

## **Module 3**

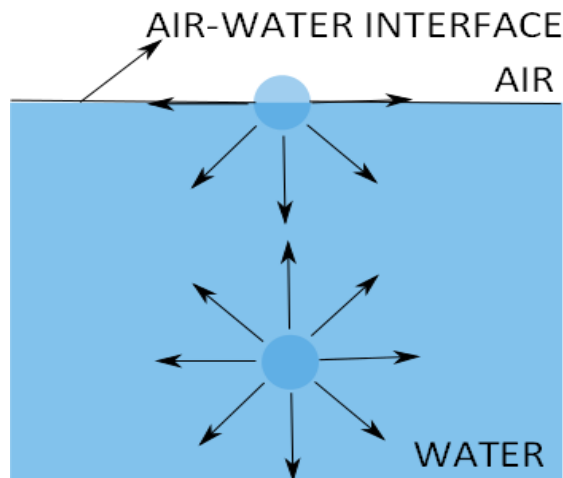
### **Lecture 1**

#### **Soil hydraulic characteristics**

Water surface acts as if it is in tension! Due to this phenomenon, small objects "float" on the surface of a fluid, as long as the objects cannot break through and separate the top layer of water molecules. Small creatures such as "water strider" and "Basilisk Lizard" thus can walk on water as the exerted pressure is not sufficient to penetrate through the water surface as shown in Fig. 3.1a (<http://norfolkwildgardens.co.uk/Pond-Skater.html>) and 3.1b. (<http://www.factzoo.com/reptiles/lizards/jesus-lizard-running-on-water.html>).

#### *Surface Tension*

Surface tension is due to an imbalance between intermolecular attractions (cohesive forces) at the surface. Water molecules hold each other due to the intermolecular cohesive forces. These forces, acting on a water molecule are effectively equal in all the directions in the bulk solution. Thus the net force on the molecules in the bulk solution is zero. However, a resultant inward force acts on the molecules at the air-water interface (surface) due to the absence of the water molecule above, as shown in Fig. 3.2. The presence of fewer water molecules at the surface also results in a stronger bond between the molecules. This inward net force causes molecules at the surface to contract and to resist being stretched or broken. Thermodynamically, the molecules at the surface must gain excess energy over those in the bulk water to retain at the surface. This surface free energy is the surface tension at the air-water interface and the surface behaves like a tension membrane.



**Fig. 2. Development of surface tension at the air-water interface**

*Interaction between air – water – solid phases*

The air-water interface will curve to form a meniscus when it comes in contact with solid surface. The meniscus angle with the solid surface, measured in the water, are lower than  $90^\circ$  (acute contact angles) when adhesive forces between solid walls and water molecules dominate the cohesive forces between the water molecules. On the other hand, obtuse contact angle are observed when cohesive forces dominate the adhesive forces. Acute contact angles are typical for interactions between pore water and soil solid surfaces. The curvatures of the menisci generate water pressures lower or higher than the air pressure depending on whether the contact angle is acute or obtuse angle, respectively. Let us consider a capillary tube of diameter  $d$  immersed in a water body as shown in Fig. 3.3. The meniscus is concave on the air side with a contact angle  $\theta$ , as shown in the same figure. The water pressure at the back of the meniscus can be calculated considering the vertical force equilibrium of the air-water interface. The resultant mathematical equation can be expressed as

$$u_w - u_a = -\frac{2T \cos \theta}{R} \quad (3.1)$$

where  $u_w$  is the water pressure just below the meniscus,  $u_a$  the air pressure,  $T$  the surface tension, and  $R$  the radius of curvature of the interface. If the contact angle is an acute angle ( $\theta < 90^\circ$ ), the gauge water pressure becomes negative, which is typical in soils. It can easily be verified the water pressures across the menisci of different diameter capillary tubes as illustrated in the following example problem.

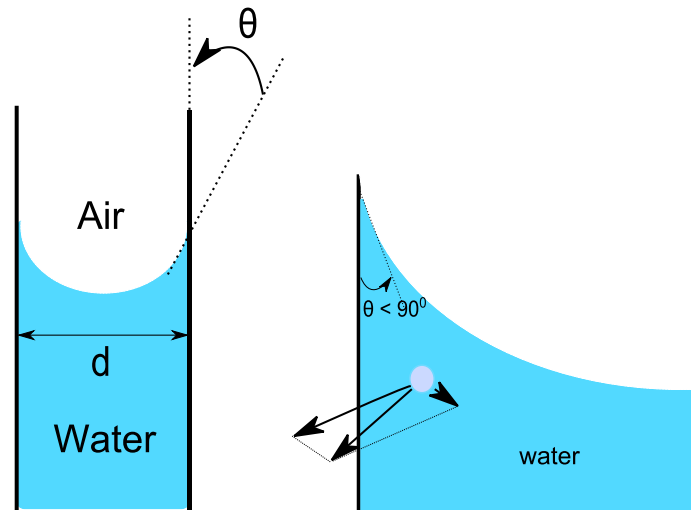


Fig. 3. (a) Curvature of the air-water interface in proximity of a solid surface (b) a closer look of the meniscus

**Problem – 1.** Calculate the gauge, and absolute water pressure at the menisci in capillary tubes having diameters of the same order of magnitude as the size of pores in clay, silt, and sand as demonstrated in the following example problem. Assume that pore diameter is about 1/20 of the grain size and contact angle  $\theta = 0$

**Solution** The water pressure equation, Eq. (1), can be simplified as

$$u_w - u_a = -\frac{4T}{d},$$

after assuming the given contact angle. The required data is calculated using the values for surface tension of water at room temperature and magnitudes of the pore diameters of clay, silt, and sand as given in the following table.

Parameter	Sand	Silt	Clay
$d_{\text{grain}}$ (mm)	2	0.075	0.0002
$d_{\text{pore}}$ (mm)	0.1	0.00375	0.00001
$u_w - u_a$ (kPa)	-2.92	-77.87	-29200
$u_w$ (kPa)	+98.48	+23.53	<b>-29099</b>

**Table 1.** Minimum sustainable gauge and absolute water pressure in capillary tubes having representative diameters as the sizes of pores in clay, silt, and sand using,  $\theta = 0$ ,  $T_{20^\circ} = 0.073 \text{ N/m}$ ,  $u_a = 101.4 \text{ kPa}$

It is clear from the **Table 1** that the absolute water pressure can be negative when the pore size is sufficiently small, as in the case of clays. Therefore, pore water can sustain high tensile pressures in unsaturated fine-grained soils.

### *Capillary rise*

The combination of adhesion forces, between water molecules and solid wall, and cohesion forces, between water molecules, causes water to rise in capillary tubes and soil pores above the free water level as shown in Fig. 3.4. The adhesion forces cause the rise in capillary, and the cohesion brings all the water molecules together to follow the upward pull. The analyses by several researchers show that the wall of the capillary tube exerts an upward force on the water through the surface free energy difference ( $T_{SV} - T_{SW}$ ), where  $T_{SV}$  and  $T_{SW}$  are the interfacial surface tension between solid-vapor and solid-water respectively. As mentioned before, the concave curvature indicates the presence of pressure difference across the meniscus. The pressure below the meniscus will be smaller than the atmospheric pressure, above the meniscus as shown in Fig. 3.4. This is because the water in the capillary tube is suspended from the meniscus, which in turn is attached to the walls by hydrogen bonds. Therefore, the water is under tension, which is defined as “negative pressure”. According to several other researchers, the pressure difference across the meniscus in the capillary is responsible for the rise of water in capillary tube.

Capillary rise is also explained in terms of the surface forces around the periphery of the meniscus. The straight-wall capillary due to upward force from the meniscus  $\pi dT \cos \theta$  is balanced by the weight of the water column. The height of the capillary tube,  $h_c$ , can be expressed from this force equilibrium as

$$h_c = \frac{4T \cos \theta}{\rho g d} \quad (3.2)$$

which can also be derived after substituting  $h_c \rho g$  in Eq. (1) for the gauge water pressure. The contact length between the top of the water column and the tube is proportional to the diameter of the tube, while the weight of the liquid column is proportional to the square of the tube's diameter. Thus, a narrow tube will draw a liquid column higher than a wider capillary tube as shown in Fig. 3.5. The capillary water can rise up to several meters above the free water level when the capillary diameter is very small, which is typical in clay soils where the capillary rise extends several tens of meters above the water table.

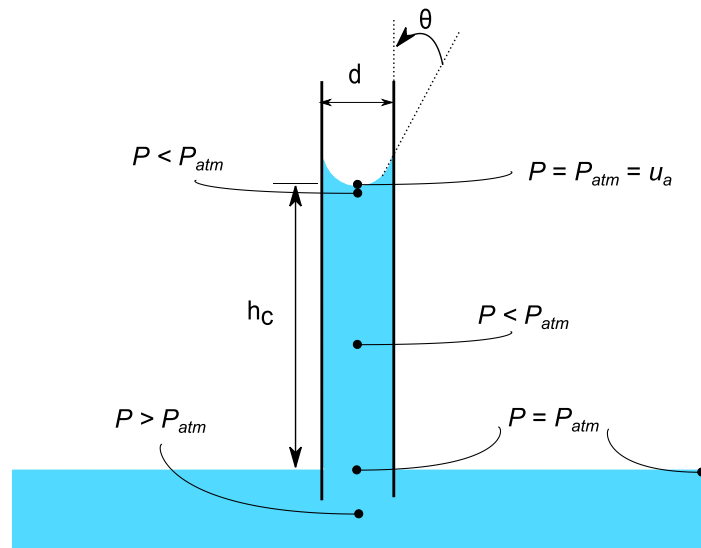
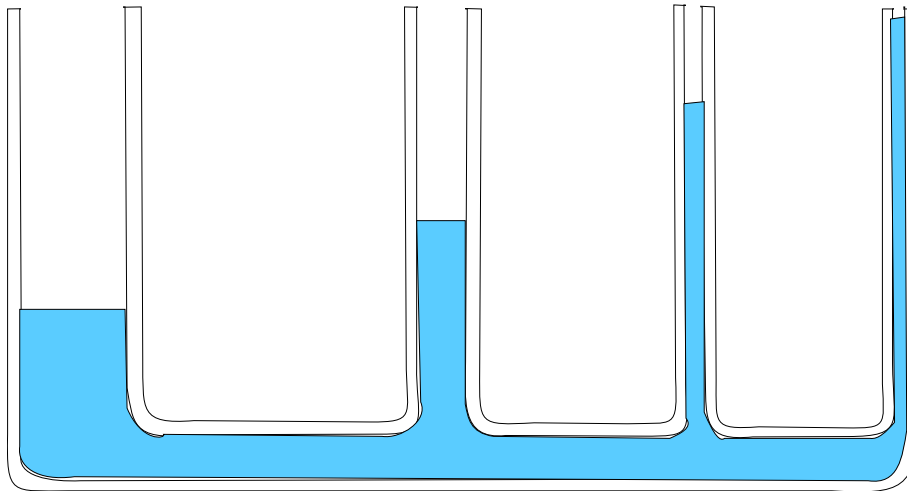


Fig. 3.4. Capillary rise



**Fig. 3.5. .** An illustration of capillary rise in tubes containing different diameters

The concept of capillary rise is very important in unsaturated soil mechanics for understanding the natural moisture levels within the soil above the water table. Several models have been proposed by earlier researchers for predicting the ultimate height and rate of capillary rise in unsaturated soils based on the statistical variations in the pore geometries and hydraulic conductivities.

## Lecture 2

### Soil Water Characteristic Curve

#### *Concept of Soil Suction*

It was demonstrated with an example problem earlier that negative pressure develops in the capillary water when the capillary diameter is very small. The pore water pressure in most of the fine-grained soils, that have very small pore sizes, is negative when the water content is less than its full saturation. Surface tension mechanism can't play a role in fully saturated soils due to the absence of air-water interface and, thus, pore water pressures are positive in such soils.

Soil suction can be defined from thermodynamics point of view as the thermodynamic potential of soil pore water relative to the free water potential. Free water in this regard is defined in many texts books as the water containing no dissolved solutes, having no interactions with other phases that impart curvature to the air-water interface, and having no external forces other than gravity. The thermodynamic potential of soil pore water may well be described in terms of the chemical potential,  $\mu$ . The chemical potential of the soil pore water represents the amount of energy stored per unit mass of pore water (Joules/mol). The mechanisms responsible for total soil suction are those that decrease the potential of the pore water relative to this reference state. The primary mechanisms that decrease the potential of soil pore water are capillary effects, short-range adsorption effects between particle -pore water, and osmotic effects while other effects such as temperature, gravity, and inertial effects are neglected. The capillary mechanism is unique to unsaturated soils. On the other hand, both the adsorption and osmotic mechanisms can occur under any degree of saturation. Capillary effects and the associated negative pore water pressures due to curvature of the air-water interface in the three-phase unsaturated soil system are well described above.

Adsorption of water molecules is primarily due to the electrical and van der Waals forces occurring within the vicinity of the solid – water interface in the soil pore space of the fine-grained soils. Clay surfaces carry net negative charge due to isomorphous substitution which results in electrical forces at the particle level. On the other hand, short-range van der Waals forces arise from atomic scale interactions between the molecules of the clay surfaces and molecules of the pore water. The van der Waals forces exist in all soils. However, the effect is more pronounced in clays due to significant net surface charge and relatively large surface area. The effect of these two forces decays rapidly with distance from the particle surface. Moreover, the short-range adsorption effects are more pronounced at relatively low degree of saturation, in which the adsorbed pore water is primarily in the form of thin films coated around the particle surfaces.

Osmotic suction is due to the dissolved solutes in the pore water. The dissolved solutes/salts reduce the chemical potential of the pore water below the free water potential. The presence of dissolved solutes in the soil pores is either due to external source (e. g., chemical diffusion through soils) or naturally occurring exchangeable cations on the clay surface. Suction arising from the combined effects of capillarity and short-range adsorption is usually grouped under the more general term *matric* suction,  $\psi_m$ . It reflects the pore water and the soil solids/soil matrix. Suction arising from the presence of dissolved solutes is referred to as *osmotic* suction,  $\psi_o$ . Total soil suction,  $\psi_t$  is generally considered the sum of matric and osmotic suctions as given follows:

$$\psi_t = \psi_m + \psi_o \quad (3.3)$$

Similarly the total decrease in pore water chemical potential,  $\Delta\mu_t$ , due to these factors can be described in terms of energy state as

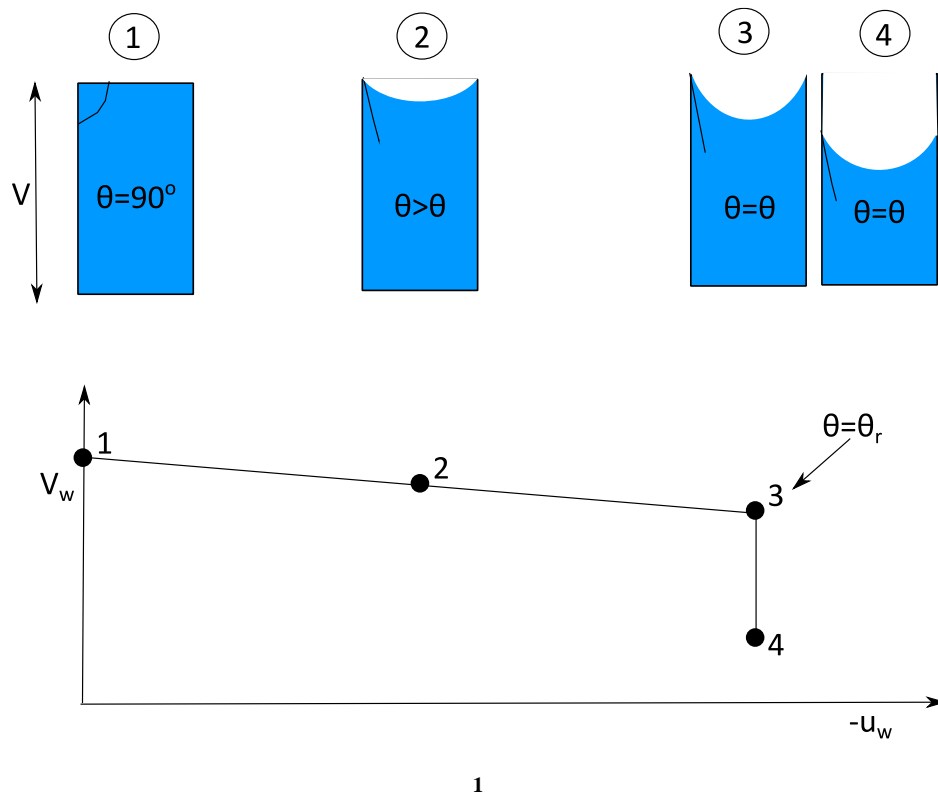
$$\Delta\mu_t = \Delta\mu_c + \Delta\mu_e + \Delta\mu_v + \Delta\mu_o \quad (3.4)$$

where  $\Delta\mu_c$  is the change in chemical potential due to capillary effects,  $\Delta\mu_e$  the changes due to the existance of electrical fields (ex: clays),  $\Delta\mu_v$  is the changes due to van der Waals fields, and  $\Delta\mu_o$  is the changes due to osmotic effects. Each term on the right hand side of eq. (3.4) is a negative value. The negative value expresses the decrease in chemical potential from the reference potential due to each factor described by the subscript. However, the soil suction is expressed as a positive value, because it describes the decrease in potential relative to a reference potential.

#### *Suction vs. water content*

Commonly known mechanisms that change the saturation levels of the soils, in nature, are evaporation, rainfall infiltration, changes in the ground water table, and the disturbances due to human activity. The effect water retention and many mechanisms can conveniently be explained by considering simple capillary tube models. The influence of evaporation on the fully saturated soil mass can be understood by conveniently approximating the network of capillaries across the pore spaces of soils with system of capillary tubes as illustrated in Fig. 3.6-3.7. The evaporation from a single thin capillary is considered and is illustrated in Fig. 3.6. At the beginning, the capillary is completely filled with water and the water content is being  $\theta$  as shown in the figure. Assuming that the air water interface initially is nearly flat and the gauge water pressure is, therefore, zero in the tube. The amount of water within the tube decreases with time as the evaporation progresses. However, the water is initially removed without the loss of interaction between air-water-solid interface viz. surface water at the edges of the capillary tube. This compels the formation of meniscus and, thus, the changes in air-water interface. With the additional loss of water from the tube due to evaporation, the

meniscus curvature increases and the gauge water pressure in the tube drops to negative values as indicated in Stage#2 of the figure. The water pressure, in Stage#3, decreases to such an extent that the contact angle is equal to the receding angle,  $\theta_r$ , which is the maximum negative pressure sustained by the surface tension forces at the air-water interface. The water pressure corresponding to this stage is called air-entry pressure,  $\psi_a$ . Any further evaporation at this stage causes lowering of the water level in the capillary tube with contact angle remaining equal to receding angle and negative pressure at the interface equal to the minimum sustainable value as depicted in Stage#4. The relation between water content and negative pressure in the tube during these stages is also shown in the Fig. 3.6. It is important to note that the degree of saturation remains 100% until Stage#3 albeit the water content is less than  $\theta$ .



The water retention behavior in a negatively charged capillary tube will be similar to the one described in Fig. 3.6. However, the decrease in the volume water with suction will be smaller when compared to the earlier case. The tube will achieve steeper receding angle than the previous case and requires more suction to lose the same amount of water. Thus, clays generally have more retention capabilities for water due to combined effects of capillary and adsorption forces when compared to sands. However, the pore structure in the clays can better be represented more realistically as shown in Fig. 3.7.



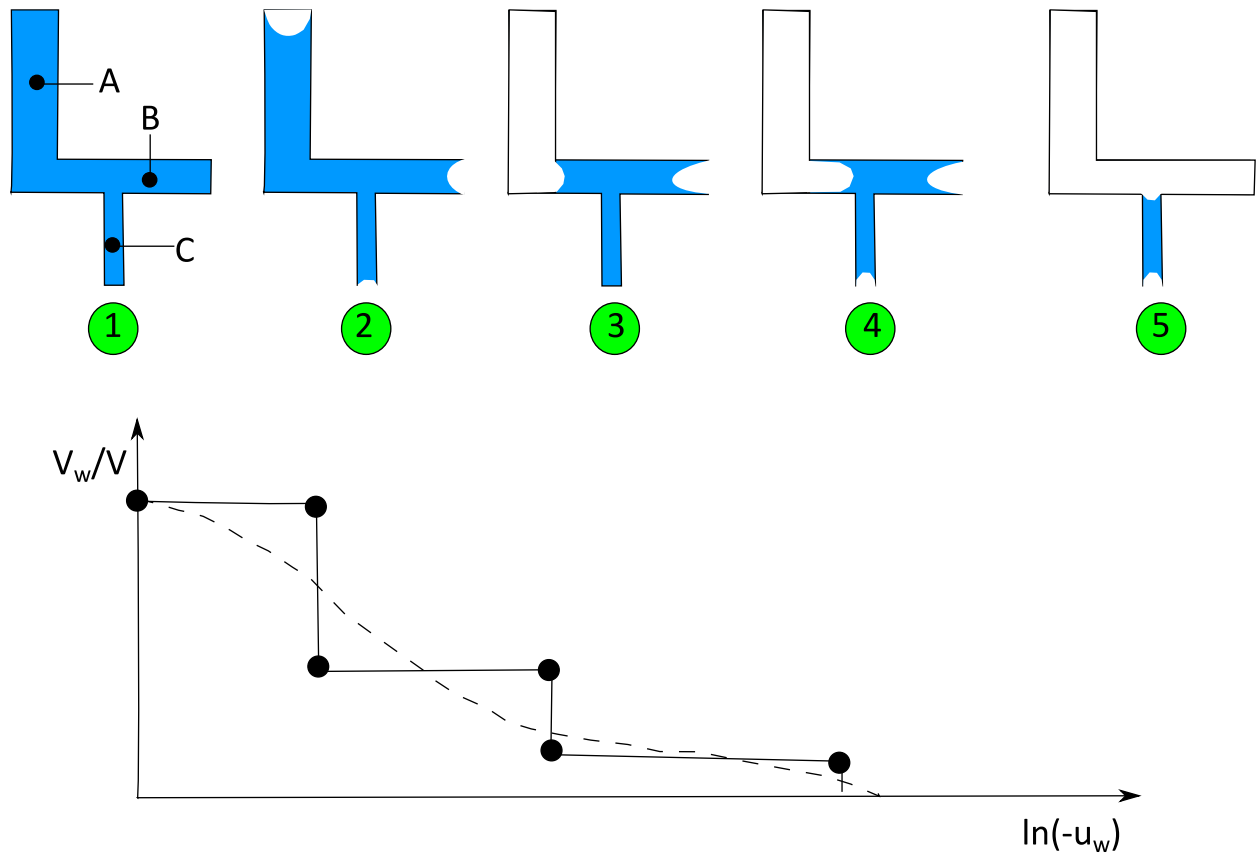


Fig. 3.7. Illustrative experiment of evaporation from a well-connected and negatively charged capillary system

The assumed system in Fig. 3.8 is formed by three horizontal capillary tubes, *A*, *B*, and *C*, respectively having the same length, *L*, diameters of the tube are  $d_A = 2d_B$ ,  $d_B = 2d_C$ . The water evaporation takes place in this system as in the earlier case, albeit the evaporation loss is different in different tubes. Since the diameters of the tubes *A*, *B*, and *C* are in descending order, the contact angles will be in ascending order in the tubes and, thus, the limit receding angle,  $\theta_{ra}$ , will therefore be reached in the larger tube first. The larger tube will empty at constant pressure at this stage, which is the minimum pressure sustainable by this tube. The remaining tubes are still saturated and, as evaporation proceeds, the curvature of the menisci is increased until the limit contact angle is reached in tube *B* and *C*. Further evaporation will eventually empty the water in smaller tubes. The relationship between degree of saturation and evaporation pressure or negative pore pressure in the capillary system is shown in Fig. 3.7. The interconnecting pore structure of the natural soils can be approximated with infinite number of capillary tubes of different sizes as given in the capillary system, Fig. 3.7. Consequently, the relation between degree of saturation of a soil and negative pore water pressure follows the same trend as described here. Such a relationship, commonly obtained from experiments in unsaturated geomaterials, is referred as *water retention curve* or *soil water characteristic curve*. The retention curve is of fundamental importance in unsaturated soil mechanics for

understanding the volume change, strength, and hydraulic characteristics of unsaturated soils.

## Lecture 3

### Water retention mechanism in soils

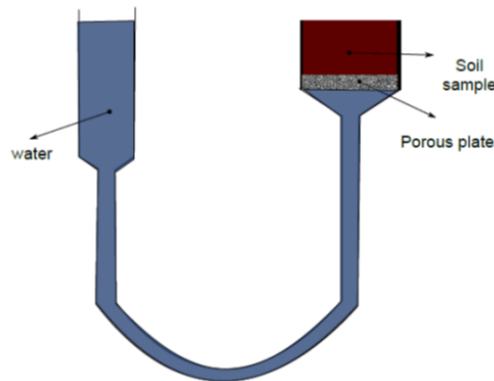


Fig. 3.8. Conceptual illustration of soil water retention

Consider a soil sample in contact with porous stone that allows only the water movement into and out of the soil. The soil is connected to a flexible burette filled with water. The water level in the burette, in the beginning of the experiment, is at the same level as the saturated soil surface as shown in Fig. 3.8. When the soil surface is raised from the previous level, the soil is still saturated due to capillary rise of water in the soil pores against the gravity. The soil starts to desaturate when the level of the soil is increased due to drainage of the pore water under gravitational force. However, the soil still holds some water in the pores due to osmotic and adsorption mechanisms. The relative contribution of these two mechanisms responsible for soil water retention in soils are discussed here, in detail. The dominant pore water retention mechanism at relatively high values of water content or very low values of suction is becomes capillarity. This is governed primarily by pore size distribution in the soils. At low values of water content and correspondingly high values of suction, osmotic mechanism plays an important role in retaining the water.

#### *Osmotic mechanism*

It is well known that the surface of the clay particles is negative charged due to isomorphous substitution. Several cations present in the diffuse double layer around the clay surface, in exchangeable state, due to the negative charge. The concentration of these exchangeable cations at the surface of the interacting particles is higher as compared to that in the solution. This concentration difference drives the water molecules to diffuse toward the interlayer in an attempt to equilibrate concentration. This mechanism of water retention in clayey soils is referred to as an osmotic mechanism.

#### *Adsorption mechanism*

At very low values of water content, the pore water is primarily in the form of thin films on the particle surfaces. The dominant mechanisms contributing to negative pore water

pressure (suction) is the electrostatic forces at the clay particle surface. Water molecules are strongly held on the particle surfaces due to these forces. They are also retained by hydration of exchangeable cations.

Consequently, capillary mechanisms play a role at relatively high degree of saturation, where as osmotic and electrostatic mechanisms become relevant at medium to low degrees of saturation. All these mechanisms are invoked due to the interaction of air and water phase with solid phase; and are, thus, associated with the soil “matrix”. This is the reason why suction generated by these mechanisms is referred to as “*matrix suction*” or “*matric suction*” (Laloui, 2010). The water retention curve (WRC) describes the corresponding constitutive relationship between soil matric suction and water content. The general shape of the SWCC of a given soil reflects the influence of several material properties, such as pore size distribution, grain size distribution, density, organic material content, clay content, and mineralogy on the pore water retention behavior (Lu and Likos, 2004). Genral shape of WRC is given in Fig. 3.9.

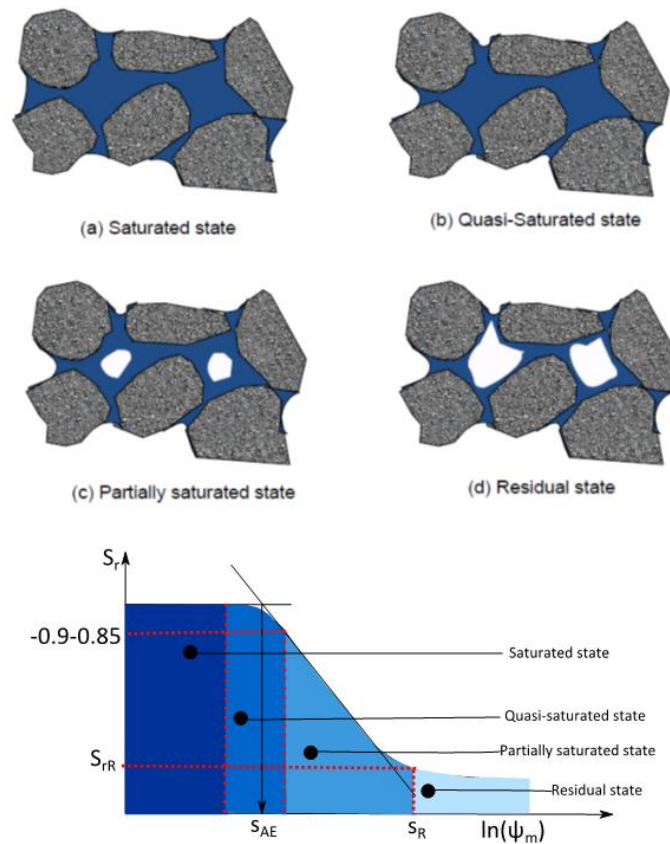


Fig. 3.9. Soil water retention curve (after, Lu and Likos, 2004)

The WRC is often plotted on a semilog plot of suction against moisture content as shown in Fig. 3.9. The curve can be approximated with three distinct line segments having different slopes, with degree of saturation ranging from zero to one, as illustrated in the figure. These segments illustrate four different stages of moisture regimes in the soil with

increasing matric suction from zero value at the saturated moisture content. The soil is fully saturated in the first moisture regime where the moisture loss is due to change in the shape of the meniscus. The thickness of this regime depends on the surface properties of the soils that can influence the receding contact angle. The contact angle reaches the receding angle at the end of this regime. As the suction increases, the soil enters the quasi-saturated regime where the moisture is lost by keeping a constant receding angle. The air enters the largest pore of the soil in this regime. Once the air-entry value is reached, the retention curve enters a regime dominated by capillary pore water retention mechanisms. the soil loses the water at faster rate with increase in the suction in this regime. The amount of water retained here is a function of the particle and pore size properties. Additional increase in suction would bring into residual state where the loss of water is very less for the increase in the suction. The amount of water retained at this stage is a function of the surface area of the soil particles, the surface charge density of the soil mineral, and the type and valency of any adsorbed exchangeable cations. Within the adsorbed film segment, water is retained in the form of thin films on the particle surfaces under the influences of short-range electrical forces, van der Waals attraction, and exchangeable cation hydration. Water molecules are strongly held on the particle surfaces due to electrostatic forces at this stage. In clays greater amount of pore water is required to satisfy the relatively large surface hydration energies associated with the high suction regime. Thus the residual regime extends to very large suction values. On the other hand, In sands very little water is adsorbed under initial surface hydration mechanisms. However, the capillary effects dominate over the majority of the unsaturated water content range in sands.

*Dependency of WRC on soil characteristics*

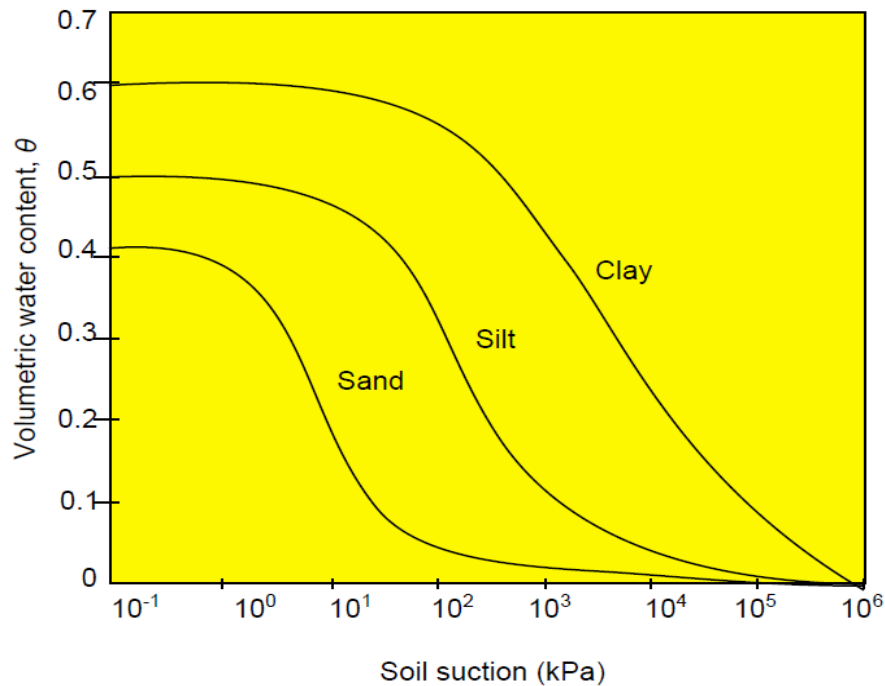
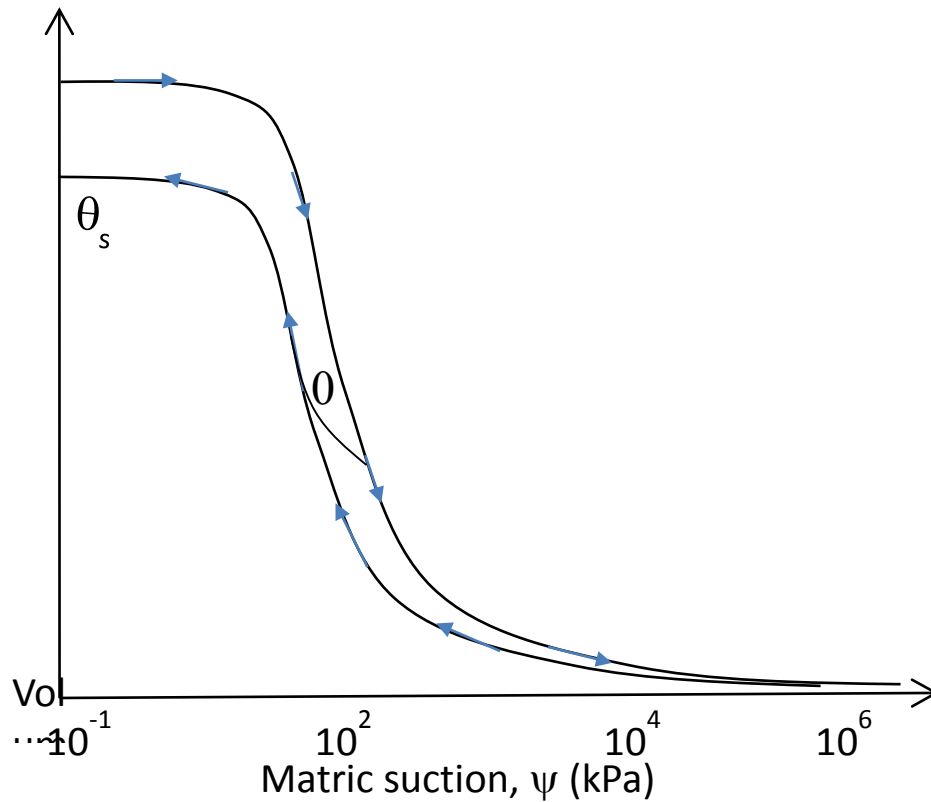


Fig. 3.10. Representative water retention curves for sand, silt and clay

Fig. 3.10 illustrates the general SWCCs of representative samples of sand, silt, and clay. It can be seen from the figure that sandy soil quickly desaturates after the air-entry pressures. The water retention capacity beyond residual state is also very poor because of the poor surface charge characteristics in sandy soils. In such soils, the overall water retention behavior is influenced by the pore size distribution. On the other hand, clays exhibit high water retention characteristics with high air-entry pressures and mild slope from air-entry suction to residual suction indicating high retention capacity. The negatively charged particle surfaces and high surface areas in clays can substantially influence the retention behavior. The retention behavior in silty soils is moderate and falls between these two extreme behaviors.

#### *Hysteresis of soil water retention*

The SWCC can be obtained either by using wetting or drying processes in the laboratory. Interestingly, the wetting SWCC is different from the drying curve due to hysteresis. Typically, the drying retention curve lies above the wetting curve as shown in the Fig. 3.11. Therefore, more water is retained by the soil during the drying process when compared to the wetting process under the same suction value. The hysteresis is not distinct near the residual water content region and very distinct in the saturation region.



The following and well-known mechanisms provide the insight into soil water hysteresis.

#### Contact angle hysteresis

According to this mechanism, there may be more than one stable contact angle can exist for a given soil solid-water system, i.e. called contact angle hysteresis. It can be illustrated by considering a drop of water on a horizontal clay surface as shown in Fig. 3.12a. The water drop attains a stable contact angle,  $\theta_c$ , under the present equilibrium condition. If the clay surface is gradually tilted to either side, the contact angle at the advancing edge of the drop will increase ( $\theta_a$ ) as shown in the Fig. 3.12b. On the other hand, a smaller contact angle ( $\theta_t$ ) develops at the trailing edge (frying front). At the equilibrium, the tangential component of the surface tension will compensate the tangential component of the drop weight, until the limiting condition is achieved. Therefore, many stable contact angles can exist for a given range from  $\theta_a$  to  $\theta_t$ .

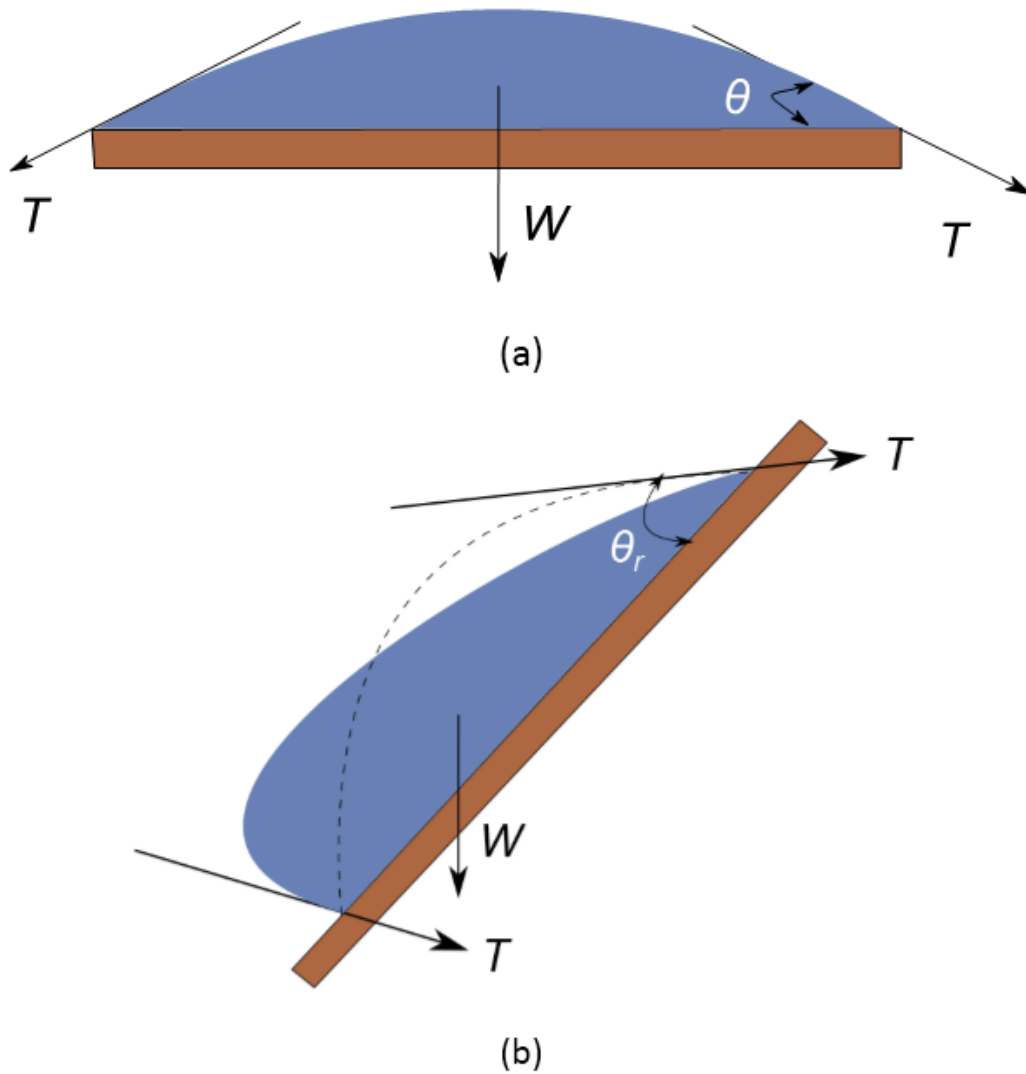


Fig. 3.11. Hysteresis of the contact angle: (a) water drop on horizontal solid surface and (b) water drop on a tilted solid surface (after Laloui, 2010)



### Ink-bottle hysteresis

Another popular hysteresis mechanism is based on the analogy of ink-bottle hysteresis. This effect in soils arises due to the non-homogeneity in the pore-size distribution. It can be explained by considering the capillary tube containing two different radii along its length, as described in the Fig. 3.12. An upward capillary flow takes place when the capillary tube is inserted into the reservoir, which is the wetting process. The capillary rise ceases at the point of intersection between smaller and larger radii and the maximum rise in the tube is controlled by the smaller radius of the tube. Contrary to this observation, the maximum capillary height in the tube may extend beyond the larger radius if the tube is initially filled as shown in the Fig. 3.12.

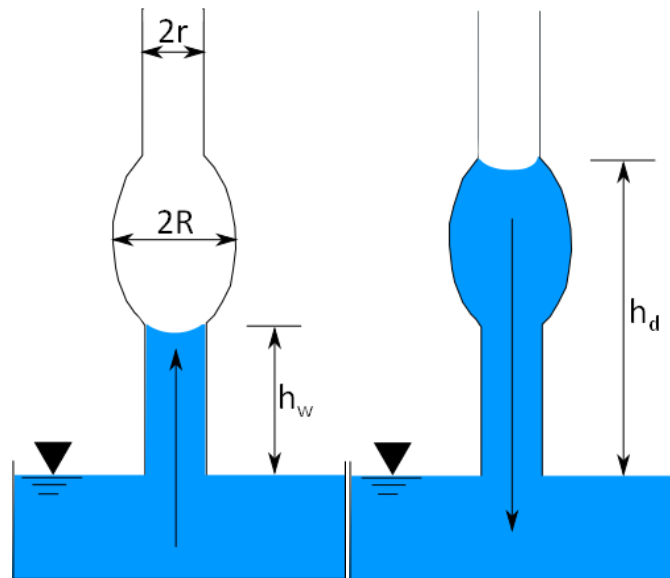


Fig. 3.12. Ink-bottle hysteresis (after Lu and Likos, 2004)

## Lecture 4

### Hydraulic Conductivity

The flow of water in a saturated soil was studied by applying Darcy's law in the basic soil mechanics text books. However, the question is: whether the Darcy's law is applicable for studying the flow through unsaturated soils. This question will be addressed here.

As we have seen in the previous lectures that a given soil may be unsaturated in several ways. The natural soil may contain two or more different liquids and air or only liquid and air. The saturation in such soils can be defined with respect to one of the fluids. The soils in nature, generally, contain air and water that are occupied in the pore space of the soil matrix. Therefore, the saturation here is in terms of the available water in the pore matrix. In such soils the air phase and water phase may form continuous phase or be separated by the other phases or soil particles. For the time being we assume that the soil only contains air and water in its pore space.

The fundamental dependent state variable responsible for the water flow through unsaturated soils is total suction,  $\psi$ , or total suction head,  $h_t$  (or  $H$ ). The total driving head can be expressed as:

$$h_t = h_g + h_m + h_o = z + h_m + h_o$$

where  $h_g$  is the gravitational head,  $h_m$  is the matric suction head, and  $h_o$  is the osmotic suction head. For most seepage problems, the osmotic suction head is neglected. This total suction head should be used in the Darcy's equation under unsaturated condition.

According to soil physics, the discharge velocity of water is understood to be proportional to the viscosity and density of the permeating fluid through the soil pores. The discharge velocity is high for permeating fluids having higher density and low viscosity, vice versa. Further, the experimental observations, supported by the theoretical analysis, reveal that the discharge velocity is dependent on the pore size and pore size distribution. Therefore, the discharge velocity is

$$q \propto d^2 \left( \frac{\rho g}{\mu} \right) \quad (3.5)$$

where  $d$  is the pore diameter (m),  $\rho$  the density of the fluid ( $\text{kg/m}^3$ ),  $\mu$  the dynamic viscosity of the fluid ( $\text{N.s/m}^2$ ).

Combining the Darcy's observation on the dependency of discharge velocity on the hydraulic gradient, the above expression can be written as

$$q = -C \left( \frac{d^2 \rho g}{\mu} \right) \nabla H \quad (3.6)$$

where  $C$  is the dimensionless constant related to the geometry of the soil pores,  $H$  is the total head, and  $\nabla H$  is the hydraulic head.

The Eq. (3.6) is in the form of Darcy's equation. Therefore, the hydraulic conductivity is the proportionality constant in the Darcy's equation which can be expressed as

$$k = (Cd^2) \left( \frac{\rho g}{\mu} \right) \quad (3.7)$$

where  $Cd^2$  is termed as the intrinsic permeability or permeability, denoted by  $K$ , often used to differentiate the material properties from the fluid properties against the pore geometry. Permeability has the units of  $\text{m}^2$  and is dependent only on the pore size, pore geometry, and the pore size distribution. The permeability varies from  $10^{-7} \text{ m}^2$  for the gravel to  $10^{-20} \text{ m}^2$  for the fine clay. It can be easily verified using the above equations that the conductivity of water is several times higher than the air under the same applied gradient and for the same pore geometry. It can readily be recalled from the earlier discussion on the influence of the state variables on the density and viscosity of the fluid. One can easily verify the influence of such state variables on the hydraulic conductivity of air and water through unsaturated soils. Other than these material constants, chemical and electrical pore fluid characteristics also strongly influence the flow behavior in unsaturated clay soils. Such characteristics can also alter the fabric of the clay. The aforementioned discussion on the hydraulic conductivity is applicable to both saturated and unsaturated soil system. However, the constant related to the geometry of the soil pores will be strongly influenced by the tortuous paths formed due to the occluded/entrapped air in the pore space of the unsaturated soils. The foregoing discussion signifies that the ratio of flux ( $q$ ) to the hydraulic gradient ( $\nabla H$ ) is non-linear under unsaturated conditions. Therefore, the hydraulic conductivity depends on the volumetric water content or the soil matric suction. The plot of flux versus hydraulic gradient is obtained as shown in Fig. 3.13. It results a family of straight lines passing through the origin. Each line represents a straight line having a slope equal to the hydraulic conductivity at the indicated moisture content,  $\theta$ , as shown in the figure. The hydraulic conductivity is no longer constant and is dependent on the volumetric water content.

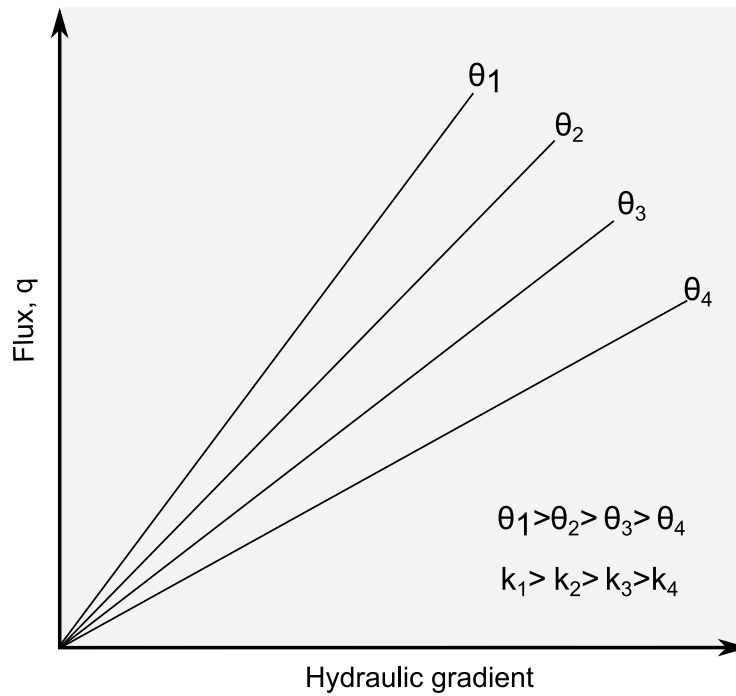


Fig. 3.13. Relationship between flux and hydraulic gradient in unsaturated soils

Therefore, functional relationships are used in Darcy's law to represent hydraulic conductivity dependency on matric suction for the flow through unsaturated soils. The modified form of Darcy's law under unsaturated conditions is given as:

$$q = K(\theta) \nabla H$$

where  $K(\theta)$  is the functional form of hydraulic conductivity. Therefore, the nature of the soil and amount of soil water content influence the hydraulic conductivity in unsaturated soils. As the water content is reduced in the initially saturated soil, the air enters through a largest pore of the soil matrix. Hence, the effective flow channels are reduced which causes the reduction in unsaturated hydraulic conductivity as depicted in Fig. 3.14. Since the contribution to conductivity per unit cross-sectional area depends on the square of the pore radius, conductivity decreases much more rapidly than the amount of water in the soil, indicating a sudden drop in the conductivity in Fig. 3.14 after the air-entry value. Moreover, the contribution of larger pores having a radius,  $r$ , is better than the combination of smaller pores equal to the same radius as the viscosity effect is large. Therefore, as the larger pores get emptied first, the conductivity decreases exponentially. Further, reduction in water causes discontinuity of the flow paths in the nearly dry soil where the water is present in the form of occluded bubbles. Therefore, the conductivity is close to zero at this water content as shown in the figure. The Fig. 3.14 represents the general characteristic curve for  $K$ -function.

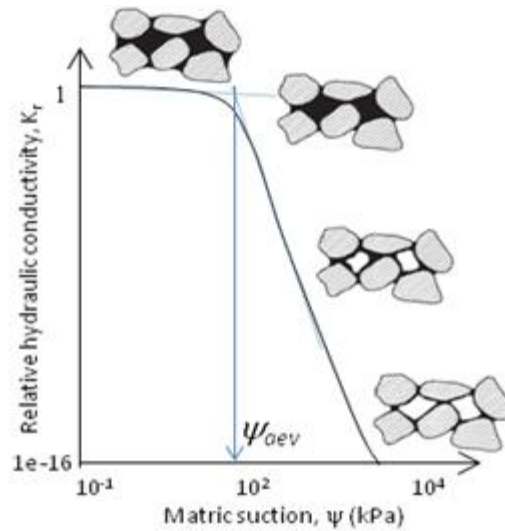


Fig. 3.14. Generalized hydraulic conductivity function

Several models representing the soil water retention and hydraulic conductivity have been used for smooth and continuous representation of the matric suction and hydraulic conductivity. Some of the important measurement techniques for hydraulic data and models are described in the following lectures.