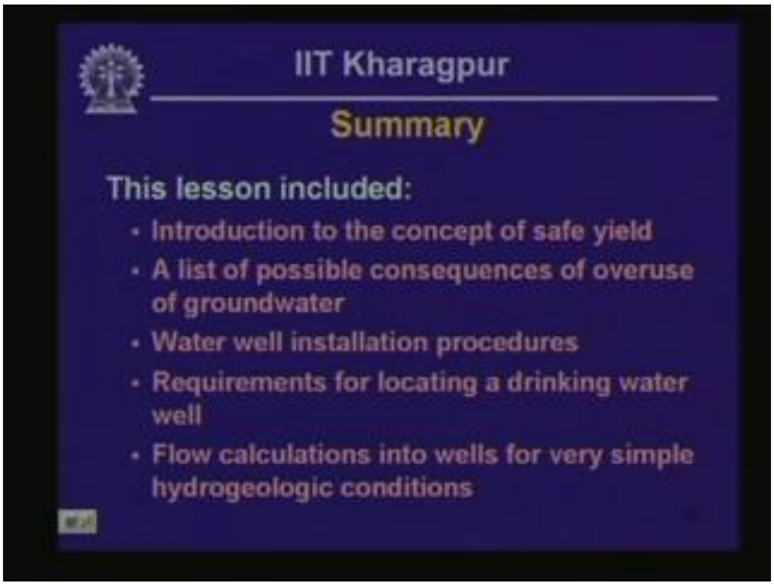

Now, we want to summarize our lesson. What we discussed in this particular lesson is the concept of safe yield. We considered a list of possible consequences of overuse of ground water. We looked at typical procedures used for installing water wells. We looked at the requirements for locating a drinking water well or what you need to consider as a minimum set back from the locations of potential zones of contamination.

And finally, we looked at flow calculations into water well for very simple hydrogeologic conditions. And you should note, that the equations that we used in this particular case can be derived from Darcy's law from relatively simple calculations which we did not want complete in this particular lesson.

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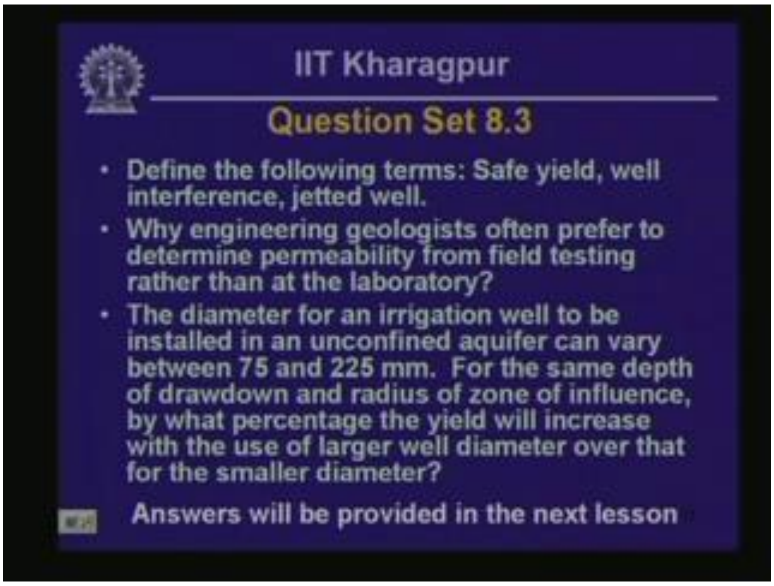

And finally, I want wrap up this lesson with a question set. You should try to answer the question set at your leisure. The first one being - define the following terms safe yield; well interference; jetted well. The second question that I asked is - why engineering geologists often prefer to determine permeability from field-testing rather than at the laboratory?

The third question is - the diameter for an irrigation well to be installed in an unconfined aquifer can vary between 75 millimeter and 225 millimeter for the same depth of drawdown and radius of zone of influence. By what percentage will the yield increase with the use of larger well diameter over that for the smaller well diameter? Try to answer these questions at your leisure and I am going to provide you my solution to these questions when we meet again with the next lesson. Until then bye for now.

Thank you.