Module 1
Lecture 1

Introduction

Soil mechanics is an important subject in the field of civil engineering. This subject is not only important in the design and analysis of natural and man-made geotechnical structures, but also in the development of infrastructure such as earthen dams, reservoirs etc. Most of the available text books on soil mechanics deal with the "*mechanics of* *saturated* *soils*" which is useful for understanding the engineering behavior of soils under the idealized condition by assuming a two-phase system (soil solids and water). The soils that are present in the nature and in the man-made geotechnical- structures do experience changes in the pore constituents to a varying degree due to environmental factors. Changes in the moisture content due to environmental or climatic conditions and changes in the pore-fluid characteristics during the exposure to the environment are significant. The recent research developments reveal that the amount of water and pore-fluid characteristics in the pore matrix of the soils significantly control the behavior of soils and important for geotechnical engineering applications. Therefore, several aspects of classical soil mechanics are re-addressed and extended to deal with the partly saturated soils with the available knowledge on the physico-chemical behavior of unsaturated soils. This web-based course is dedicated to deal with the fundaments aspects of unsaturated soils and their engineering significance.

Unsaturated soil mechanics

A few decades ago, the mechanics of soils was understood to be the application of laws of mechanics and hydraulics to predict the engineering behavior of soils. The prominence of unsaturated soil mechanics in various geotechnical engineering applications refines this classical definition by introducing the physic-chemical mechanism. Unsaturated soils contain water-contents below their full-saturation levels. Therefore, in the unsaturated soils the pore spaces of the soil matrix are occupied by both water and the air as shown in the phase diagram, Fig. 1.1. The quantitative illustration of mass and volume of air, water, and solids with subscripts a, w, and s, respectively, are given in the same figure.

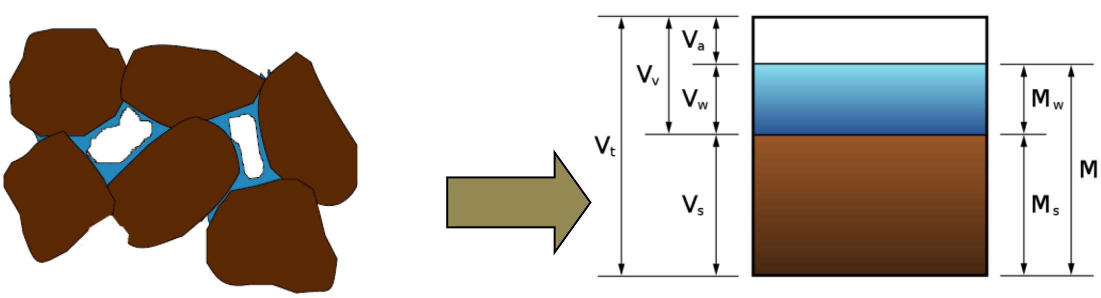

Fig. 1.1 Soil phase diagram

The existence of three phases in soils is very common in the nature. Therefore the degree of saturation is commonly less than unity in the shallow depths of ground surface as illustrated in Fig. 1.2.

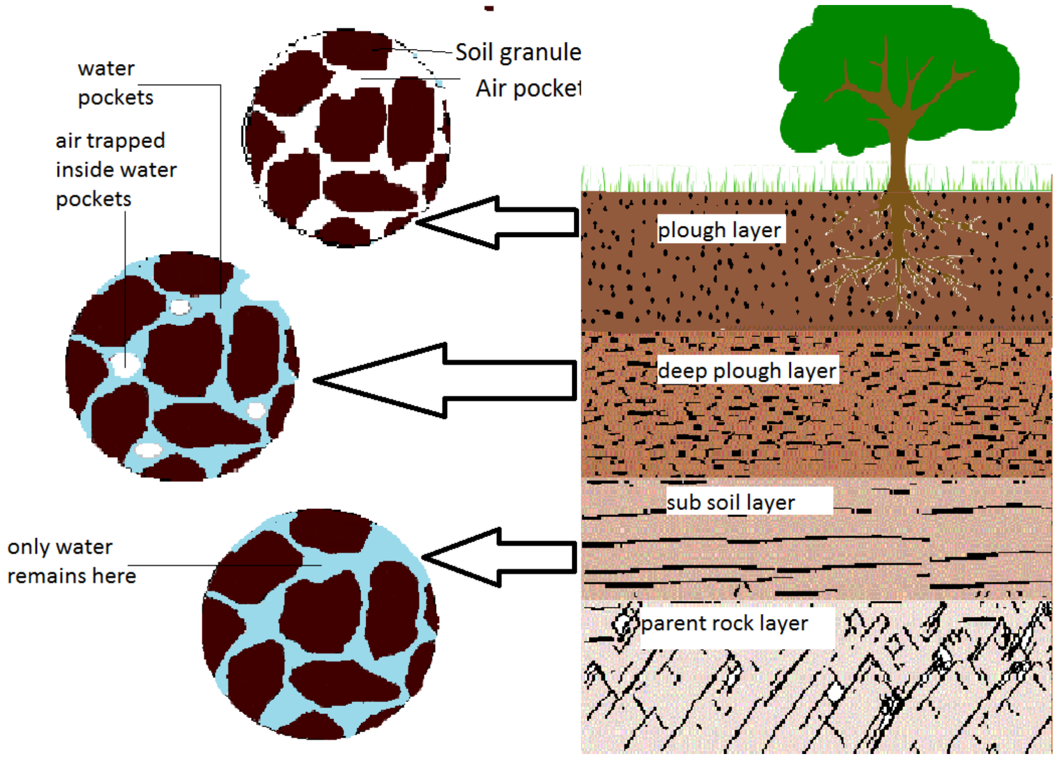

Fig. 1.2 Spatial distribution of moisture content within the field soil

The Fig. 1.2 shows the spatial variation of soil matrix in the field soil consisting of different amounts of water and air in the pore spaces. The top soil is usually unsaturated with a varying degree of saturation from zero to unity from season to season. The deeper layers of the soil but above the ground water table (the capillary zone), the degree of saturation is "full" (S_r = 1). The unsaturated zones in the environment can extend (above the ground water label) from meters to hundred of meters in depth. The presence of partial saturation in soils in our environment varies from place to place and season to season. Several engineering activities usually take place on such soils. The behavior of the soils due to changes in the saturation levels can greatly influence the stability of the structures constructed on such soils. Climatic (Environmental) variables influence the variation of the saturation levels of soils to a great extent. Therefore, the unsaturated soils play an important role in the natural hydrological cycle as shown in Fig. 1.3. The amount of water in the unsaturated zone located between the water table and the ground surface represents only ~ 0.01% of the total water involved in the hydrologic cycle. However, because this zone forms the essential transition between the atmosphere and larger groundwater body, the movement of water within this small portion of the cycle is very significant. The hydrological processes such as infiltration, evaporation, and transpiration occurring in the near-surface unsaturated soil zone influence the behavior of the soils.

Thus it is important to consider the concepts of interfacial physics such as equilibrium among different phases of air, solid, and water; the transition of water from one phase (vapor) to another. The application of interface physics makes the understanding of unsaturated soils different from the saturated soils. It will be shown in the following lectures that the traditional framework of soil mechanics fails to adequately describe and predict the behavior of the natural soils as the saturation was not considered as a state parameter. In partly saturated soils, equilibrium of different phases is important for understanding the Soil behavior. Interfacial physics deals with the equilibrium between different phases. Similarly, the clay behavior is dictated by the environmental factors which can be understood by physico-chemical equilibrium. Therefore, the classical definition of soil mechanics is extended to define the unsaturated soil mechanics as 'the application of the laws of mechanics, hydraulics, interfacial physics, and physico-chemical equilibrium for understanding the engineering behavior of partly saturated soils'.

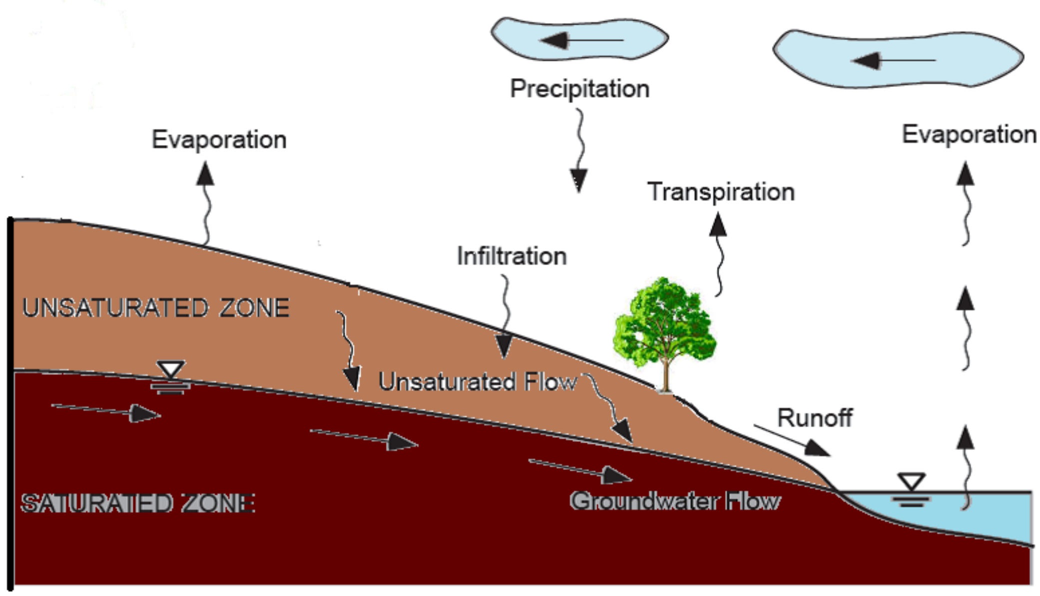

Fig. 1.3 Hydrological processes occurring in the near-surface unsaturated soil zone

Application areas

Many traditional geotechnical engineering problems can be better understood in the framework of unsaturated soil mechanics. Mechanical compaction is a classical application of unsaturated soil mechanics in the geotechnical practice which has been used to improve the mechanical and hydraulic properties of soils in the earthen embankments. Similarly, the problems due to the behavior of expansive and collapsing soils can be better addressed with the knowledge of state variables and material constants of the governing phenomena for the mitigation of soil hazards. Rainfall induced landslides is another important area where the principles of unsaturated soil mechanics can be well appreciated. Many fundamental aspects of unsaturated soil mechanics and some applications of unsaturated soil mechanics in geotechnical practice will be addressed in this lecture series.

Organization of the lectures

The organization of the lectures in the present lecture series is presented below:

- Introduction and applications
- Material variables and influencing factors
- Characterization of unsaturated soils
- Measurement of soil suction
- Soil hydraulic characteristics
- Measuring and modeling hydraulic characteristics
- Engineering behavior of unsaturated soils
    - Flow through unsaturated soils
        - Steady and transient flows
        - Experimentation
        - Capillarity and capillary barriers
    - Shear strength
        - Modified M-C criterion
    - Volume change behavior

Flow and stress phenomena have been given more importance in this course. The settlement or volume change phenomena are discussed only briefly due to lack of time.

Lecture 2

Motivation for unsaturated soil mechanics

It is well know that the behavior of saturated soils is very complex and the mechanisms responsible for the engineering behavior are still not understood completely. It is not at all hyperbole, therefore, to describe the complexity of unsaturated soil behavior due to the presence of more number of phases and interdependency of different phases. The advent of technology has greatly helped in augmenting our understanding of the mechanisms responsible for the behavior and augmenting our ability to model complex geotechnical problems involving unsaturated soils in real time. The important geotechnical problems involving the role of mechanics of unsaturated soils and the current advances in seepage, shear strength, and volume change behavior of soils are briefly described here.

Flow related problems

Of late, an increased number of problems involving flow through unsaturated soils have been encountered by geotechnical and geo-environmental engineers. The flow problems involving seepage pressure computations in the earthen embankments and the design of early warning systems, landfill cover systems, tailing ponds and landfill liners need to be addressed by the engineers. Some of these problems are briefly discussed in the following section.

Studies on rainfall induced slope failures:

Most of the landslides in India occur during the monsoon season. The strength of the soil decreases due to increase in the degree of saturation during the rainfall infiltration into unsaturated soil slope as illustrated in Fig. 1.4. Understanding the rainfall-induced landslides require the knowledge of infiltration rates into initially unsaturated soil slopes and the changes in the shear strength of the soils. Such studies would help in designing the early warning systems. The strength aspect of soils is discussed little later. Studies on the infiltration characteristics of natural slopes require the knowledge of seepage rates due to the rainfall. The primary requirement of seepage studies is the estimation of hydraulic conductivity of unsaturated soils. The estimation of hydraulic conductivity of unsaturated soils is not trivial as conductivity is not a unique value for a given soil, but is a function of the soil state (degree of saturation) and initial conditions (initial void ratio or density). There are several studies in the laboratory to understand the advancement of temporal wetting fronts in the soil slopes as illustrated in Fig. 1.5. Such laboratory studies are useful for estimating the “time for evacuation”.

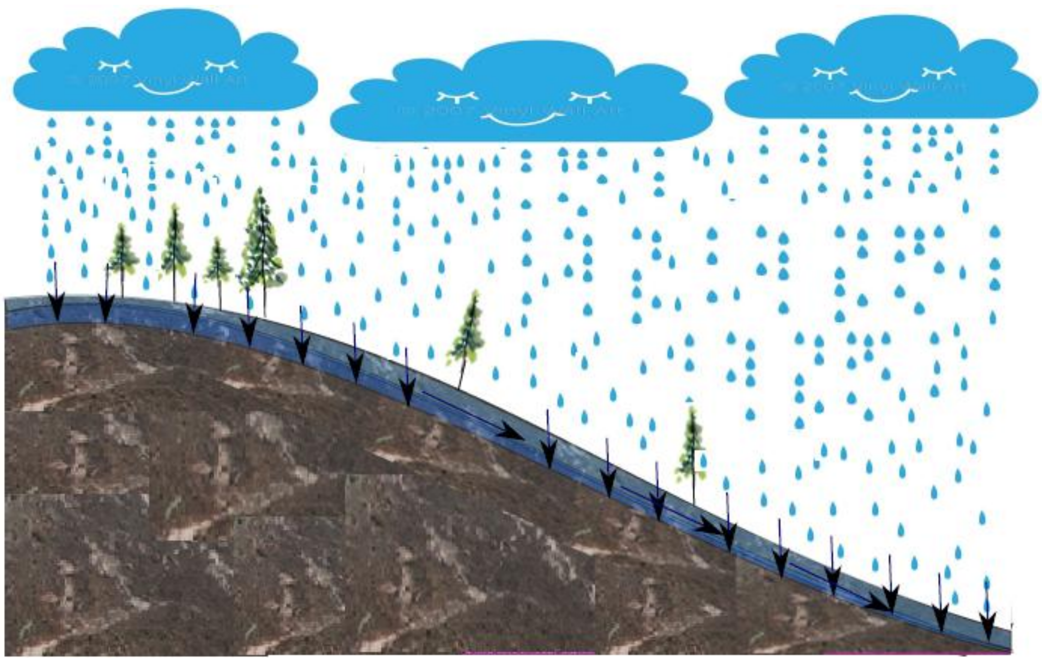

Fig. 1.4. Illustration of infiltration and run-off on the natural slope

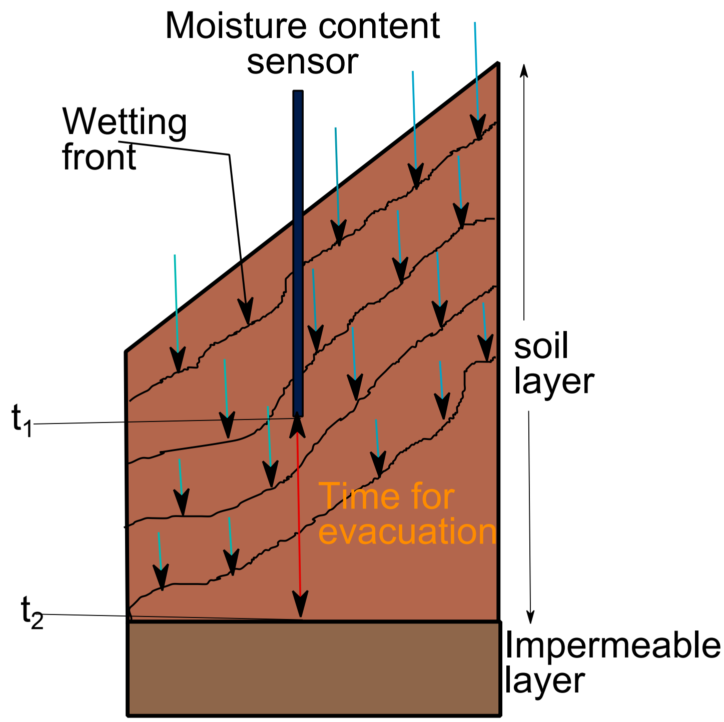

Fig. 1.5. Laboratory simulation of rainfall-Induced slope failure using the moisture content measurements

The laboratory findings on the model tests are useful for developing the real-time warning systems in the field. The moisture distribution and negative pore pressures in the field can also be measured using the moisture and suction sensors, respectively. These measurements enable one to estimate the temporal and spatial distribution of moisture content in the real-time. Therefore, the use of unsaturated soil mechanics concepts has moved from the stage of theoretical studies to the field application.

Applications in cover design for waste containments:

Another important unsaturated flow problem is associated with the design of contaminant barrier system. Cover systems are used for controlling the exchange of water on the surface of waste disposal facilities. The most promising cover designs, in the present day, uses a combination of various soils having different grain sizes. Such layered systems, typically located above the water table under unsaturated conditions, may produce capillary barrier effect when a relatively fine-grained material overlies a coarser soil material. The difference in unsaturated hydraulic properties between the layered soils then tends to limit the downward flow of water at their interface because the coarse-grained material is easily drained and thus, typically shows a much lower unsaturated hydraulic conductivity than the finer material located above it. The concept of capillary barrier mechanism is illustrated in Fig. 1.5.

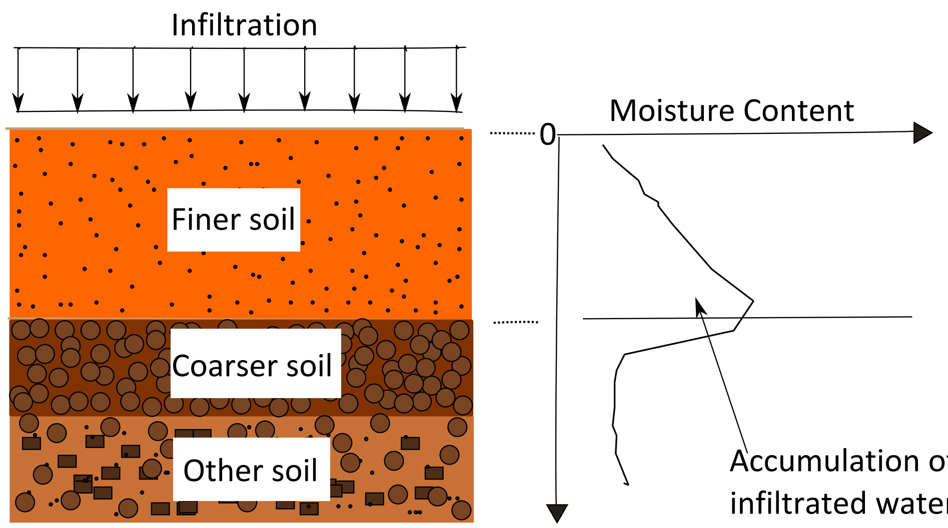

Fig. 1.5. Schematic diagram showing capillary barrier effect at the interface of Sand-Gravel

In addition to the application of capillary barrier phenomenon in engineered cover systems, it is important to understand infiltration rates into natural soil strata. It is the underlying mechanism controlling moisture storage within the natural and coarse-textured soils to replicate a given range of moisture regimes at the site. It is vital to establish soil capping prescriptions that will create an equivalent land capability by increasing the field capacity of soils.

Strength/Stability issues

Rainfall induced slope failures:

Landslides are the significant natural hazards that commonly occur in all mountainous landscapes of Himalayan and North-east regions of India. Some of these landslides occur suddenly and travel many kilometers at high speeds. They damage the property and pose grave threat to the human life as demonstrated in Rohtang Pass of Himachal Pradesh, India, during the monsoon of 2012. The landslides triggered by heavy rains in that year have also claimed many lives in Sikkim and other North-eastern parts of India. The file photos of the landslide events in the south district of Sikkim and Mamit district of Mizoram are shown in Figure 1.6a (http://images.indiatvnews.com/mainnational/Five_killed_in_17563.jpg) and 1.6b (http://images.indiatvnews.com/mainnational/Four_die_in_lan18083.jpg) respectively. These landslides are commonly induced by extended and intense rainfalls.

The slow moving landslides are usually triggered by accumulation of rain water precipitations for extended period of time and, contrarily, rapid landslides usually activated by intense or large storm events. However, in both these cases, the changes in the pore water pressures of partly-saturated soils trigger such earth movement.

Mechanism!

The prolonged dry periods encourage soil desiccation and the formation of tension cracks due to excessive evaporation on the slope surface. This situation increases hydraulic conductivity of soils near the surface. On the other hand, the pore-water pressures in the unsaturated slopes will become more negative and can contribute to higher shear strength in the soil. The Open cracks on the slope surface, with a higher permeability, encourage more infiltration of the rainwater into the slope. The negative pore water pressure or matric suction of the partly saturated soil which has been supporting the slope, decreases with increase in the saturation during wet season. As a result, the shear strength of the soil will decrease and stability of the slope will reduce to a low value to trigger landslides.

How to handle?

A real-time early warning system can be developed for reducing the damage caused by the landslides. The development of such systems requires a comprehensive understanding of the failure processes of the slopes due to rainfall infiltration. A combination of artificially created rainfall infiltration tests on small scale soil slopes, and data of field instrumented slopes come in handy to gain a complete picture of instability-dynamics of the slopes. Of late, several researchers have undertaken small-scale laboratory studies for understanding the hydrological responses of model slopes to the saturation process. The small-scale model tests are presented in Fig. 1.7.

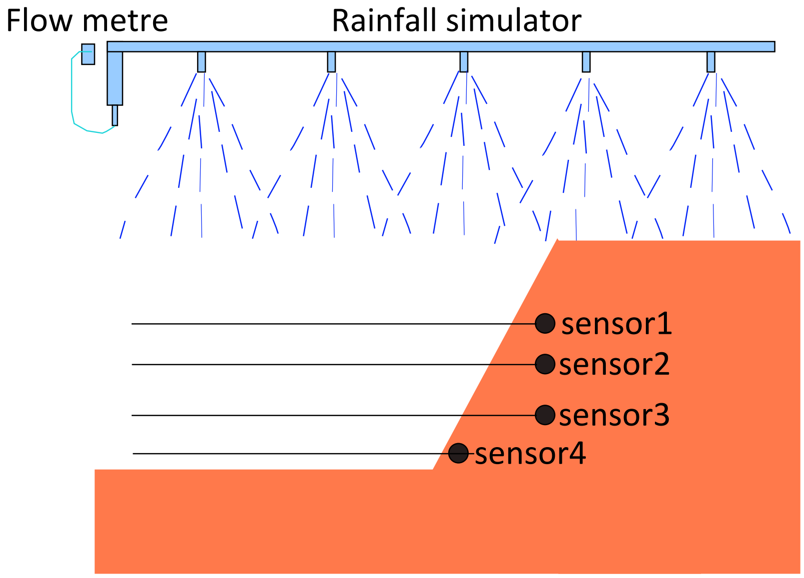

Fig. 1.7 Laboratory experiments on model slopes

<u>Role of unsaturated soil mechanics</u>:

The changes in the soil state parameters such as matric suction, due to ingress of moisture or movement of the wetting front are necessary to address rainfall-induced slope failures.

It is useful for the prediction of critical depths at which the shear strength of the soil is no longer contributing to the stability of the slopes. The concepts are also useful in the analysis for invoking the factors viz. rainfall intensity, duration and antecedent conditions that influence the slope stability. This study emphasizes the importance of concepts of unsaturated soil mechanics in slope engineering.

Lecture 3

Applications Associated with Unsaturated Soils

Stability of river banks:

Land loss due to stream-bank erosion and channel bed degradation is a major concern in river and ocean engineering. Fig. 1.8 depicts the Brahmaputra river bank erosion in Chilmari area of Bangladesh. The bank soils remain unsaturated during most of the year. Thus these banks usually have high shear strengths due to negative pore water pressures. During the floods or severe rainfalls, the excess strength obtained from matric suction disappears due to the saturation during the flow events. In these situations, the concepts of unsaturated soil mechanics are must to provide adequate explanation and analysis of bank failures. The classical soil mechanics can't provide such explanations for slope stability during the moisture variations.

Fig. 1.8 Brahmaputra river bank erosion in Bangladesh (Courtesy: Tonmoy Sarker photography (2012): River Bank Erosion)

The alternative bank failure mechanism is depicted in fig. 1.9. This diagram refers to the alternative wetting and drying stages during which the stream flow into bank and out of the bank observed. It has been observed that such alternative events are believed to be responsible for most of the failures related to river banks.

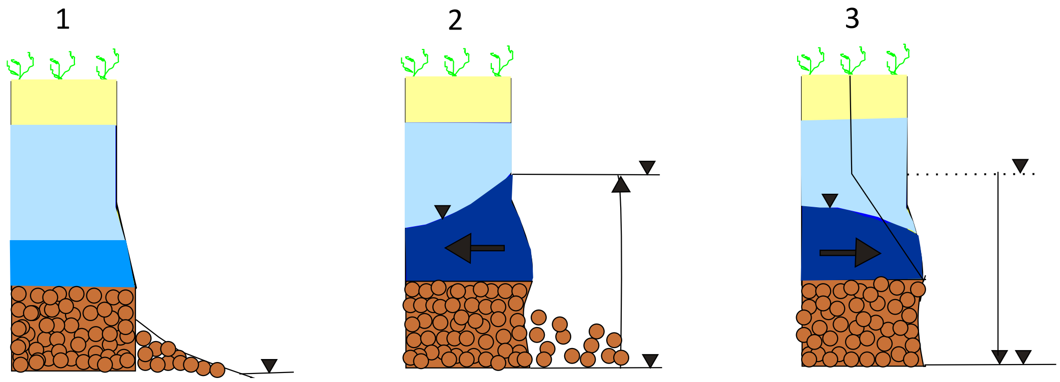

Fig. 1.9 Mechanisms responsible for river bank stability (after, Rinaldi et al., 1999)

Force equilibrium formulation can be used by considering matric suction component for shear strength to obtain dynamic changes in the safety factors for the slopes during the seasonal variations. Such stability mechanisms are also important in the stability of earthen embankments of roads and railways.

<u>Success stories!</u>

Recently, China engaged in south-to-north water diversion channeling project to transfer 23 trillion litres a year from the Yangtze and Han Rivers to Beijing and Tianjin. The stability of the channel banks demonstrated the application of unsaturated soil mechanics principles in practice.

Volume change behavior

The volume of the soils will either decrease or increase upon wetting. The volume of unsaturated expansive soils will increase, while volume will decrease (collapse) for loessial soils upon wetting under a constant applied stress. The following sub-sections describe the characteristics of these soils due to changes in the moisture content.

Naturally existing active clays

Active clays or the expansive clays are the clays that experience usually large swelling strains upon wetting due to their mineralogical composition. The continuous swelling of soil can cause damages to the buildings and other structures constructed on it. It was reported that the damage and, thus the loss, due to expansive soils in many countries is more than the damage due to natural calamities. As the water from irrigation or rainfall seeps into the foundation soil, the swelling mechanism triggers, which is mainly responsible for pushing the structure gradually upwards as shown in Fig 1.12.

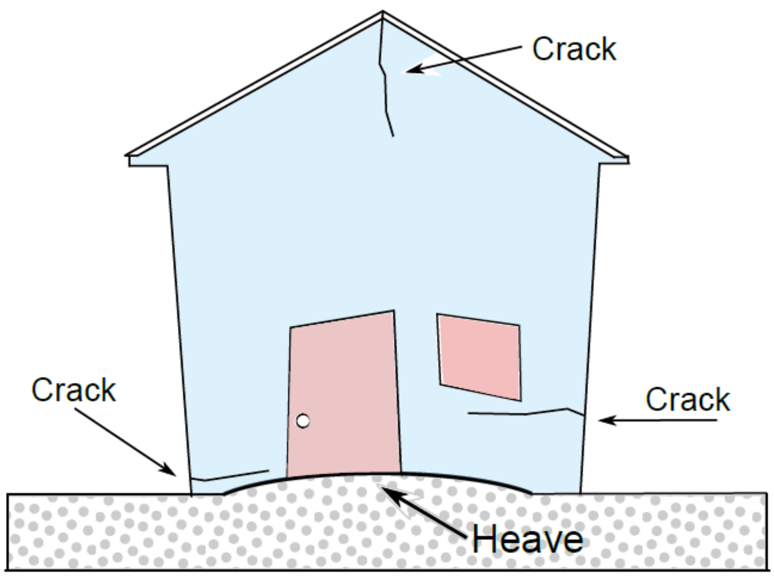

Fig. 1.12. Illustration of damaged buildings constructed on expansive clays

The presence of expansive clays reflects the environment, as they are usually associated with semiarid and arid climates, mineral composition containing significant amounts of smectite group minerals. Most expansive clay deposits in India and elsewhere are either residual soils formed from igneous/montomorillonitic rocks or sedimentary deposits. These clays contain high percentages of montomorillonite minerals. The swelling in montomorillonitic soils is due to the chemical attraction of water into crystal lattice of clay minerals. Layers of water molecules diffuse between the flat and submicroscopic clay platelets. Different mechanisms involved in swelling phenomena in clays are described below as reported by Popescu (1986):

(i) Interparticle or intercrystalline swelling: In a residual or pendular regime where the soil remains nearly dry, particles are held together under capillary tensile stresses. These stresses are relaxed upon wetting that encourages the expansion of clay as shown in the Fig 1.13a.

(ii) Intracrystalline swelling: This swelling mechanism is primarily a characteristic of montmorillonite group of minerals. The layers of crystals in montmorillonite are weakly bonded. The water enters, upon wetting, not only between crystals, but also between the individual layers of single crystal as shown in Fig 1.13b. The increase in the water content also increases thickness of diffuse double layers (water layer around the particles) of the clay platelets and manifests in the form of swelling.

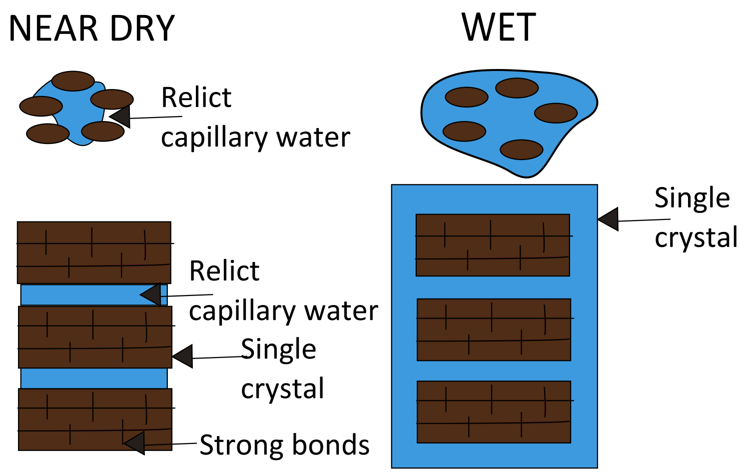

Fig. 1.13a Interparticle or intercrystalline swelling

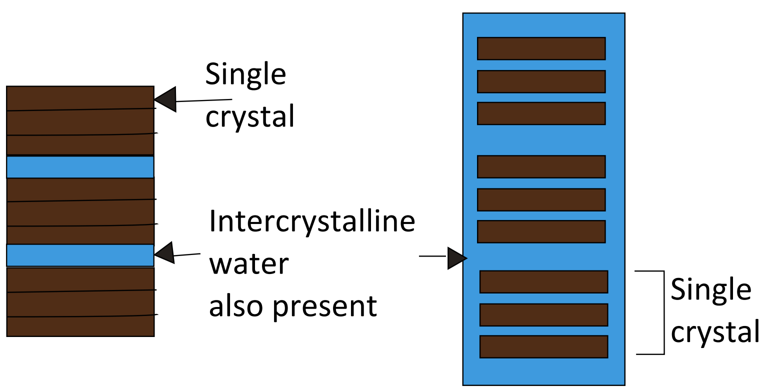

Fig. 1.13b Intracrystalline swelling (after popescu, 1998)

The swelling behavior of unsaturated expansive clays are often treated using the concepts of strain energy coupled with Elasto-plastic models and by accounting the most important characteristic parameters of the unsaturated soils, “matric suction” (Yuan and Ju, 2013).

As a buffer and backfill material

There is another important application of unsaturated soil mechanics in geo-environmental engineering where the swelling characteristics of unsaturated soils are studied. Many countries are investing in the development of smart disposal facilities for high-level radioactive nuclear wastes. Compacted plastic clays, such as bentonites, are receiving a great attention of professionals, across the globe for their usage as sealing and barrier material in the repositories (Fig. 1.14).

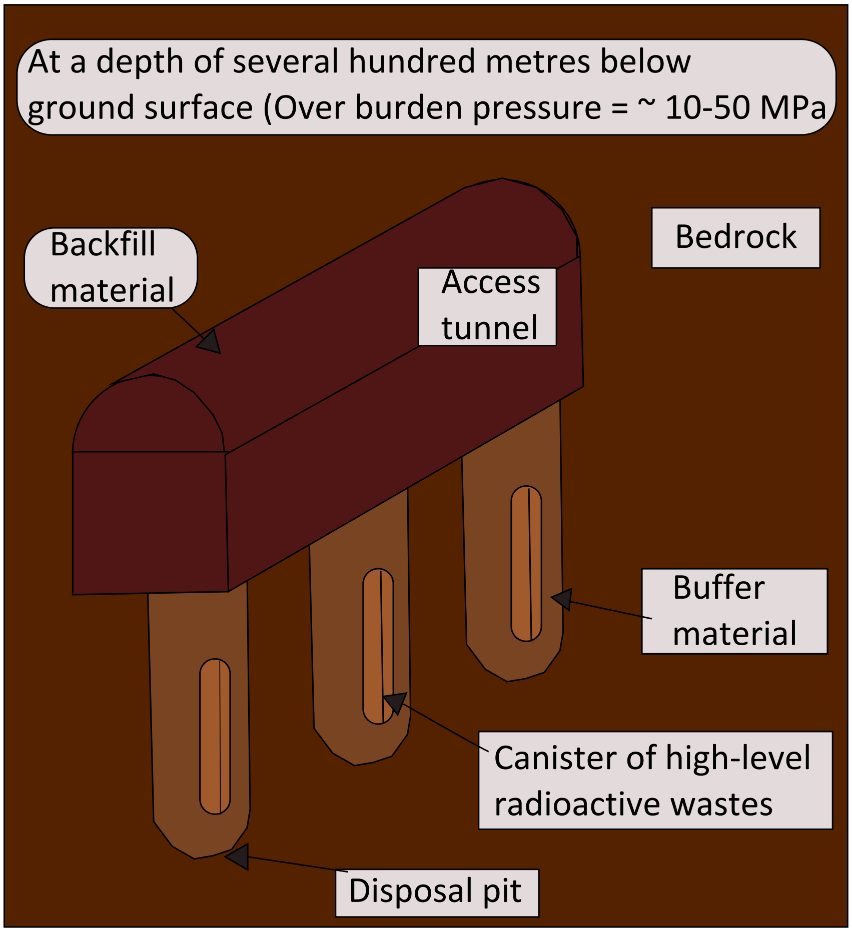

Fig. 1.14. Illustration of nuclear waste disposal facility (repository) for high-level radioactive wastes

The bentonite serves the following functions (Kanno and Wakamatsu, 1992) in the repositories:

(a) buffer material delays the movement of groundwater that intrudes into the repository and reaches the container and delays the migration of radionuclides from the corroded containers to the host rock
(b) holds the containers in place and prevent transfer of excessive stresses to the containers against creep of the host rock; and
(c) transfers heat generated in the waste to the host rock

The bentonite carries several advantages for this purpose because of its low hydraulic conductivity; low water diffusivity; and high amounts of adsorption capacity, cation exchange capacity, and swelling potentials. The determination of swelling pressures and swelling potentials in these facilities requires the application of unsaturated soil mechanics.

Collapsible soils

Partly saturated/dry soils are often relatively stiff and they suffer only small compressions under normal foundation loads. However, under constant normal loads such soils undergo a marked decrease in their volume upon wetting. The rate of volume change depends on the rate at which water diffuses into the soil mass. The volume changes are rapid when the water has an easy access and the subsequent phenomenon is referred to as "collapse". The amount of collapse is function of several factors including degree of saturation, initial void ratio, stress history of the materials, thickness of the collapsible strata, and the amount of stress applied (Barden et al., 1973). Loess is a collapsing soil. It is predominantly a silt-sized (5 to 50μm) alkaline, amorphous sediment deposited through aeolian agencies in pen-glacial regions. Such collapsing soils of the loessial type are found in many parts of the earth, including India. The distribution of loess soils in the northern parts of India is given in Fig. 1.15. The figure indicates the prevailing manifestation of aeolian processes both in cold arid and hot arid regions. The collapse mechanism in these soils is found to be due to the local shear failure between soil grains upon wetting. Several land subsidence problems have been noticed in such soils. Land settlement can damage man-made structures such as foundations, pavements, and irrigation works. The collapse process has been studied experimentally in terms of two components of effective stresses, viz. the applied stress and the suction (Barden et al., 1969). It was shown that the following three conditions favor the collapse (Barden et al., 1973):

(i) An open and potentially unstable partly saturated structure

(ii) A high applied stress to develop a metastable condition

(iii) A high value of soil suction to stabilize inter-granular contacts

The reduction in soil suction on wetting leads to collapse. Thus, the stability of these soils depends on the matric suction, which is the unsaturated soil state variable. Thus it stresses the importance of mechanics of unsaturated soils in understanding the stability.

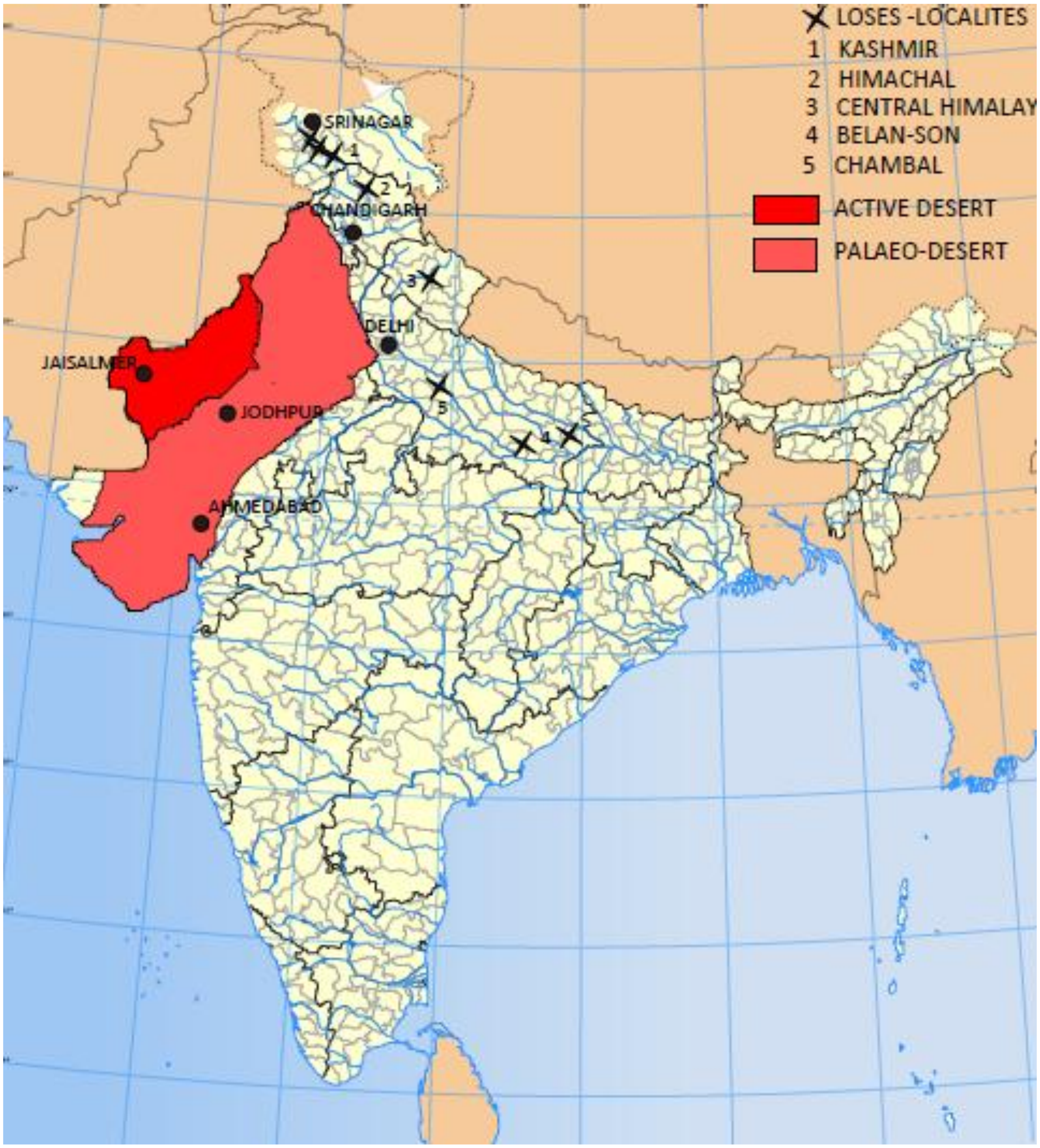

Fig. 1.15. Loess soil distribution in India

Understanding and predicting such soil behavior requires the knowledge of unsaturated soil mechanics.