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Soil Water Movement – Saturated and Unsaturated Flow

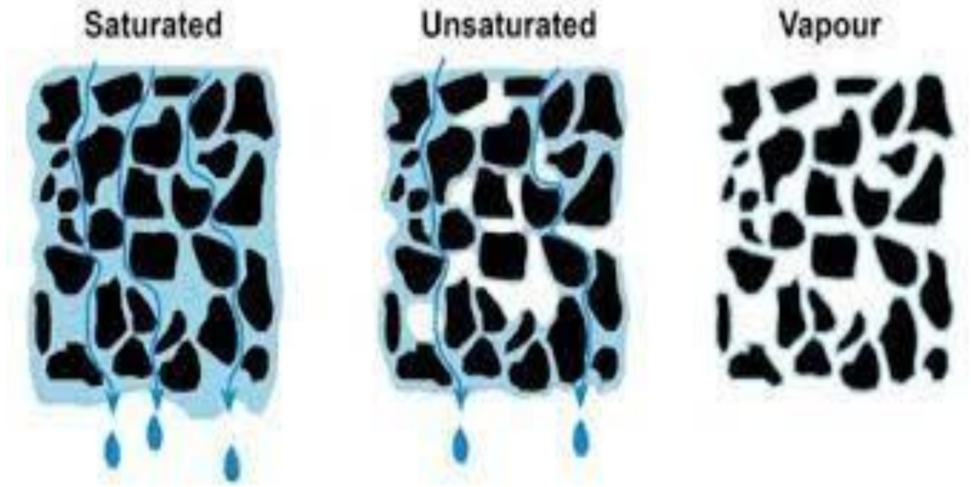
S. Arunkumar
Ph.D. Scholar, Department of Soil Science and Agricultural Chemistry, School of Agriculture, Lovely Professional University, Jalandhar, Punjab

SUMMARY

Water is a highly dynamic component in soil system. It moves in all three phases: solid, liquid and vapour. In saturated or flooded situation, water moves in liquid phase, while in a partially dry or unsaturated soil, it moves in both liquid and vapour phases. Movement in solid phase as commonly occur in frozen soil is also believed to take place closer to clay surface. The flow of liquid water is due to a gradient in matric potential from one soil zone to another. The irection of flow is from a zone of higher matric potential to one of lower matric moisture potential. Saturated flow takes place when the soil pores are completely filled with water. Unsaturated flow occurs when the pores even in the wettest soil zones are only partially filled with water. In each case, moisture flow is due to energy - soil relationships.

INTRODUCTION

Water movement in soil can be in any direction, depending on conditions. Water flows through the open pores between soil particles. In an ordinary silt loam, for example,half the soil volume is pore space. Water and air share this pore space. For most plants it mustbe possible for air from the root zone to exchange with air from the to the plant in soils with large pores. Water moves until the forces balance, at which point the curvature of air water interfaces is the same, except for some vertical differences that exist because of gravity. If thesoil is not uniformly homogeneous, the portions of the soil that have the smallest pores retain water most strongly. Two major forces move liquid water through the soil pores; these forces are gravity and adhesion. The movement of water is entirely different under these two conditions. To understand the differences, first one should know surface tension of liquid water. You have seen raindrops or drops from a dripping tap, and you probably noticed they are roughly spherical, with a positive radius of curvature. They are held in this shape by a force called surface tension, which acts at the air-water interface in a somewhat similar manner as a rubber balloon, opposing a positive pressure inside of the droplet. Now, much of the water you see - water from a tap, water in a lake or stream, or water in the cup you drink from - is under positive pressure. This is how most people think of water. Water under positive pressure moves in response to the pressure of a column of water or by gravitationalforces.



Soil Water Movement in Saturated Condition

Concept of Flow

Water movement through soil is proportional to the product of the driving force and the conductivity of soil for water.

$$Q = c\ DK$$

Where, Q = Flow velocity C = Proportional factor
D = Driving force K = Conductivity of the medium.

This relation holds true for heat transfer and for flow of electricity as well as for watermovement.

The driving force in case of water is a pressure gradient. Water moves from a positionof high pressure to a position of low pressure in both saturated and unsaturated conditions, including in vapour state.

The permeability of soil for water vapour is proportional to the volume of water free pore space, regardless of size of pores. Free path plays significant role rather than size of pores.

Soil Water Movement in Saturated Condition

Under saturated condition of soil, all the macro and micro pores are filled with waterand any water flow under this condition is referredto as saturated flow.The saturated flow of water depends upon twofactors namely hydraulic gradient i.e., the hydraulic force driving the water through the soil andhydraulic conductivity i.e., the ease with which the soil pores permit water movement.

Assuming the soil to be a bundle of straight and smooth tubes, knowledge of the size distribution of the tube radii could enable us to calculate the total flow through a bundle caused by known pressure difference, using Poiseuille's equation:

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

Where, q = volume of flow per unit time cm^3/sec
P= pressure difference between two ends of the tube of length l, dynes/cm^2
r = radius of the tube, cm
l = length of the tube, cm
μ = viscosity of liquid, dynes-sec/m^2

The above equation indicates that the pore size is of outstanding significance, as its fourth power is proportional to the rate of saturated flow. Generally the rate of flow follows:

Sand > Loam > Clay

Unfortunately, soil pores are not like straight tubes, but are of varying shapes and sizes, highly irregular and interconnected. This complexity in shape causes change in fluid velocity from point to point, even along the passage. For this reason, flow through complex porous media is generally described in terms of macroscopic flow velocity vector, which is the overall average of the microscopic velocities over a total volume of soil. Thequantity of water flowing through a section of saturated soil per unit of time is given by the Darcy's law.

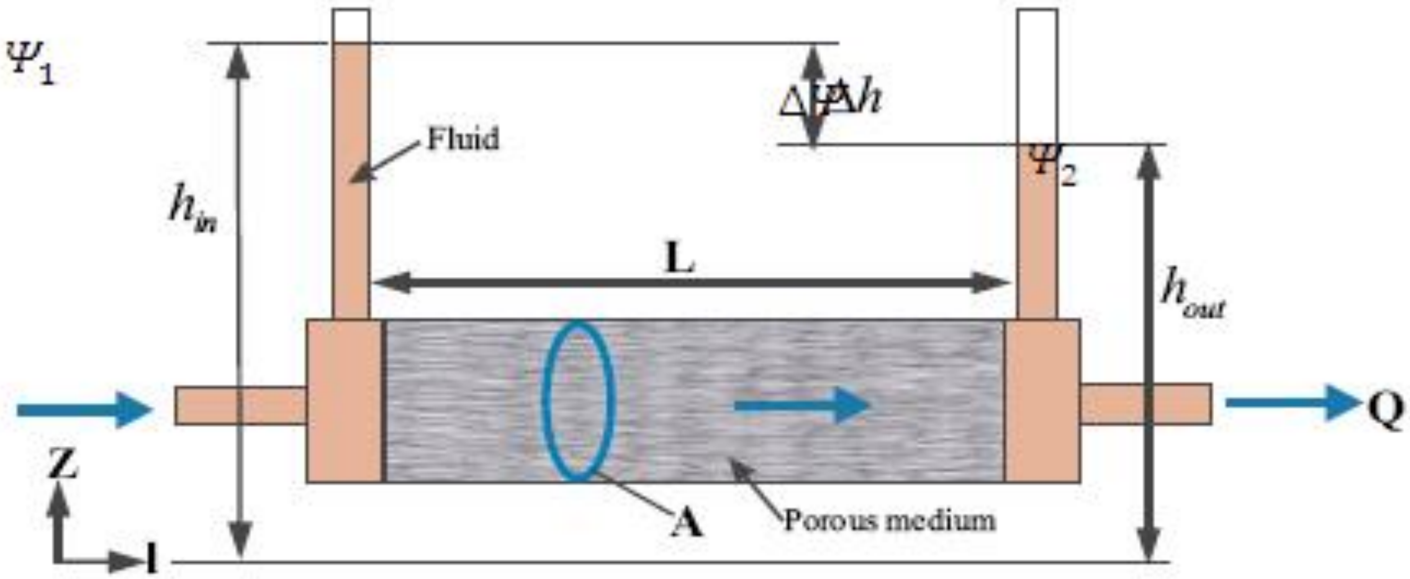


Fig. Definition sketch of Darcy's Law.
(**Source:** http://doi.ieeecomputersociety.org)

The law states that, the quantity of water passing through a unit cross sectional area of soil is directly proportional to the hydraulic gradient. Mathematically,

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

$$\frac{q}{A} = V = -K_{sat}\ .i$$

Where, Q = volume flow cm^3
q = volume of flow per unit time cm^3/sec
t = time, sec
A= cross-sectional area of the soil through which the water flows, cm^2
K_{sat}= saturated hydraulic conductivity, cm/sec
Δh = change in water potential between the ends of the column, cm
L = the length of column, cm
i= , hydraulic gradient.
V = velocity of flow cm/sec or velocity flux, v. It is the flow per unit area.
The negative sign denotes that the direction of flow is opposite to that of the head causing the flow. It is omitted in further discussions as its significance lies only in indicating the direction which is the same (towards the decreasing gradient) in all cases.
Darcy's law is valid only when flow is laminar. Reynold's number, the index used for describing the nature of flow is given by

$$Re = \frac{\rho v d}{\mu}$$

Where, Re = Reynold's number
= density of fluid
V=velocity of flow
D = mean diameter of the soil particles
μ= dynamic viscosity of the fluid.

The Darcy's law is valid for flows where Re is less than one.
In equation replacing Δμ by Δψ and we get

$$v = -K_{sat}\frac{\Delta\Psi}{l}$$

Where, Δψ = is the change in potential between two points at a distance l.
Application of Darcy's law and continuity equation of three dimensional flow of an incompressible fluid through a porous medium results in the derivation of Laplace equation. It is given by

$$\frac{\partial^2\Psi}{\partial x^2} + \frac{\partial^2\Psi}{\partial y^2} + \frac{\partial^2\Psi}{\partial z^2} = 0$$

It states that the second partial derivatives of the water potential with respect to x,y and z directions sums to zero.

Unsaturated Water Movement

As gravity drainage continues the soil macrospores emptied and aremostly filled up with air and the micro pores or capillary pores with water and some air. Movement of wateroccurring under this condition is termed as the unsaturated flow condition. In the case of unsaturated flow condition, the water potential is the sum of metric potential (ψm) and gravitational potential (ψg) . Metric potential is only applicable in the case of horizontal movement of water. In the case of downward movement of water, capillary and gravitational potential act together. In the case of upward capillary movement of water, metric potential and gravitational potential oppose one another. For unsaturated flow condition of water through soil, equation can be modified as:

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

Darcy’s law can be applied in the case of unsaturated flow conditions with some modifications.
Unsaturated, 1-D horizontal flow is given by

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

Unsaturated, 1-D vertical flow is given by

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

Where K is hydraulic conductivity and D is diffusivity.

As drainage proceeds in a soil and the larger pores are emptied of water the contribution of the hydraulic head or the gravitational component to total potential becomes progressively less important and the contribution of the matric potential ψm becomes more important. The effect of pressure is generally negligible because of the continuous nature of the air space. The solute potential (osmotic potential) ψs does not affect the potential gradient unless there is unusual concentration of slat at some point in the soil. The negligible effect of solute potential is due to the fact that both solutes and water are moving. Thus, in moisture moment under unsaturated conditions, the potential ψ is the sum of the matric potential ψm and, to some extent the gravitational potential ψg. In horizontal movement, only ψm applies. Under conditions of downward movement, capillary and gravitational potentials act together. In upward capillary movement ψm and ψg oppose one another. For unsaturated flow (Equation 7.28) may be rewritten as:

$$\Delta (\psi m + \psi g) v = - k$$

$$\Delta I$$

The direction of *I* is the path of greatest change in (ψm + ψg).

Under unsaturated conditions Darcy’s law is still applied but withsome modifications and qualifications. It is applicable to unsaturated flow if *k* isregarded as a function of water content, i.e. *k* (0) in which 0 is the soil moisture content. As the soil moisture content and soil moisture potential decreases, the hydraulic conductivity decreases very rapidly, so that ψsoil is – 15 bars, *k* is only 10^{-3} of the value at saturation. The rapid decrease in conductivity occurs because the larger pores are emptied first, which greatly decreases the cross-section available for liquid flow. When the continuity of the films is broken, liquid flow no longer occurs.

In unsaturated soil moisture movement, also called capillary movement, *k* is often termed as *capillary conductivity*, though the term hydraulic conductivity is also frequently used. The unsaturated conductivity is a function of soil moisture content as well as number, size and continuity of soil pores. At moisture contents below field capacity, the capillary conductivity is so low that capillary movement is of little or no significance in relation to plant growth. Many investigations have shown that capillary rise from a free water table can be an important source of moisture for plants only when free water is within 60 or 90 cm of the root zone.

Movement of unsaturated flow ceases in sand at a lower tension than in finer textured soils, as the water films lose continuity sooner between the larger particles. The wetter the soil, the greater is the conductivity for water. In the ‘moist range’, the range of unsaturated flow in soils of various textures is in the following order:

Sand < loam < clay

It may be noticed that this is the reverse of the order encountered in saturatedflow. However, in the ‘wet range’ the unsaturated conductivity occurs in the same or similar order as saturated conductivity.

Water vapour movement

Water vapour movement is significant only in the ‘moist range’. In the ‘wet range’ vapour movement is negligible because there are few continuous open pores. In the ‘dry range’ water movement exists, but there is so little water in the soil that the rate of movement is very small. Water vapour movement goes on within the soil and also between soil and atmosphere, for example, evaporation, condensation and adsorption. The rate of diffusion of water vapour through the soil is proportional to the square of the effective porosity, regardless of pore sizes. The finger the soil pores, the higher is the moisture tension under which maximum water vapour movement occurs. In a coarse textured soil pores become free of liquid water at relatively low tensions and when the soil dries out there is little moisture left for vapour transfer. But a fine textured soil retains substantial amounts of moisture even at high tensions, thus permitting vapour transfer. It is interesting to note that maximum water vapour movement in soils vapour movement is ofgreatest importance for the growth and survival of plants.

CONCLUSION

Movement of soil water in unsaturated soils involves both liquid and vapour phases. Although vapour transfer is insignificant in high soil water contents, it increases as void space increases. At a soil moisture potential of about-15 pars, the continuity of theliquid films is broken and water moves only in the form of vapour. Diffusion of water vapour is caused by a vapour pressure gradient as the driving force. The vapour pressure of soil moisture increases with the increase in soil moisture content and temperature, it decreases with the increase in soluble salt content.

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