Flow Through Unsaturated Soil

Lecture 1

1.0 Introduction

Soils that are partially saturated with water are often referred to as unsaturated soils. Some soils exhibit distinctive volume, strength and hydraulic properties when become unsaturated. For these soils, a change in the degree of saturation can cause significant changes in the volume, shear strength and hydraulic properties. Nevertheless, the distinctive volume, strength and hydraulic behaviour for unsaturated states should be treated as material nonlinearity and modelled consistently and coherently. After all, all soils can become partially saturated with water and an unsaturated soil is only a state of the soil, not a new soil.

In the last two decades or so, significant advances have been made on constitutive modelling of unsaturated soils. A large number of constitutive models can be found in the literature. Recent reviews of these models can be found in Gens (2010) and Sheng (2011). Notwithstanding these advances, some fundamental questions remain unanswered or not fully answered:

- Reconstituted soil versus compacted soil: What are the main differences in the hydro-mechanical behaviour of these soils? What are the implications of a unimodal and a bimodal pore size distribution (PSD) in constitutive modelling? Can a reconstituted soil become collapsible?
- Relationship between volume change, yield stress and shear strength?

A soil can become partially saturated in different ways. Two types of unsaturated soil samples are often used in laboratory: (1) dry soil powders mixed at specified water contents are statically or dynamically compacted, (2) saturated samples reconstituted from slurry (at moisture contents in excess of the liquid limit) are dried to unsaturated states. The first type of samples (compacted soils) is far more common than the second type of samples (reconstituted soils), because it is more difficult to desaturate a slurry sample than a compacted sample. It has been noted that most constitutive models for unsaturated soils are based on experimental data for compacted soils (Sheng et al. 2008). Compacted soil samples can be prepared dry of optimum or wet of optimum. Reconstituted samples can be air-dried, heat-dried, freeze-dried or osmotically-dried. Different sample preparation methods usually result in different soil microstructures. For example, soils compacted dry of optimum usually have a double-porosity microstructure, meaning that the pore size distribution curve exhibits two or more peaks. In these soils, there usually exist two types of pores: large interaggregates pores which are collapsible upon wetting and small intra-aggregates pore which are more stable. On the other hand, soils air-dried from slurry usually exhibit a unimodal pore size distribution, at least at low stresses. Nevertheless, as recently pointed out by Tarantino (2010), the boundary between compacted and reconstituted soils is not always clear and the microstructure of a soil can change with stress and hydraulic paths.

The shear strength – suction relation is related to the volume change equation. In constitutive models, the shear strength of an unsaturated soil is determined by (1) the apparent tensile strength function, and (2) the friction angle of the soil. The apparent tensile strength is usually a function of suction and this function can be derived from the volume change equation. The apparent tensile strength surface in the stress-suction space also represents the zero shear surface, as the soil has no shear strength when suction and stress change along this surface.

2.0 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 .

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. 1 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.

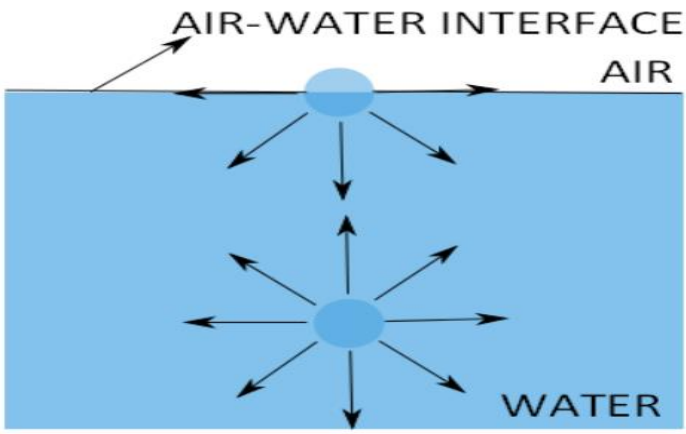

Fig. 1. Development of surface tension at the air-water interface

2.1 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 90^0 (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. 2. The meniscus is concave on the air side with a contact angle θ , 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 :

$$Uw - Ua = \frac{2TCOS\,\theta}{R} \qquad \text{------(1)}$$

where Uw is the water pressure just below the meniscus, Ua the air pressure, T the surface tension, and R the radius of curvature of the interface. If the contact angle is an acute angle ($\theta < 90^0$), 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.

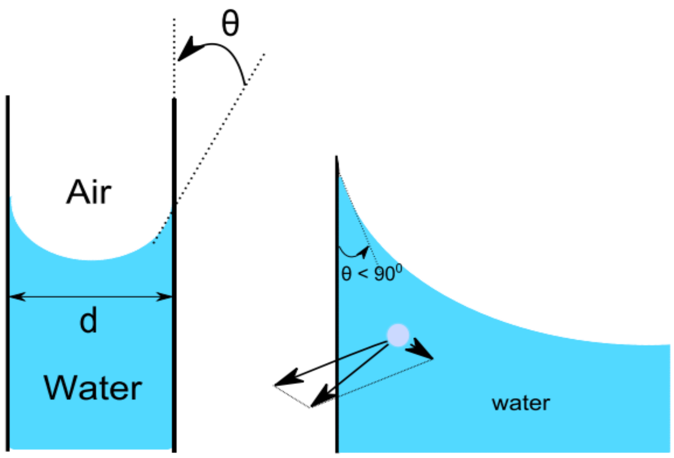

Fig. 2. (a) Curvature of the air-water interface in proximity of a solid surface (b) a closer look of the meniscus

2.2 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. 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 (Tsv – T sw), where Tsv and Tsw 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. 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 **π dT cos θ** is balanced by the weight of the water column. The height of the capillary tube, hc, can be expressed from this force equilibrium as :

$$hc = \frac{4T\cos\theta}{\rho g d} \qquad \text{---------(2)}$$

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. 4. 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.

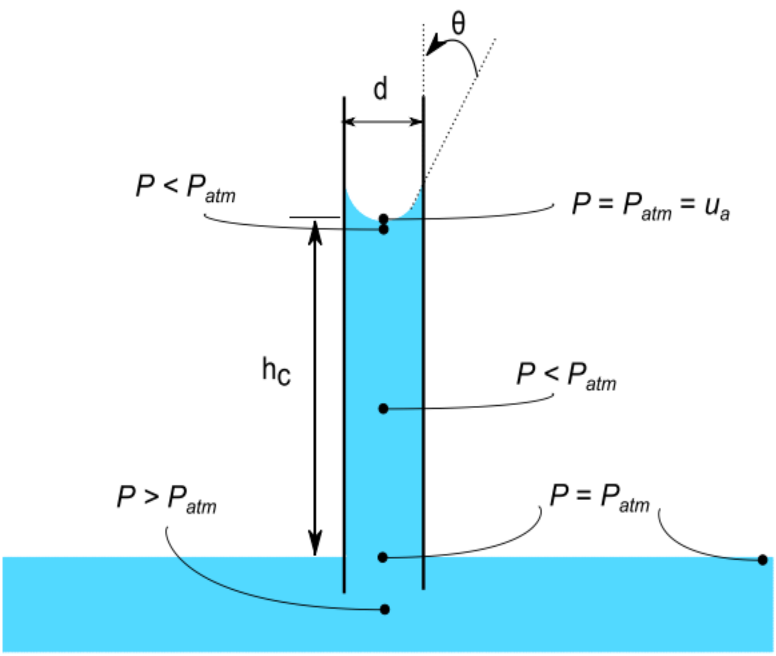

Fig. 3. Capillary rise

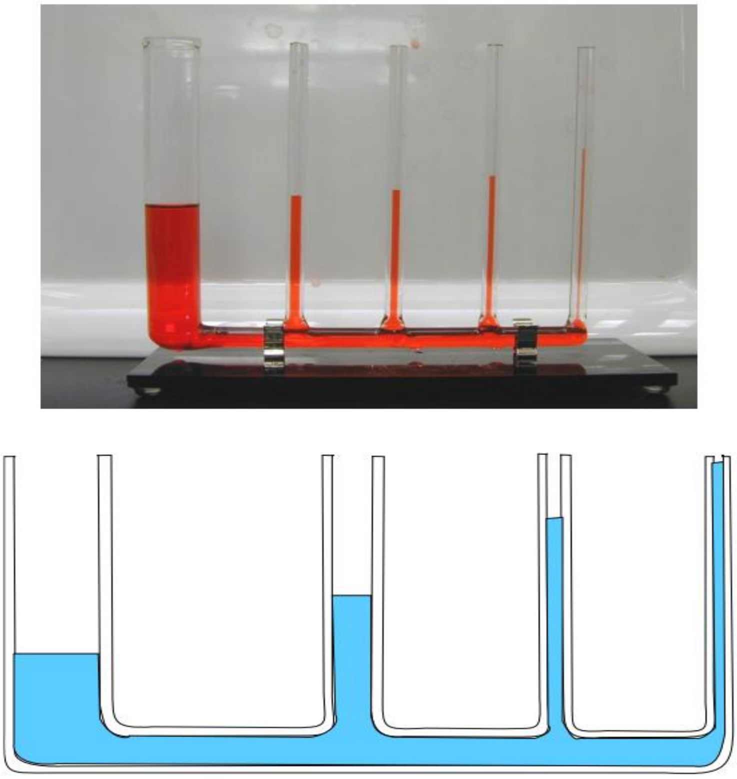

Fig. 4. An illustration of capillary rise in tubes containg different diameters

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.