Micro Irrigation Engineering

Prof. Kamlesh Narayan Tiwari
Agricultural and Food Engineering Department
Indian Institute of Technology-Kharagpur

Lecture-04
Soil Water Constants and Infiltration

Welcome to the 4th lecture on soil water constants and infiltration. Soil water constants are the two limits where irrigation water is a decided amount of water, i.e. how much it should be given. And in this lecture, we will be also dealing with the movement of the water when we supply from source as you know micro-irrigation drip emitter.

And we are dealing with what is the soil water content and how the soil water movement takes place when it is in saturated condition? When it is an unsaturated condition?

So, depending on the aspects of the soil water content, the movement of water takes place. Now, when we say soil water constants mean soil water constants are the basis for irrigation water application. So, different terminologies which are referred to in soil water constant one is saturation capacity. Saturation capacity means all the macro and micro-pores are filled with water. So, here as I was referring there the soil consist of pores and these pores may have water, may have only air, or partly filled with the air.

So, if all the pores are filled with water means macro-pore, macro means the larger size pores and micro-pores. If all these are filled with water we call it a saturation capacity. And this is what you are seeing here that the soil is saturated and then water is coming out of the soil particles. The soil is at maximum water retention capacity means all the pores are filled with water.

So, here soil water retention is maximum and the metric section is almost 0. Another important parameter in a soil water constant is field capacity. Field capacity means water is held in the soil after excess water has been drained by the force of gravity. So, gravitational water has been removed. When this condition attains after the gravitational water from the soil has been drained out of the soil mass.

So, it depends on the type of soil, if it is clay soil it takes more than 48 hours to 72 hours. If it is a say very coarse soil, sandy soil it takes only a few hours that it could be 6 hours itself. So, that type of situation exists depending on the soil texture. So, field capacity of what we are seeing here the water is drained and then part of the pores are filled with the air and water. Now there is a range for field capacity, it is the value is given as 0.1 to 0.33 bar, which is soil moisture tension, which means it is negative pressure. So, the negative pressure available is from 0.1 to 0.33 bar.

So, it will depend upon the particular texture means if it is a fine texture soil you are finding that it is a 0.1 and it goes up to 0.33 bar. So, it will depend upon the soil. So this is an upper limit of available soil water content from an irrigation point of view.

The permanent wilting point, plant roots are not able to extract soil moisture, means soil moisture which is available in the soil is not adequate that can be withdrawal by the plant for meeting the transpiration requirement. So, means here what we are seeing is there is a moisture content available, but the presence of air is dominating in case of permanent wilting point. So, it is the lower limit of available water.

And then soil moisture tension at a permanent wilting point is about 15 bar. Of course, this is the uppermost limit. But you know this varies with the range, which means it can be lower than this 15 bar, it could be 7 bar in some soils. Say coarse-textured, very coarse textures soil where gravel is present, the permanent wilting point could be in the order of 7 to 10 bars.

And it could be as you know 22 bars in the case of clay soil. So, a general value that is used is 15 bars for wilting point. Available water is the moisture content available between field capacity and permanent wilting point. Now, this particular diagram explains the available means when we say that, this is the total available water from field capacity that is theta FC to theta WP that is your moisture content at wilting point.

So, this is the total water available, and readily available water means that there is some kind of a moisture content which is a critical moisture content beyond which the plant does not feel any deficiency in moisture content. So, a limit is decided when we are planning a strategy for giving irrigation. So, this theta t it is decided in such a way that it does not affect.

So, when we want to partially give water content means we are making some strategy to give deficit irrigation in that case we are maintaining moisture content at theta t. And this ratio of the RAW and the TAW gives the value of the management allowable deficit. So, the total available water is theta FC minus theta WP multiplied by the depth of the root zone. And here it is this particular soil moisture stress coefficient (K_s).

$$TAW = \left(\theta_{FC} - \theta_{PWP}\right) \times drz$$

Now, this soil moisture is stress coefficient is maintained to give a specific level of stress when we have a deficit water supply. This means, it is not always to keep moisture content up to theta FC that is at field capacity, one can have less than that values may be theta t can be maintained. So, there is actually how much level of water stress one can maintain, this is the meaning of Ks.

Now soil water potential is the driving force for water to flow when soil plant atmosphere is being maintained in the soil water potential. Water flows from higher potential to lower potential means higher moisture content to the lower moisture content. And it indicates the amount of work needed to be done to displace a unit quantity of water from a given reference point.

So, if I put it say there is a saturated soil column, from saturated coil column because of the capillary force the water is moving from that particular reference point to a specific point. So, that is the amount of work that has been done to displace this particle by the capillary force. Now the total soil water potential (Ψt) can be explained by this equation, which is equal to the summation of the matric potential ($\Psi p(m)$).

$$\Psi t = \Psi p(m) + \Psi z + \Psi o$$

It is the summation of gravitational potential (Ψz); it is the summation of osmotic potential (Ψo). This means, all 3 potential when these are added and this is the metric potential because the soil moisture content means the amount of water that is held by the soil particles. So, the matric potential, matric force comes into the picture. Gravitational potential in the case of a saturated case when the gravitational water takes place.

This is the case of osmotic potential when there is concentration in the soil salt. So, I was telling you in the previous lecture about the osmotic potential or osmosis, this is the case when there is a concentration of salt in water or it is in the case of saline soil. Now this particular diagram, explains the soil water potential versus the volume of soil water content. So, if I look, these are the three types of soil when there is a large amount of sand is present means sandy soil. When the clay silt and the sand it is available, that is your loamy soil and the third one is your clay soil. So, what we see the soil water potential for a given mean soil water potential for a given moisture content it is in the case of clay soil is higher as compared to the sandy soil.

It is a simple case if I put it here say it is a 10 kilo Pascal soil water potential or soil moisture tension if I say soil water tension is 10 kilo Pascal or in tension when we are putting that in the negative part that is a minus 10 it is written here. So, the value of volumetric water content is 0.1. For the same you know 10 kilo Pascal case the moisture content is high in case of loamy soil. And in the same soil water potential when we are maintaining in case of clay soil the value is considerably high. So, soil water potential how it is varying with a different type of soil for the given soil moisture content varies with this.

So, this is an important consideration one has to see when we are giving irrigation water supply. Soil water moment, is a complex phenomenon and its variation, means it states the variations, it is moving in a particular direction and then variation in the force that causes its movement. So, this is the one particular case when soil is saturated means all the pores are filled with the water, when we are giving irrigation or we are supplying water, it is simply just gravitational water or the free flow of water takes place.

When it is an unsaturated case, you are seeing the soil pores are partly filled with the water and partly filled with the air, this is the case of an unsaturated case. And so the movement of water will be less because it is partly filled with the air. And in case of vapor means soil particles highly it is dry soil and when it comes with the water vapor. So, movement of water does not take place, it is simply adhering with the soil particles.

Soil water movement in a saturated condition is the hydraulic gradient that takes place from higher potential to lower potential. And gradients when we say, so this potential are divided by the length of the flow path will be the gradient and then what is the transmissive capacity of this soil, that is hydraulic conductivity. So, this can be explained by Poiseuille’s equation and which explains that the rate of flow (q) is equal to

$$q = \frac{P\pi r^4}{8l\mu}$$

So, q is the volume of flow per unit time or rate of flow or discharge we can say. And P is the pressure difference between two ends of the tube, or simply you know capillary tube and let it be the soil particle where it consists of the pores. So, it forms a capillary action, and then the diameter of here the important part what is the diameter of this capillary tube when the water flow takes place from the soil.

So, you can see how the diameter plays a role, so it is the 4th power of the diameter which is dominating the rate of flow. And so it is inversely related to the length of flow or length of the capillary tube and then inversely proportional to the dynamic viscosity of the fluid or water. So, this can be given that sandy soil has got a high rate of flow. The area or diameter of the soil pores is indeed larger as compared to the loamy soil or clay soil. So, pore size is a dominant factor when we apply Poiseuille's equation.

Darcy's law is used for the majority of our case means of the flow through porous media. So, if we are considering say a soil column which is cylindrical in nature of having length L and then we are measuring 2 say there are 2 sides, one is the inlet end and another one is the outlet end that is the downstream end and then the area of cross-section of flow is A. So, the difference in the head that it is *h* when we are telling that *h* in and this is your *h* out.

$$\frac{Q}{t} = q =- AK_{sat} \frac{h_{in} - h_{out}}{L} =- AK_{sat} \frac{\Delta h}{L}$$

Where, Q = volume flow cm^3

q = volume of flow per unit time cm^3/sec

t = time, sec

A = cross-sectional area, cm^2

K_{sat} = saturated hydraulic conductivity, cm/sec

Δh = change in water potential between the end of the column, cm

So, *h* in minus *h* out divided by *L* will give the hydraulic gradient. So, this delta h by delta L is directly proportional to the discharge or rate of flow**.** And then it is directly proportional to the area of cross-section of the flow. And if I put it that rate means the flow through porous media is directly proportional to the hydraulic gradient. So, this is a case at the proportionality constant which we call a saturated hydraulic conductivity.

So, the expression of flow through porous media is given by Darcy's law. Darcy law is valid only when the flow is laminar and the Reynolds number is less than 1. In many cases the when the flow is simply is a flow means saturated flow, literature say that for groundwater flow the value of this Reynolds number is between 1 to 10.

Now from an irrigation point of view, we do not deal with the saturated flow. For groundwater flow through porous media, we deal with the saturated flow, but from an irrigation point of view, it is unsaturated flow. So, water potential that is the matric potential is the only dominating case, the gravitational potential is that not dominant in this case. But we do take into consideration while we are means when we are taking soil column when it is in a vertical soil column, so this Z value is considered.

So, Darcy's law is applied or when we are using the matric potential in the case of horizontal flow we are considering. So, here it is applied for unsaturated flow with some certain modifications. So, the rate of flow is your velocity of flow or it can be given by

$$v = - K\frac{\Delta(\Psi_g + \Psi_m)}{\Delta l}$$

minus K psi, this is your delta psi g plus psi m. Now psi g is the gravitational potential and then this is a metric potential divided by l that is the gradient it maintains.

Now when we consider it unsaturated case means hydraulic conductivity is a function of moisture content. Now, this can be explained by the rate of change of soil moisture content when we considered one direction dimension means the one-dimensional case we are considering. Let us say in x-direction when we are putting it, so the del by del x K theta delta psi by delta x. So, delta psi by delta x means this potential with respect to x.

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial x}\left[K(\theta)\frac{\partial\Psi}{\partial x}\right]$$

Now, this particular term can be written K theta we can write. So, when we are considering the Z-direction that is in the vertical direction when we are considering, so the rate of change of moisture content. This means the change of moisture content with respect to time can be given by del Z that is in the vertical direction downward direction. This is the diffusivity term multiplied by del theta by del Z plus del K theta by del Z. K theta is the hydraulic conductivity with respect to moisture content. And D is the diffusivity term which is also a function of moisture content.

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[D(\theta)\frac{\partial \theta}{\partial z}\right] + \frac{\partial K(\theta)}{\partial z}$$

Now hydraulic conductivity is a very important parameter which is playing a role when we are considering flow through the unsaturated or saturated column. So, it is the ability of soil to transmit water when subject to the hydraulic gradient. So, K will depend upon the particular type of soil texture and also water holding. So, soil texture is a function of how the pore geometry exists and accordingly the how much will be the water content is available.

So, that is dominating and it is a proportionality constant. And this particular diagram, when you look, that how hydraulic conductivity is changing with respect to the different types of soil and also soil water potential. So, hydraulic conductivity and the soil water potential from a negative sense means negative pressure point of view I am putting here.

So, if I put it the soil water potential 0.01 to 10 means, this is in minus you know, so minus 0.01 means the moisture content is higher at 0.01 mega Pascal as compared to 10. So, as the moisture content is negative potential increases, hydraulic conductivity of the soil decreases exponentially and this can be explained by this diagram. So, field capacity and wilting point how it is varying? You can see hydraulic conductivity at the field capacity is greater as compared to the hydraulic conductivity at the permanent wilting point.

So, the moisture content is influencing the soil hydraulic conductivity and that can be also seen in the case of these types of two soils it is given. One is the 2 are the 2 different soils and how important it is? The clay soil is fine-textured and you know the soil water potential values are relatively higher as compared to the sandy soil. So, hydraulic conductivity how it is decreasing with the increase in soil water potential is negative. So, the dimension of length per unit time which is the same for hydraulic conductivity it has a dimension of the same as the velocity.

Now the values of K that are sandy soil, sandy loam soil, loamy sand soil, a loamy soil the value of K, these are some experimental based values that have been obtained. And for many irrigation experiments, these values are used while we are deciding to give irrigation.

And when we want to find out hydraulic conductivity in laboratory conditions, we use the constant head permeameter method, also we use variable head permeameter. So, this is the diagram that you see here, this is a constant head permeameter, and on the right-hand side of diagram B, it refers to the variable head permeameter. So, as you know, when we are bringing soil core sample putting here undisturbed core sample.

It is kept in a chamber and then the particular head constant head is maintained and this head difference head at the top of the saturated soil column to the center of the outlet of this particular cylinder. So, we are maintaining a constant head and this value delta h is used to find out the head difference. And this is used to find out the hydraulic conductivity. So, a constant head gradient is maintained by adjusting the inflow, this is what you are seeing by adjusting the inflow. So, when becomes a constant then only this value is used.

$$K = \frac{V.L}{A.t.\Delta h}$$

And then we use this expression that is K equal to the volume of flow divided by the time this becomes the Q and then that is divided by area, so this becomes velocity unit. And then L refers to the length of the saturated soil core sample and delta h is the head difference. So, this value is used to find out the hydraulic conductivity. So, this expression is applied to obtain the hydraulic conductivity.

Now the other one is the falling head permeameter. Now falling head parameter is used for fine-grained soil particles even for the laboratory purpose any soil sample it can be brought, but it should be an undisturbed soil sample and that is brought here. So, the liquid that percolates through the saturated soil column, is a saturated column and is kept unsteady means, here in this case we were maintaining the constant head case we were maintaining.

Here this particular head is not maintained constant; we are maintaining an unsteady-state flow regime as well as the head is also variable. So, the not necessarily constant head is maintained during the test and we operate the system in such a way that suppose, there is one head at the particular time we are keeping the h_1 and then we are maintaining the head h_2. And these two heads values are used to find out the hydraulic conductivity (K).

$$K = \frac{L\,a}{A(t_2 - t_1)}\, ln\left[\frac{h_1}{h_2}\right]$$

And say this is the diameter of the soil column or core and then the tube diameter is A. So, the length of the tube (L) and then area of the tube (a) are divided by the area of the smaller tube divided by the area of the column 2 minus t_1 means per 2-time interval when the values are taken and then corresponding h_1 and h_2 is measured. So, logarithmic values of h_1 and h_2 and then per 2-time interval when t_1 and t_2 is maintained, the hydraulic conductivity is determined.

And these are the parameters that V is equal to the volume flow rate in time t, a is the cross-sectional area, L is the length of the sample, this is the length of the sample, and h_1 and h_2 are the 2 heads at the 2 different times which is being taken and t_1 and t_2 is the time interval. These are used to find out the variable permeameter value for the hydraulic conductivity.

Infiltration is another process that explains the entry of water into the soil. And this particular diagram explained how the infiltration takes place from the saturated media and then the moisture content is high. You are finding and then when the drip system when you are operating a dripper, so interesting part is the dripper explains the typical movement of the water, this kind of movement of water it takes place.

But the water is moving vertically downward and the rate at which water interest is known as infiltration rate. And if the experiment is continued for a longer period so the accumulated depth of water infiltrated with time, total time in a given time is known as an accumulated depth of infiltration. When the rate of infiltration becomes constant, after a certain time a steady-state is reaches such a distant filtration rate is known as a basic infiltration rate.

And this infiltration test is used for the design of experiments, design of irrigation experiments. And mainly for irrigation purposes, we are using the value of infiltration, when we are applying a sprinkler system when we are applying the drip system so that it does not form runoff. The application rate should match the infiltration rate of the soil.

Now when we conduct the experiment and find out the infiltration depth, so what do you find that with the time when you are putting it and then the depth of infiltration you are plotting, cumulative depth of infiltration you find it this kind of a graph it exerts. It develops, this is known as a cumulative depth of infiltration. Now when you take the derivative of this curve, when you are taking derivatives of that curve with respect to time, this is known as the infiltration rate curve.

And at this particular point when we are seeing that it has reached the steady-state or constant rate of infiltration, this is known as a basic infiltration rate. Now infiltration rate decreases with time. Because the topsoil pores become saturated, moisture content has increased. So, that has caused a decrease in the rate of infiltration.

Now, infiltration can be measured by using a single-ring infiltrometer or double-ring infiltrometer. So, in the case of a single ring infiltrometer you are finding out the depth of water in this cylinder. Now, it may happen beyond this depth of cylinder, water may go in the lateral direction. So, that is one limitation in the case of a single-ring infiltrometer.

But when we are using a double-ring infiltrometer means the smaller cylinder is kept inside the outer cylinder. So, there is 2 concentric cylinder and they are of 60 centimeters in diameter, the inner cylinder is 30 centimeter in diameter and then water is being poured from the top and then it is allowed such that this outer cylinder depth of water it maintains a buffer zone, so water enters vertically downward.

So, this is the type of flow which we are observing here, that here it is moving lateral direction whereas water level fall in the inner cylinder is measured by using the scale by using the gauge it could be point gauge or it could be the hook gauge. And the cumulative depth of infiltration with time is being monitored and then the cumulative depth of infiltration is plotted.

And then we get this kind of a graph, which means accumulated depth of infiltration with time when it is plotted it gets this kind of a graph. And this graph is explained by Kostiakov's equation which is given by

$$Z = a\, t^{b}$$

When in the infiltration rate form when you are making the differential form of the equation

$$I = (a\, b)\, t^{b-1}$$

Where,

Z = depth of infiltration, cm

t = time or intake opportunity time, min

I = infiltration rate, cm/min, and

a and b= parameters ($a > 0$ and $0 < b < 1$)

And we can see that this will be the infiltration rate equation. And if you want to take the logarithmic part of this equation. It becomes a linear equation and this linear equation can be used to obtain the value of a and b.

log Z = log a + b log t

log I = log (ab) + (b-1) log t

Modified Form:

$$Z = a\, t^{b} + c.t$$

$$I = (ab)\, t^{b-1} + c$$

c is the steady state infiltration rate

So, there are other infiltration equations that are used, one is Horton's equation, these equations are superior to the Kostiakov's equation. And it is used mainly in the hydrologic study as well as and the value of K as well as f_0, f_c these values they are being obtained from by conducting the experiment.

Horton infiltration equation:

$$f_p = f_c \times (f_o - f_c) \times e^{-kt}$$

Where,

f_p = infiltration capacity in mm/hr at any time t

f_o = initial infiltration capacity in mm/hr

f_c = final constant infiltration capacity mm/hr at saturation, dependent on soil type and vegetation

t = time in hour from the beginning of rainfall

k = an exponential decay constant dependent on soil type and vegetation

And then Phillips equation is another equation:

$$F(t) = a + \left(\left(\frac{S}{2}\right) \times t^{-0.5}\right)$$

Where,

a = Minimum infiltration capacity

S = Initial infiltration capacity

So, these are some important equations which are being used to establish their constant and then this is being used.

So, in this particular lecture, dear participants we studied soil water constants and soil water potential, we studied soil water movement in relation to irrigation water application, we studied infiltration models, we also studied how to conduct infiltration tests. We did study how to determine the hydraulic conductivity of the soil in laboratory conditions. So, there are methods also to find out the hydraulic conductivity by using the field test.

So, those are there, now in the forthcoming lecture, we will work out some problems that we discussed in previous lectures that are on fundamentals of fluid mechanics we studied, we also studied soil water movement as well as infiltration. So, we will work out in the coming lecture we will do exercises and so that you get hands-on experience on these topics.

So, you may refer to these books, these are A.M Michael by irrigation theory and practice which can be used as a textbook. And then there are other books which can be used and then these materials are available in E-course developed by us at IIT-Kharagpur for ICAR. So, such material can also be referred from there.

Thank you very much.