Teaching Unsaturated Soil Mechanics as Part of the Undergraduate Civil Engineering Curriculum

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Introduction

- Soil mechanics textbooks do not address the full scope of problems encountered in geotechnical engineering
- Textbooks for undergraduate students focus on the behavior of saturated soils
- Undergraduate students are generally taught very little about unsaturated soil behavior

Personal Observation Upon Graduation From University

- *After graduation I realized I had been taught soil mechanics courses related to saturated soil behavior and then found myself faced with attempting to solve many problems where the soil was unsaturated. After 2 years I observed that about 90% of the problems I had addressed involved soils with negative pore-water pressures. I began to feel that I had been taught soil mechanics for saturated soils and then had to go out and practice soil mechanics for unsaturated soils. I was ill-equipped to face a world with unsaturated soil mechanics problems*

Undergraduate Student Needs

- Undergraduate engineering students need:
  - to be better-equipped to face a geotechnical world with unsaturated soils problems
  - to better understand the basic differences between the behavior of saturated and unsaturated soils
  - to know the concepts and fundamentals behind unsaturated soil behavior and learn to ***"think the way the unsaturated soil behaves"***

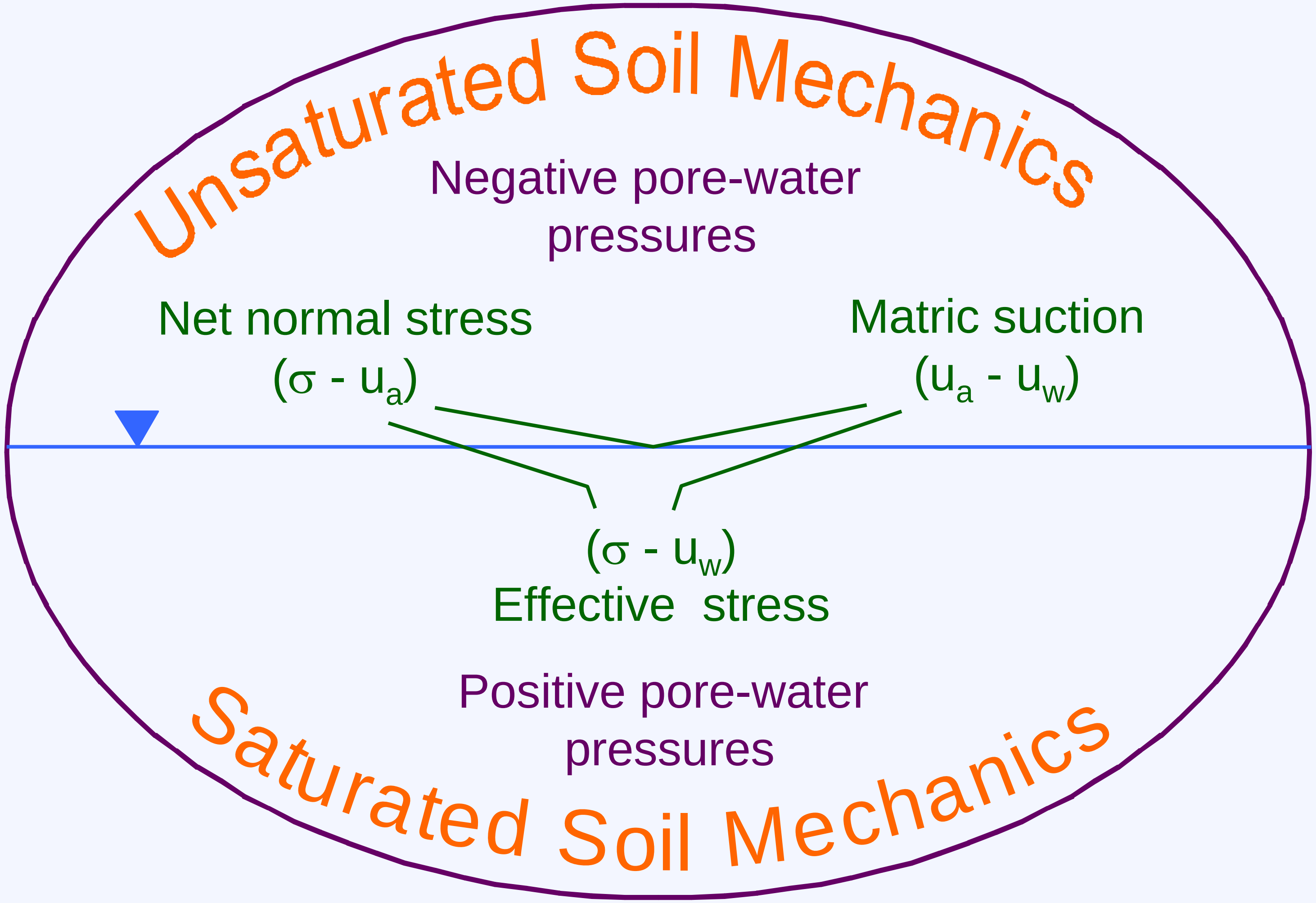
Is There a Need to Teach Unsaturated Soil Mechanics?

- *Many Civil Engineering problems involve the interaction between the climate and the unsaturated soil zone (i.e., flux boundary conditions)*
  - *Foundations of many structures are near ground surface*
  - *Expansive soils problems impose a large financial burden on society in many countries*
  - *Human Beings usually contaminates the environment starting at the ground surface*

Teaching Unsaturated Soil Mechanics at the Undergraduate Level

- To-date there has been little desire to teach unsaturated soil mechanics at the undergraduate level
- It may be easier to introduce the basic concepts of unsaturated soil mechanics at the undergraduate level than at the graduate level
- It is suggested that the basic concepts of saturated-unsaturated soil mechanics be taught using simple illustrative diagrams

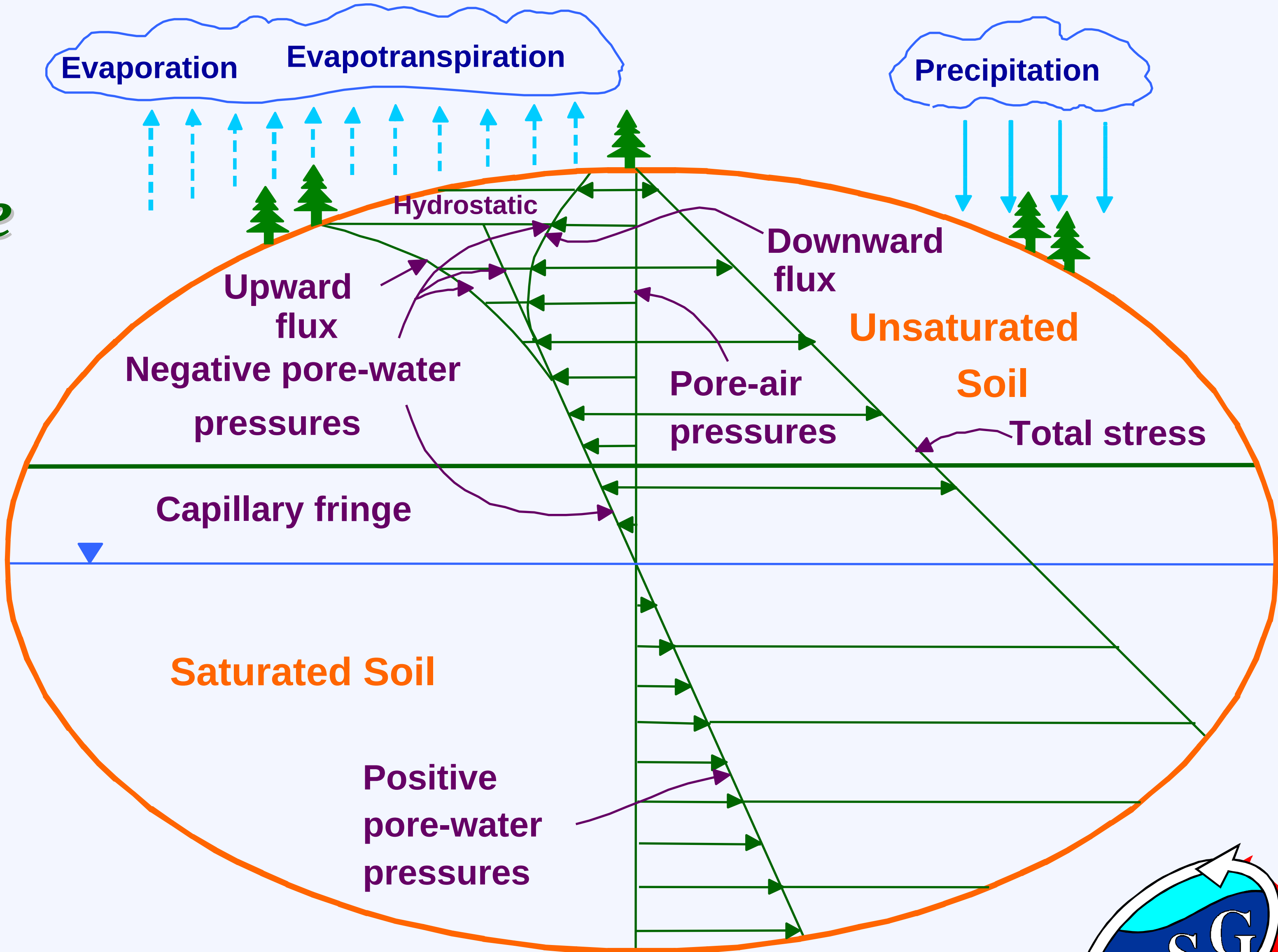
Broad Categorization of Soil Mechanics Based on Stress State Variables



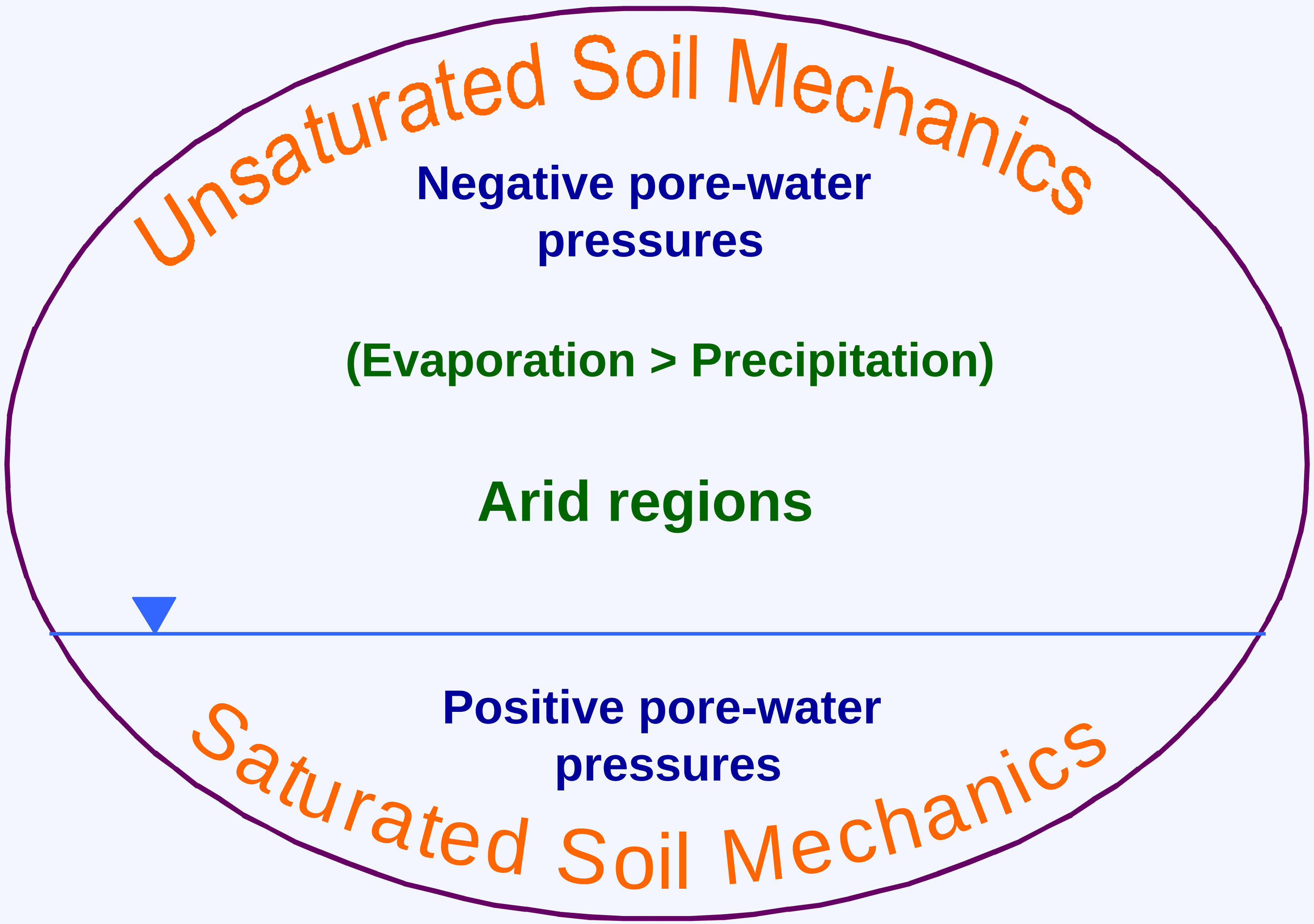
The "Real World" has a Moisture Flux Boundary Condition

- *Saturated soil mechanics has largely ignored ground surface moisture flux conditions*
- *Changes in negative pore-water pressure (and consequently matric suction) in unsaturated soils can be caused by:*
  - *precipitation and infiltration*
  - *evaporation*
  - *transpiration*
  - *covers*

Visualization of the Role of the Surface Flux Boundary Condition



Long Term Response of the Water Table to Arid Climatic Conditions



General Objectives of Teaching Undergraduate Soil Mechanics

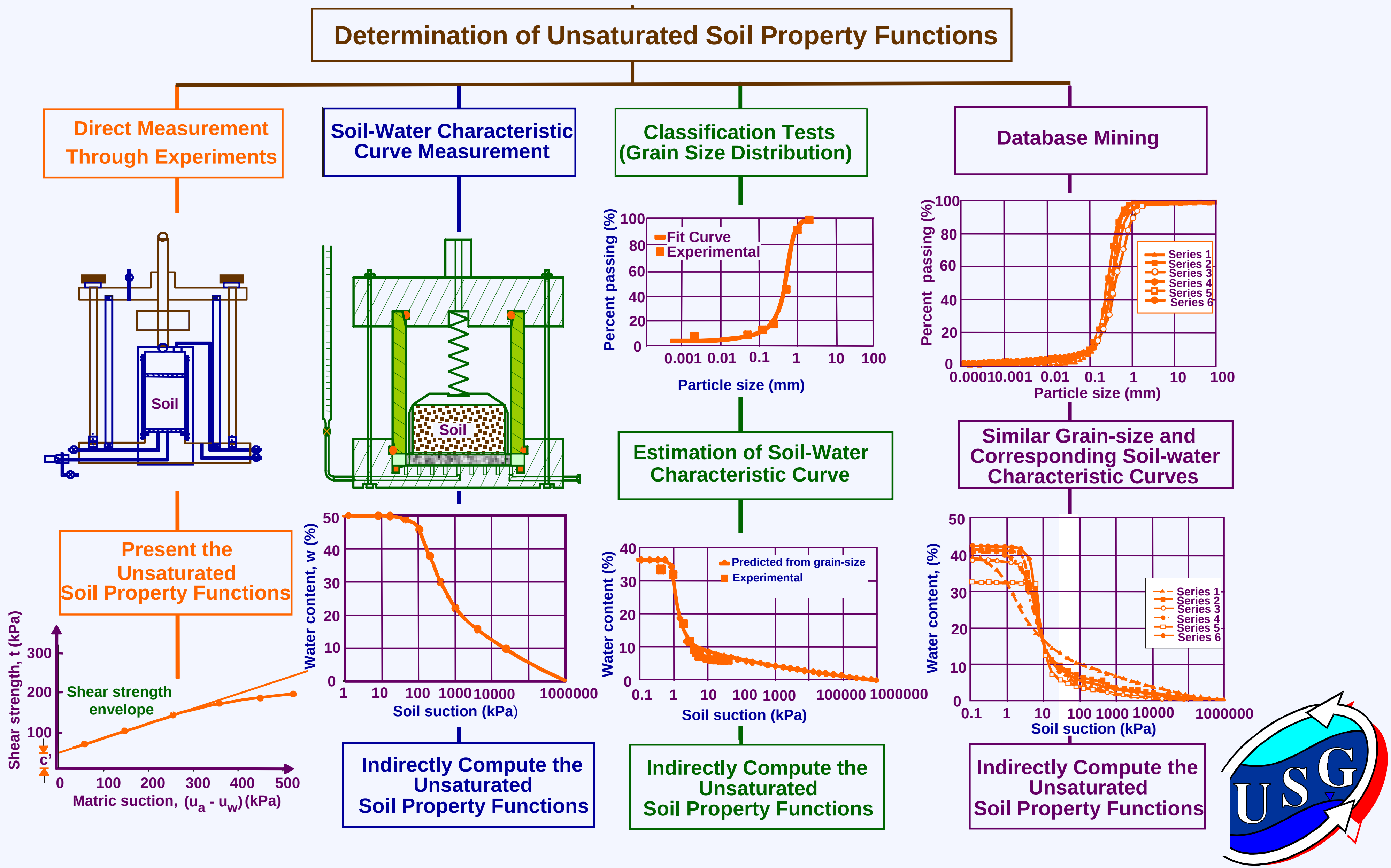
- *To present the basic concepts and fundamental principles of soil mechanics based on the student's background in mechanics, physics and mathematics*
- *To provide background knowledge for a life-time of learning geotechnical issues*
- *Teaching should integrate modern learning principles, teaching techniques and use learning aids* ***(From several recent Soil Mechanics Textbooks)***

More Specific Objectives of Teaching Undergraduate Soil Mechanics

- Undergraduate engineering students should learn:
  - theories related to the physical and mechanical properties of soils
  - means whereby relevant measurements can be made in the laboratory or in the field
  - application of the theories and measurements to the analysis of geotechnical problems
  - procedures whereby the physical and mechanical properties can be estimated or approximated

Need for a New Paradigm for Unsaturated Soil Mechanics

- Implementation of Unsaturated Soil Mechanics Generally Requires:
  - the estimation of unsaturated soil property functions, USPFs
  - USPFs are estimated largely through use of the soil-water characteristic curves, SWCC
  - a new paradigm or mindset is required that respects estimation and approximation procedures for USPFs



Determination of Unsaturated Soil Property Functions
Direct Measurement Through Experiments
Soil-Water Characteristic Curve Measurement
Classification Tests (Grain Size Distribution)
Database Mining
Soil
Soil
Percent passing (%)
Fit Curve
Experimental
Particle size (mm)
Series 1
Series 2
Series 3
Series 4
Series 5
Series 6
Estimation of Soil-Water Characteristic Curve
Similar Grain-size and Corresponding Soil-water Characteristic Curves
Present the Unsaturated Soil Property Functions
Shear strength, τ (kPa)
Shear strength envelope
c'
Matric suction, (u_a - u_w) (kPa)
Water content, w (%)
Soil suction (kPa)
Water content (%)
Predicted from grain-size
Experimental
Water content, (%)
Indirectly Compute the Unsaturated Soil Property Functions
Indirectly Compute the Unsaturated Soil Property Functions
Indirectly Compute the Unsaturated Soil Property Functions
USG

Fifteen bar Pressure Plate equipment manufactured by GCTS, U.S.A.

- ***Wide range of applied suctions***
- ***Applies total stresses***
- ***Measures water and total volume change***
- ***Measure diffused air***
- ***Test individual specimens***
- ***Null-type initial suction***
- ***Drying and wetting modes***

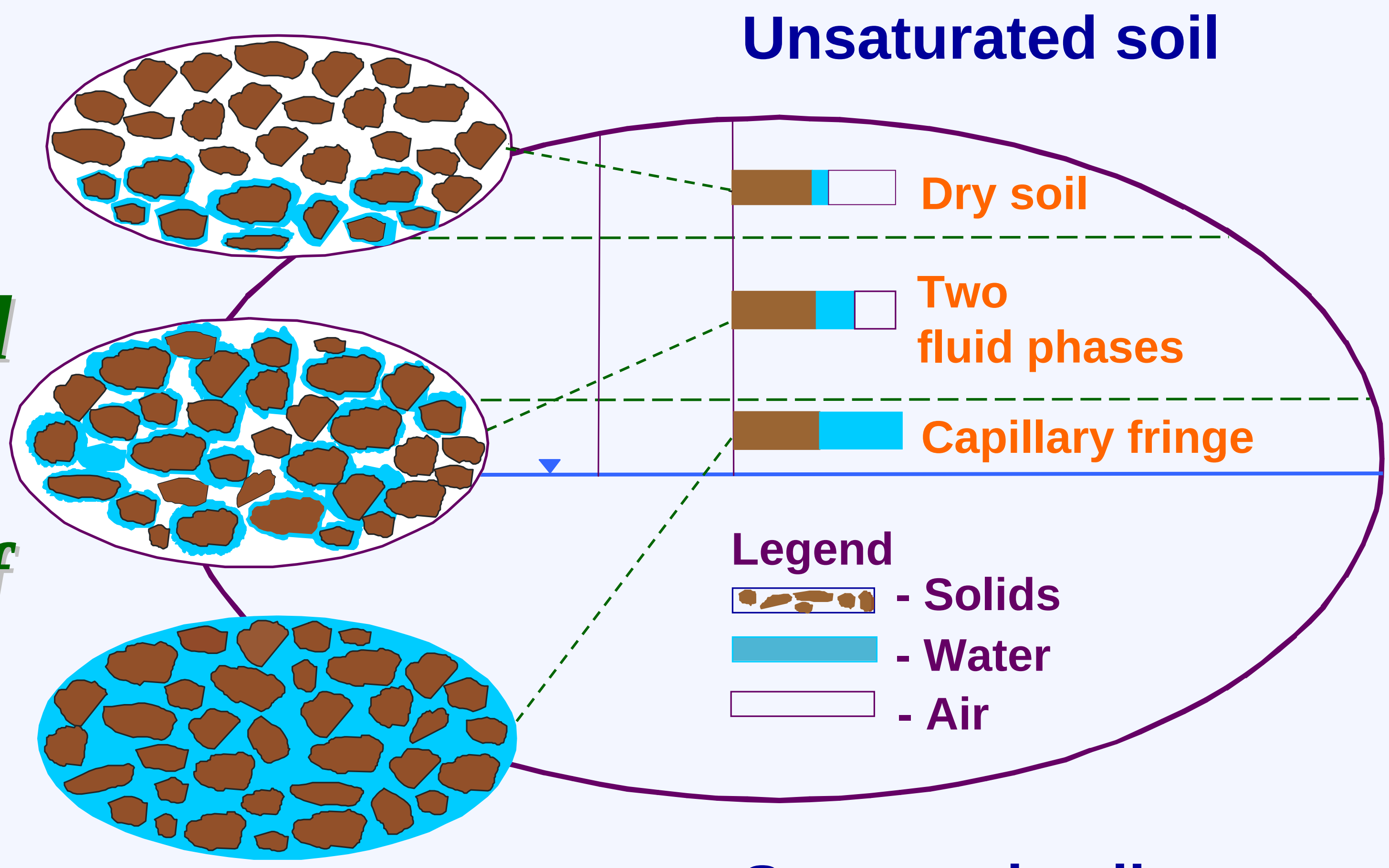
What is an Unsaturated Soil?

- Definition:
  - a soil that has water and air in the voids separated by a contractile skin (air-water inter-phase)
  - a soil where the pore-water pressures are negative relative to the pore-air pressures

Partly Saturated & Partially Saturated terms seldom used

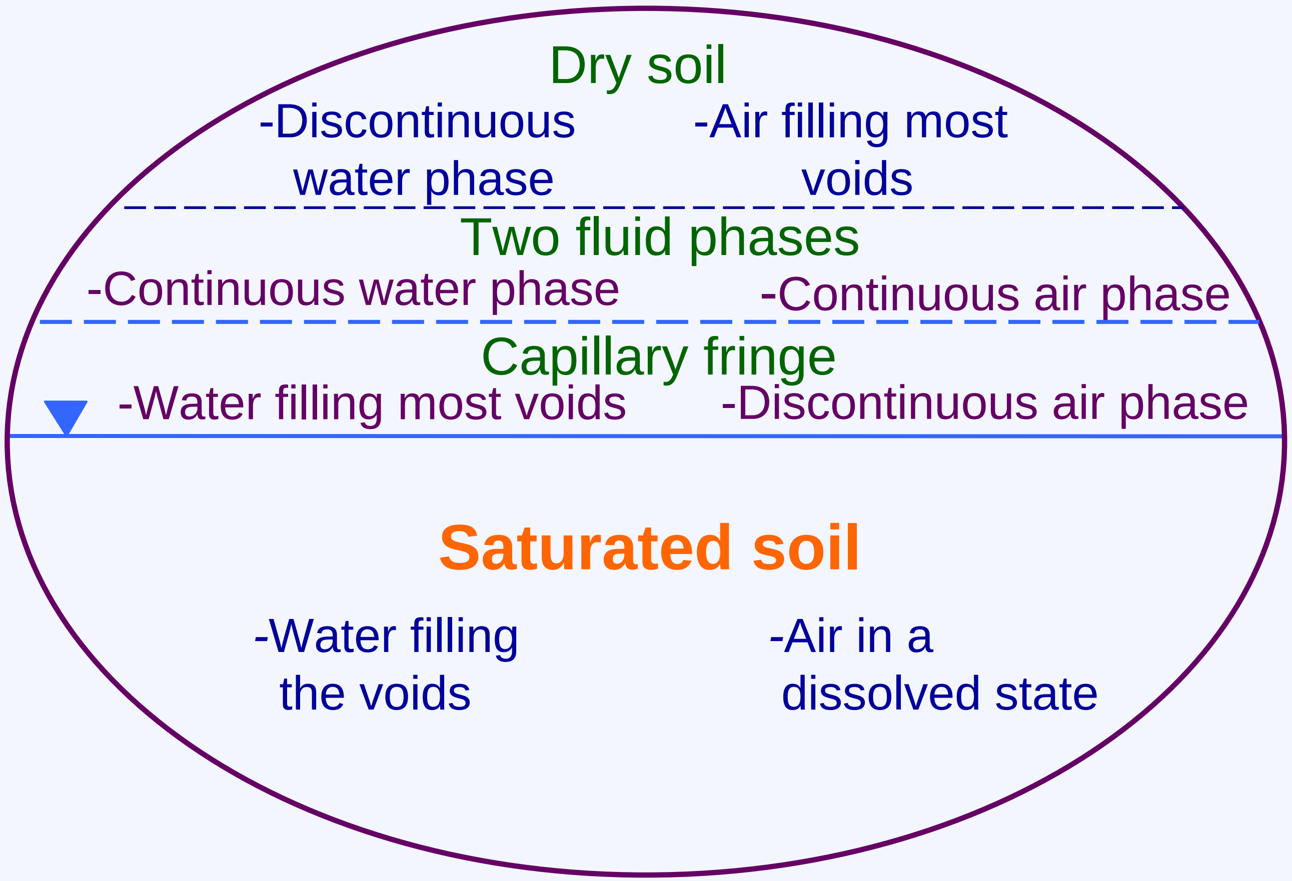
- Note: the smallest amount of air renders a soil unsaturated but it is the relative pressures between air and water that is most important

Subdivision of Soil above the Water Table based on Variation in Degree of Saturation

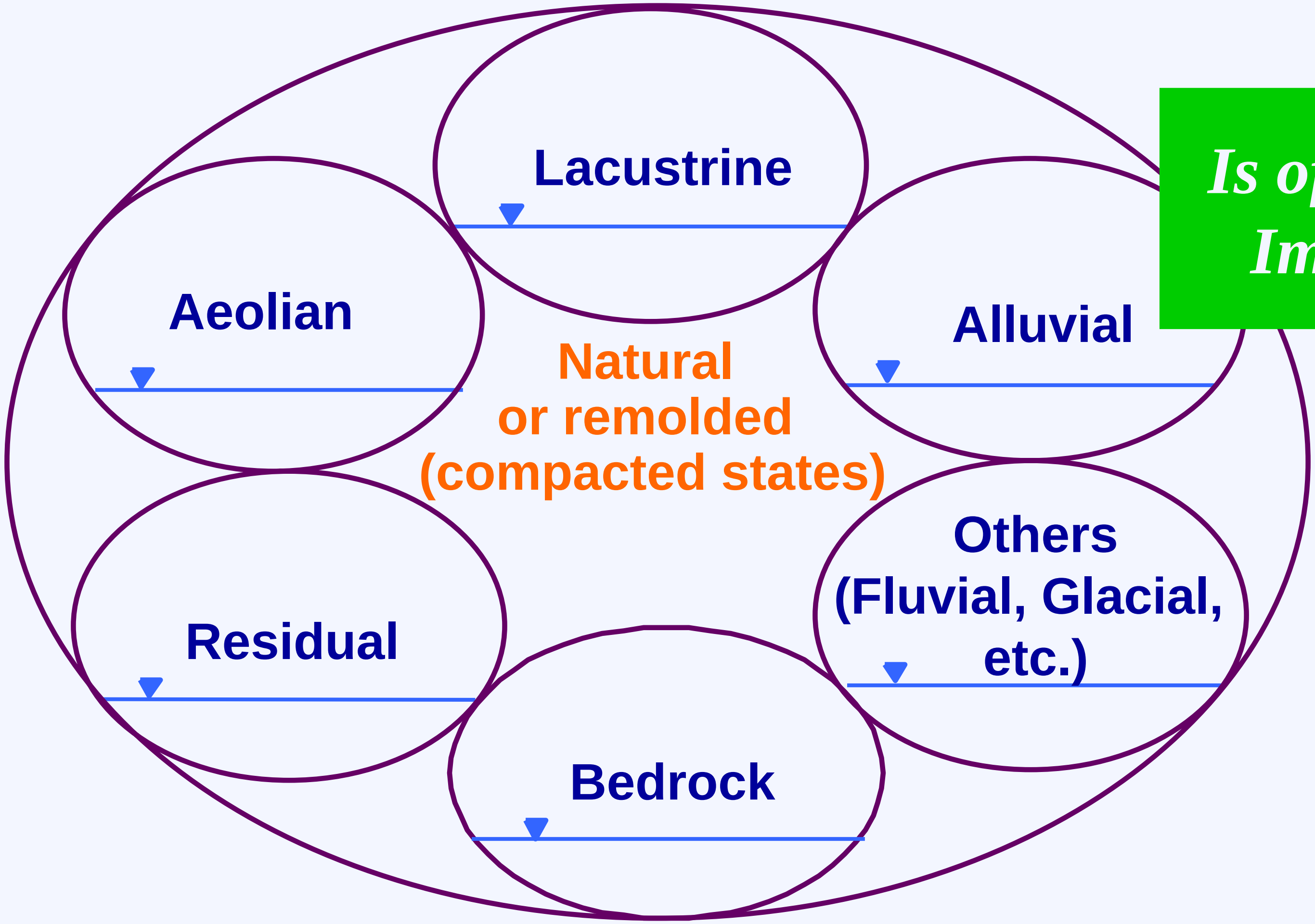


Categorization of Soil Mechanics Based on the Nature of the Fluid Phase

Unsaturated soil



Categorization of Soil Mechanics Based on Geological Origins



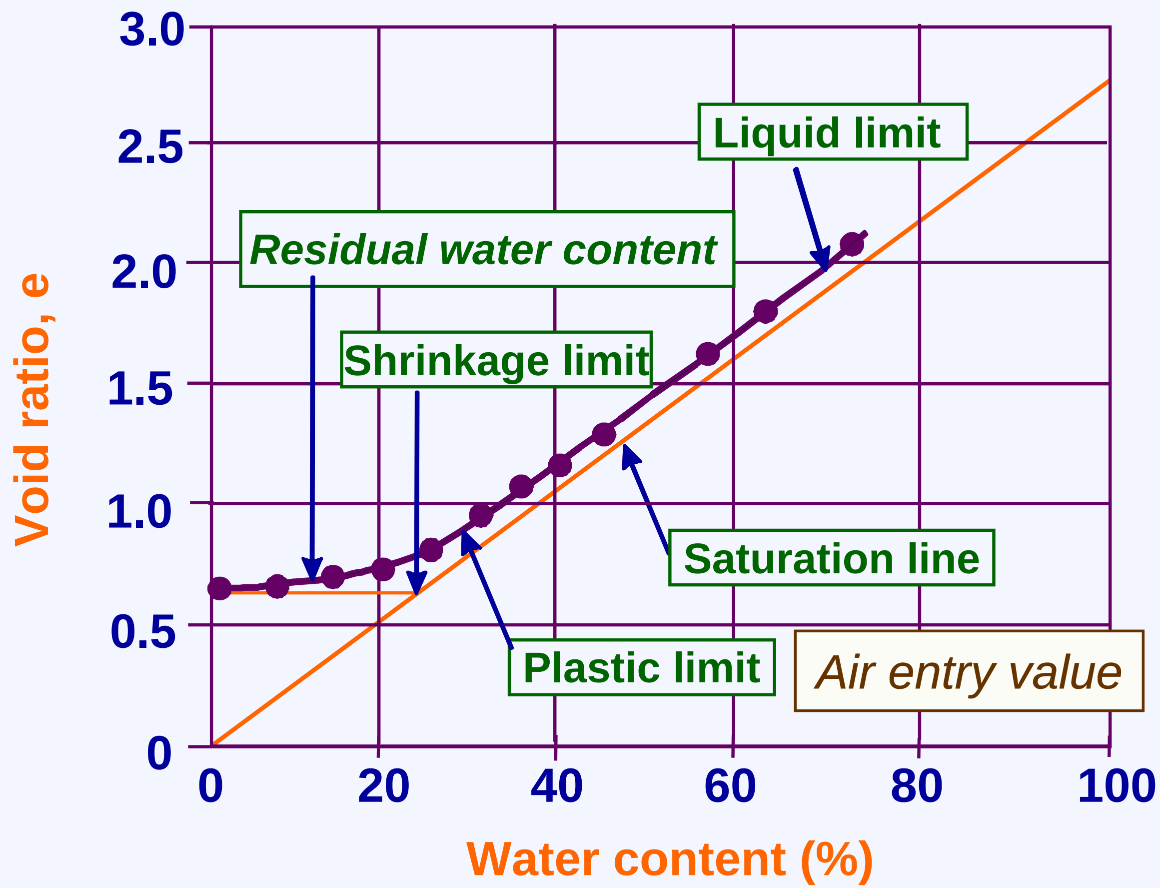
Is of Secondary Importance!

Example Where 'Soil Classification' Pertains to Unsaturated Soil Mechanics

- Shrinkage curve:
  - subdivides soils into states:
    - » the liquid state
    - » the plastic state
    - » the solid state
    - » the semi-solid state
  - is the response of an initially slurried soil to an increase in soil suction
  - relates water contents to the SWCC

Subdivisions between "states" relate to soil suction levels

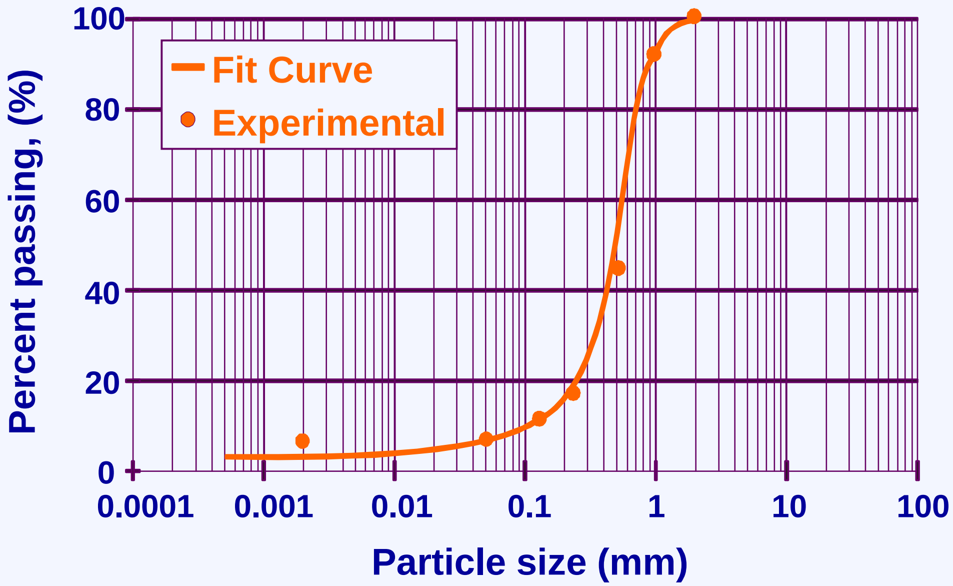
Relationship between Atterberg Limits and the Shrinkage Curve for a Highly Plastic Clay



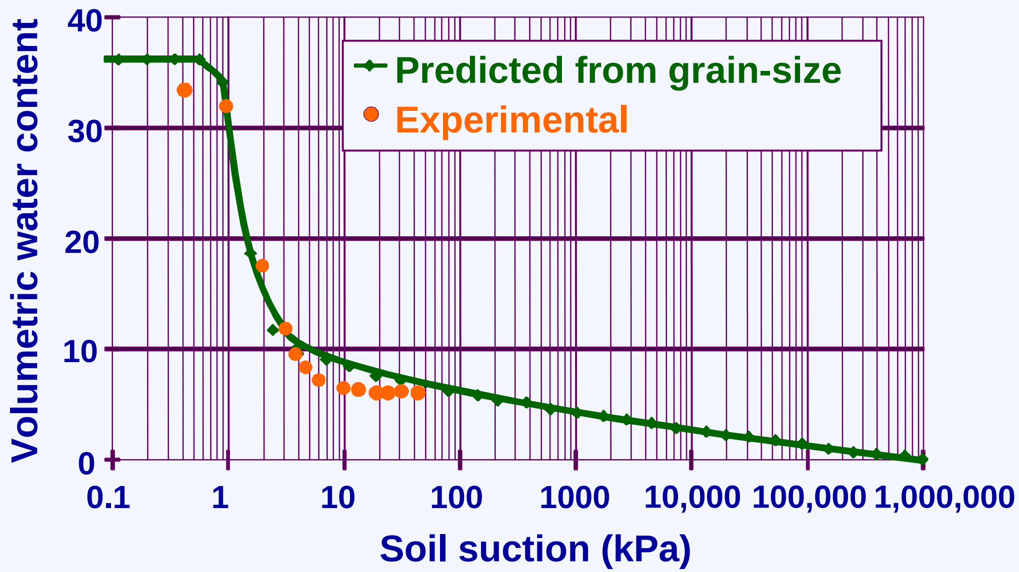
Example of the Relevance of the 'Grain-Size Distribution' to Unsaturated Soil Mechanics?

- The grain-size distribution curve:
  - provides a measure of the soil solids distribution
  - The inverse of the soil solids distribution (i.e., distribution of the voids) forms the basis for the estimation of the SWCC
  - Require the use of the Capillary Theory to calculate the SWCC

Comparison between the Grain-Size Distribution Curve and the Soil-Water Characteristic Curves for Sand



Grain-size distribution for sand



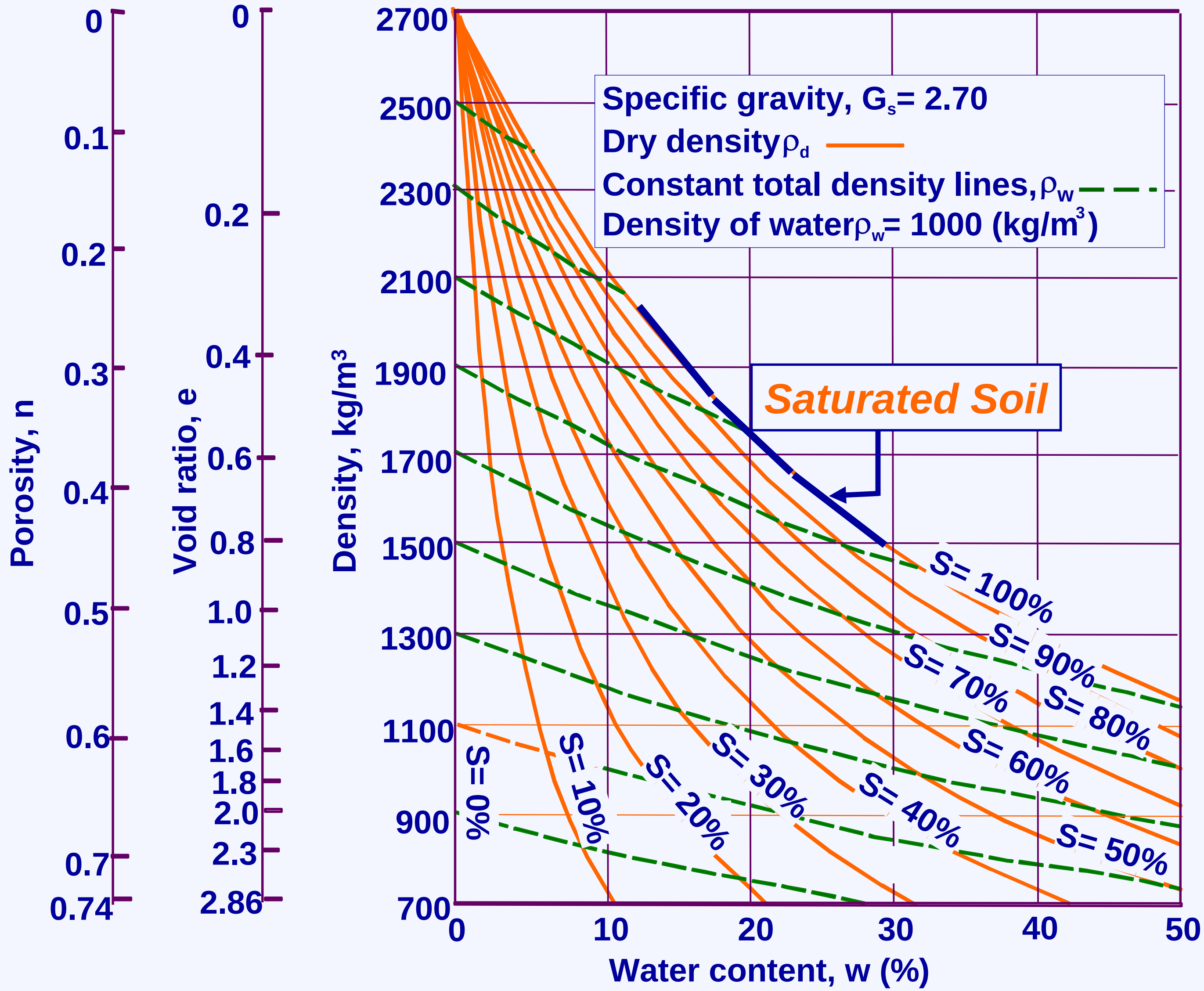
The soil-water characteristic curve for sand (after Fredlund, 1987)

Topics of Unsaturated Soil Mechanics Covered in Classical Soils Mechanics

- Soil compaction and volume-mass relationships
- Reveals that two volume-mass constitutive relationships are necessary to compute changes in soil properties during any process

$$S\,e = w\,G_s$$

Volume-Mass Relations for a Soil

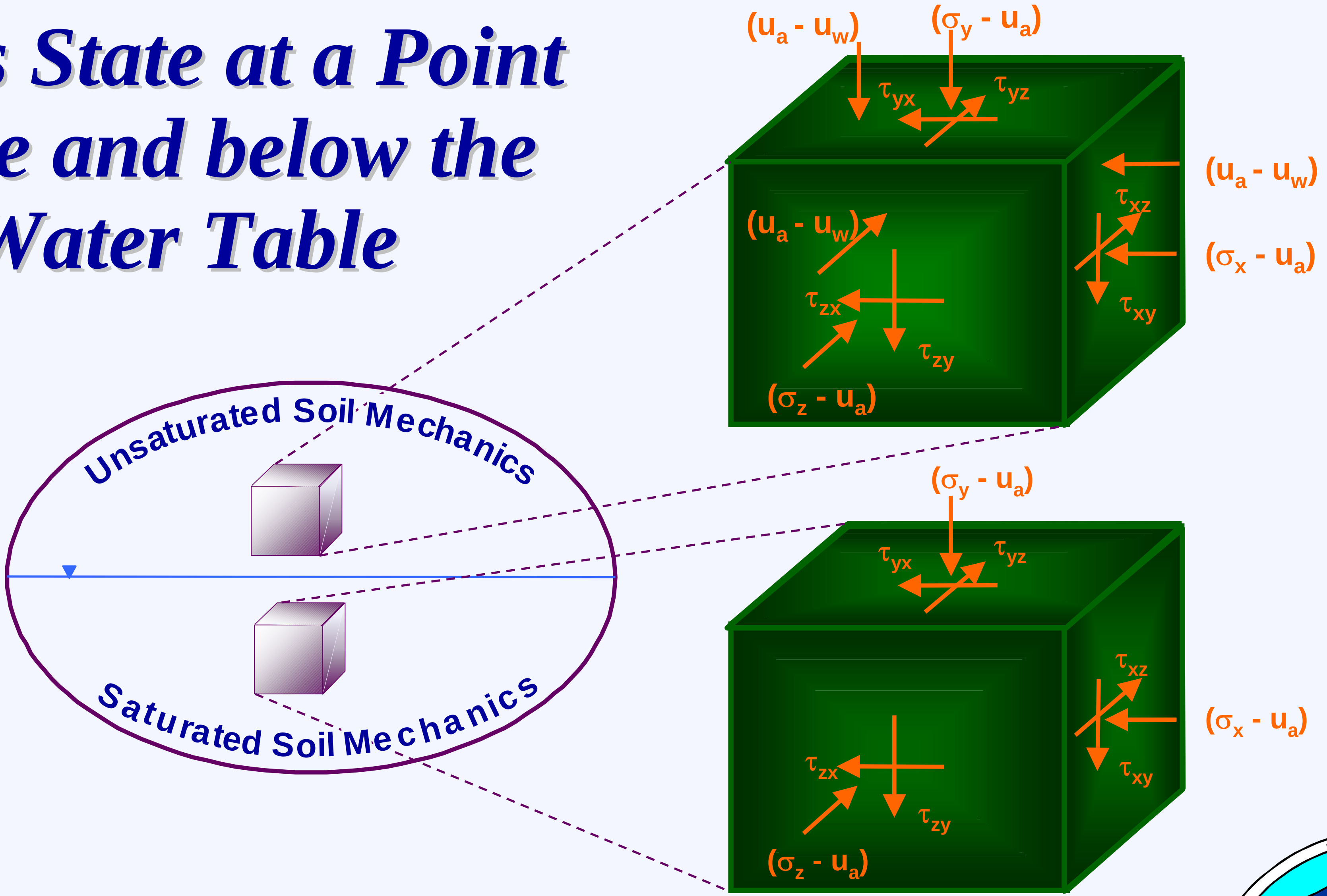


Specific Gravity = 2.70

The Centrality of Stress State Variables

- *Undergraduate students are generally taught about stress tensors in classes such as strength of materials*
- *Stress state variables combine to form of two independent stress tensors for unsaturated soils*
- *A soil always behaves in response to the stress state variables and changes in the stress state variables*

Stress State at a Point above and below the Water Table



Saturated Soil Mechanics as a Special Case of Unsaturated Soil Mechanics

- *There is a smooth change from the stress state for an unsaturated soil to that of saturated soil:*
  - *water pressure approaches to air pressure*
  - *matric suction stress tensor drops out*
  - *stress state reverts to the single effective stress tensor*
- *Smooth transitions should also exist for all constitutive relationships*

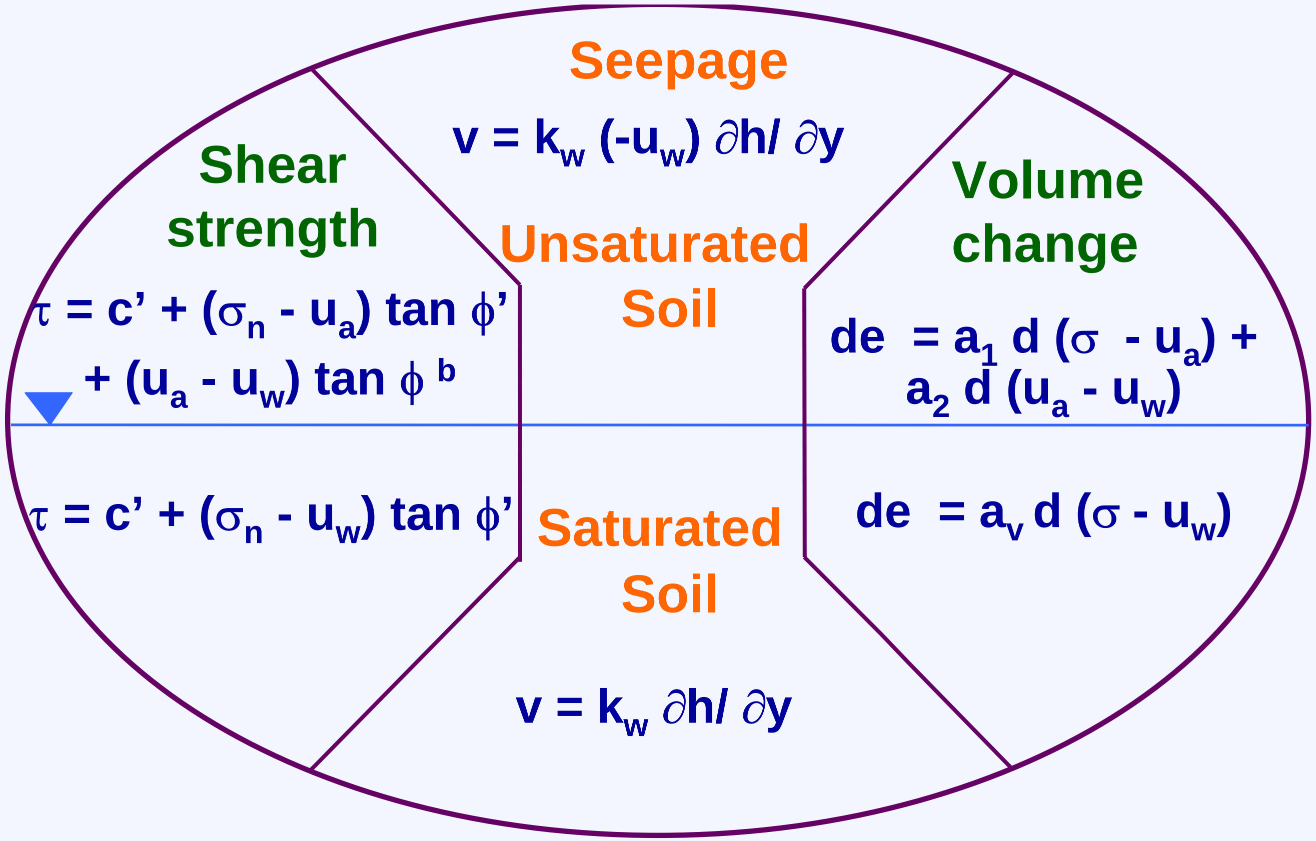
What is the Primary Need and Responsibility of the University Professor of Geotechnical Engineering?

- *To teach all students the fundamental concepts of saturated-unsaturated soil behavior and thereby teach the students to **"think the way saturated-unsaturated soil systems behave"!***

Differences between Unsaturated and Saturated Soil Mechanics

- Unsaturated soil properties are highly nonlinear
- Constitutive relations for the classic areas of soil mechanics need to be extended to embrace unsaturated soils
- Formulations need to be extended
- Solutions need to be obtained through numerical modeling using a computer

Constitutive Equations for the Classic Areas of Soil Mechanics



Visualization of the Coefficient of Permeability Function in the Unsaturated Soil Zone

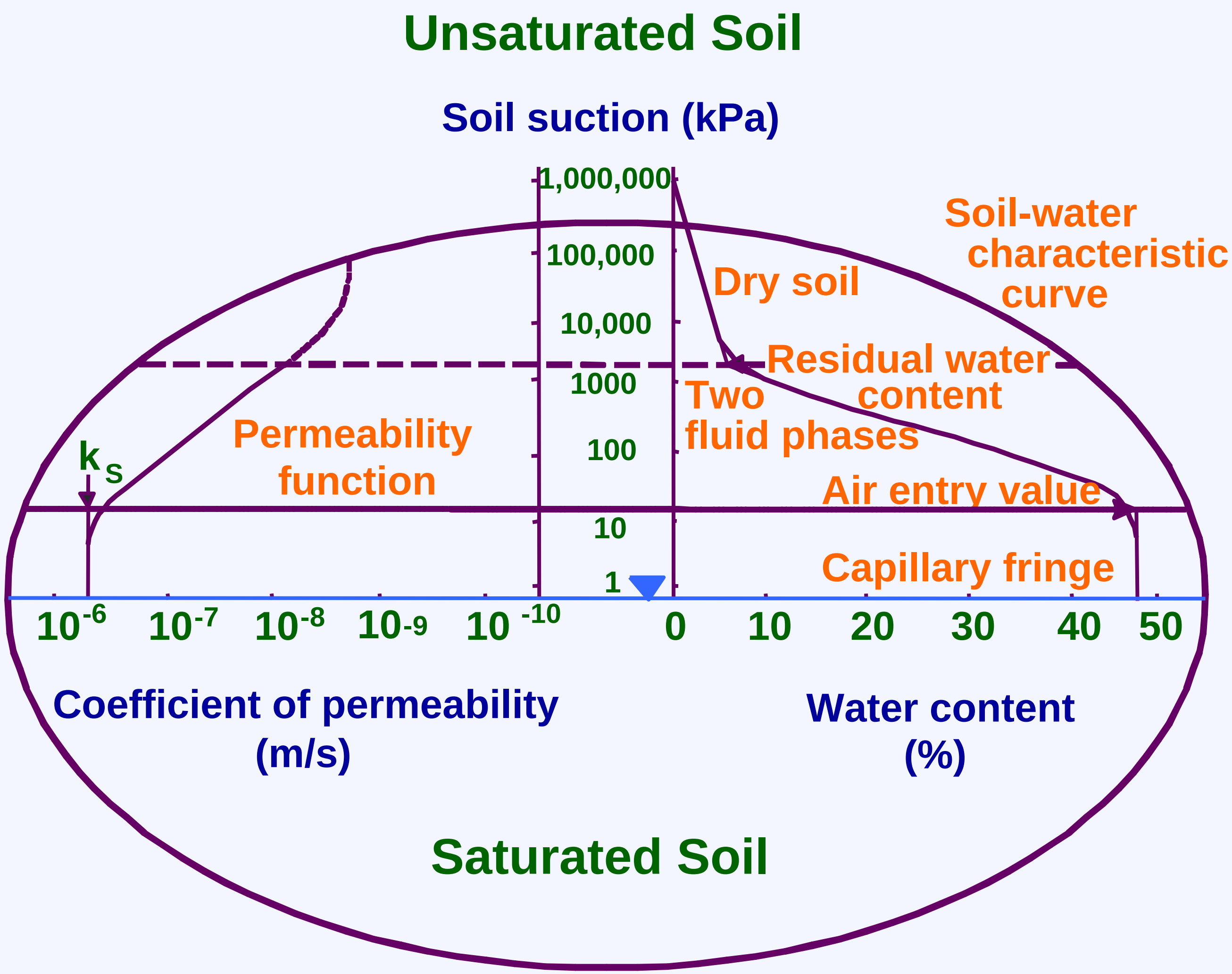
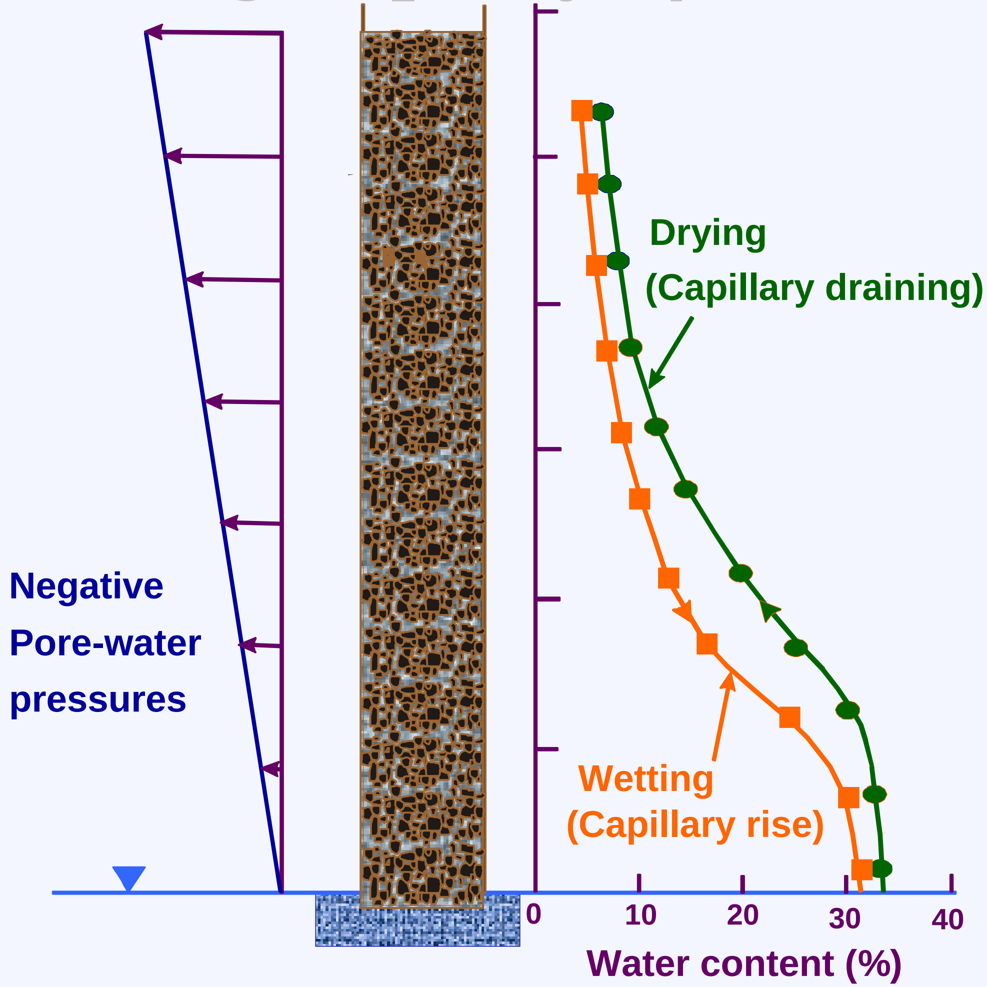
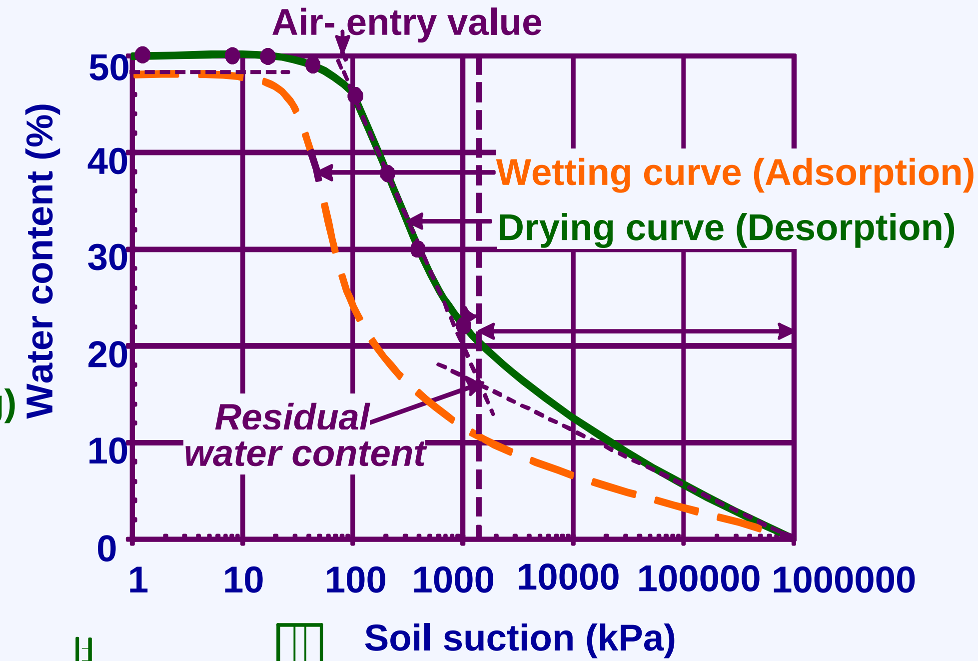
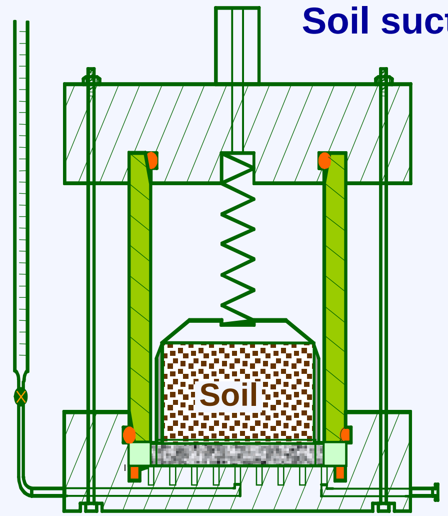


Illustration of Water Holding Capacity of a Soil

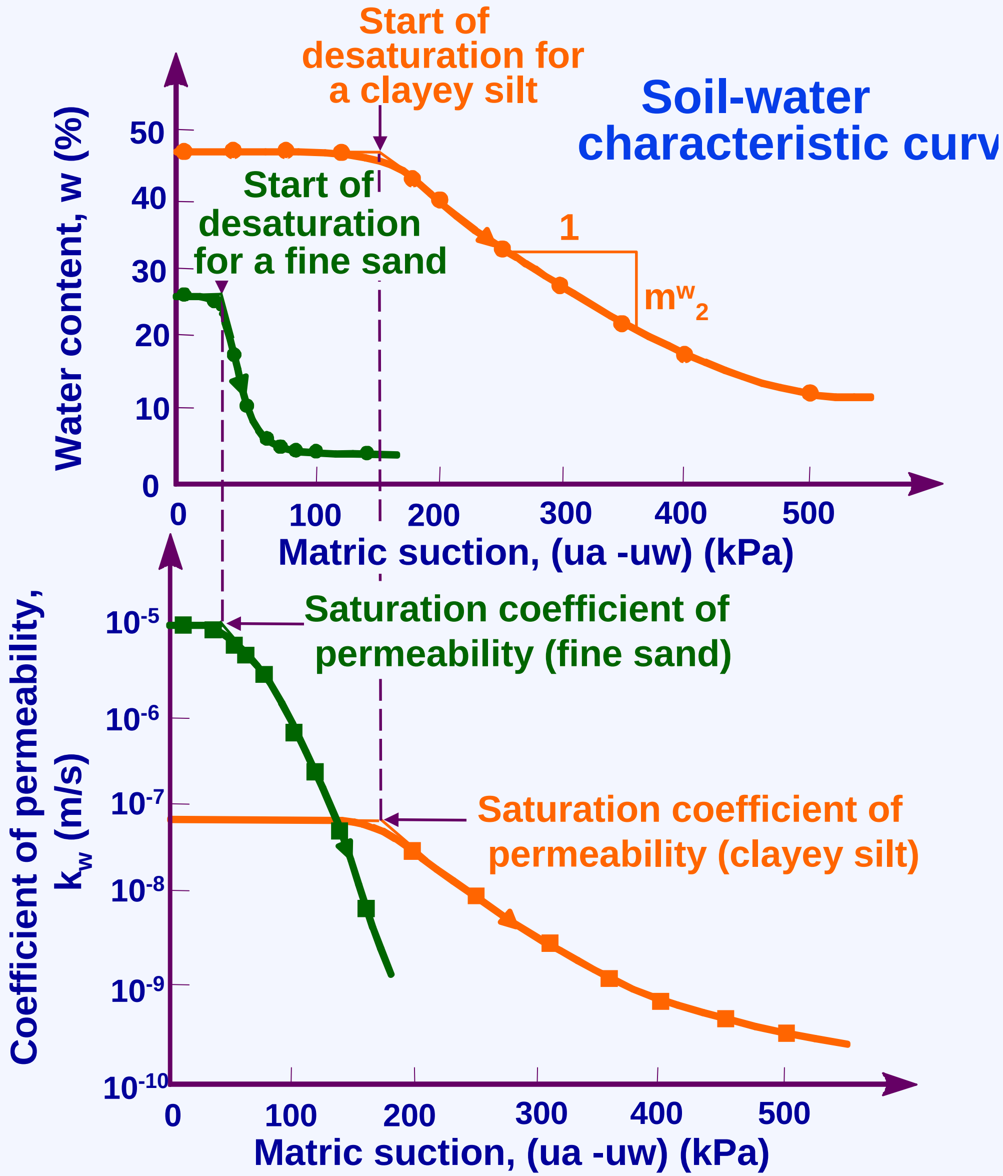


SWCC Laboratory test



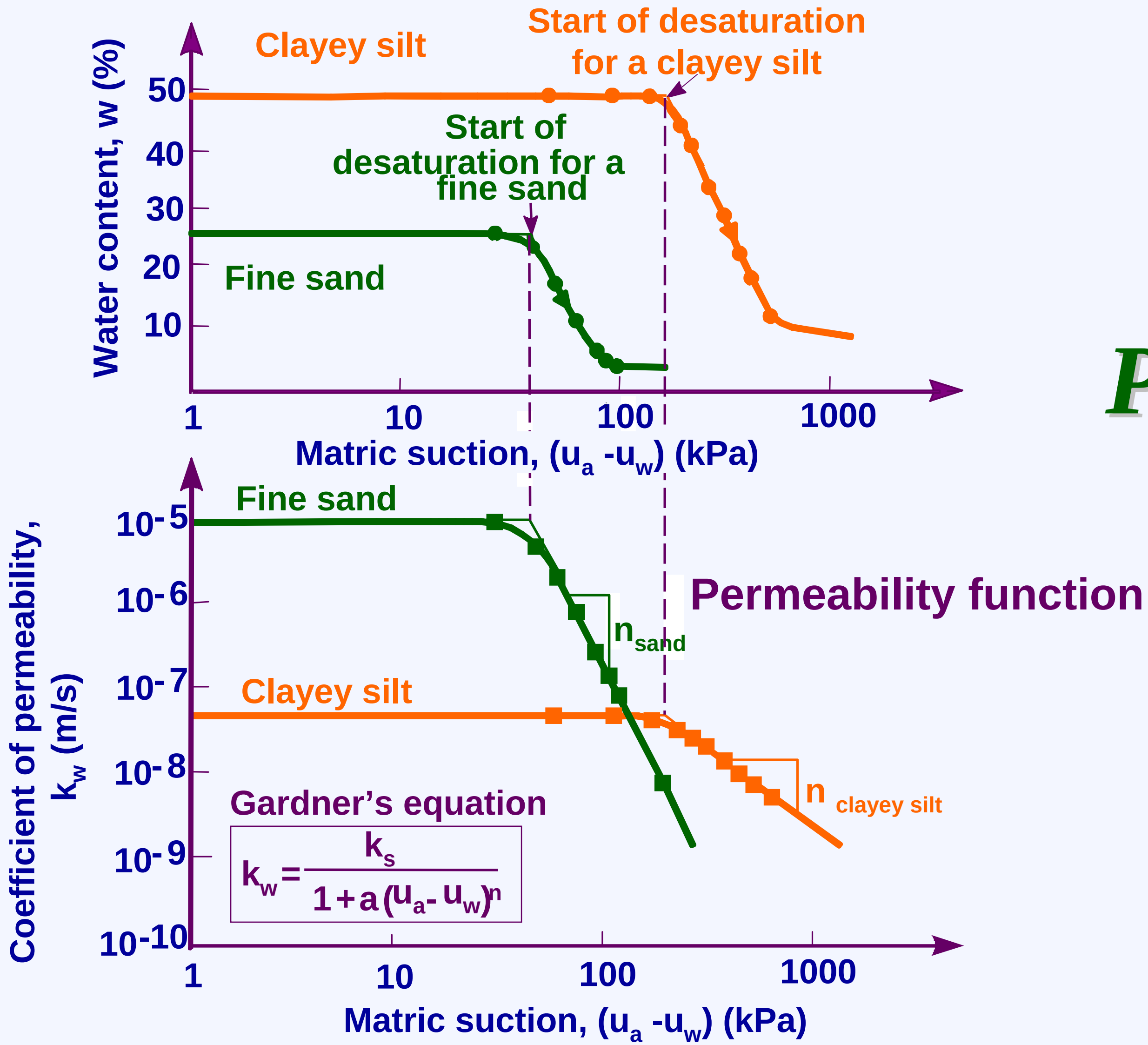


Pressure Plate Apparatus

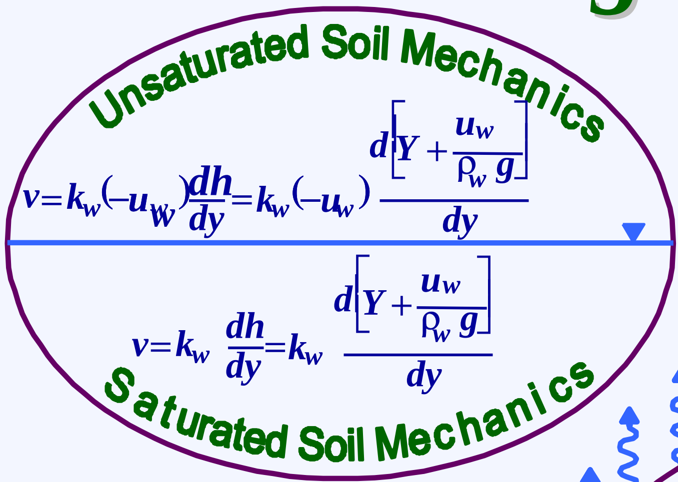


Relationship between Soil-Water Characteristic Curve and the Permeability for a Fine Sand and a Clayey Silt

Typical Gardner Empirical Permeability Functions for a Fine Sand and a Clayey Silt



Steps Involved Implementing an Engineered Solution



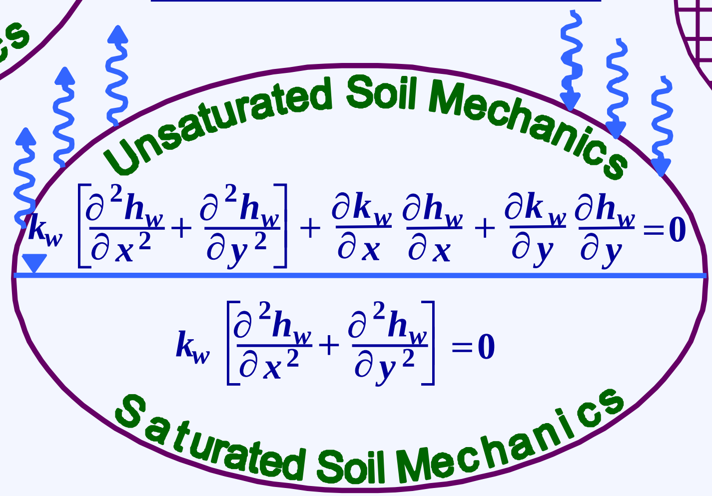
$$v = k_w(-u_w)\frac{dh}{dy} = k_w(-u_w)\frac{d\left[Y + \frac{u_w}{\rho_w g}\right]}{dy}$$

$$v = k_w \frac{dh}{dy} = k_w \frac{d\left[Y + \frac{u_w}{\rho_w g}\right]}{dy}$$

Seepage flow laws

Constitutive

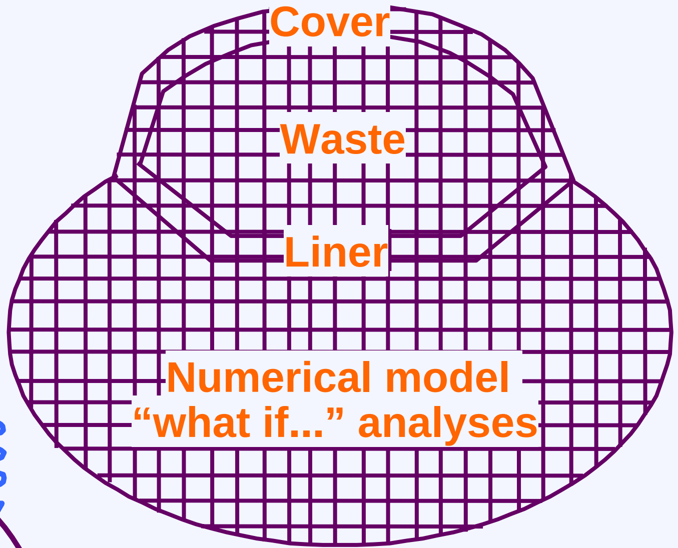
Formulation



$$k_w\left[\frac{\partial^2 h_w}{\partial x^2} + \frac{\partial^2 h_w}{\partial y^2}\right] + \frac{\partial k_w}{\partial x}\frac{\partial h_w}{\partial x} + \frac{\partial k_w}{\partial y}\frac{\partial h_w}{\partial y} = 0$$

$$k_w\left[\frac{\partial^2 h_w}{\partial x^2} + \frac{\partial^2 h_w}{\partial y^2}\right] = 0$$

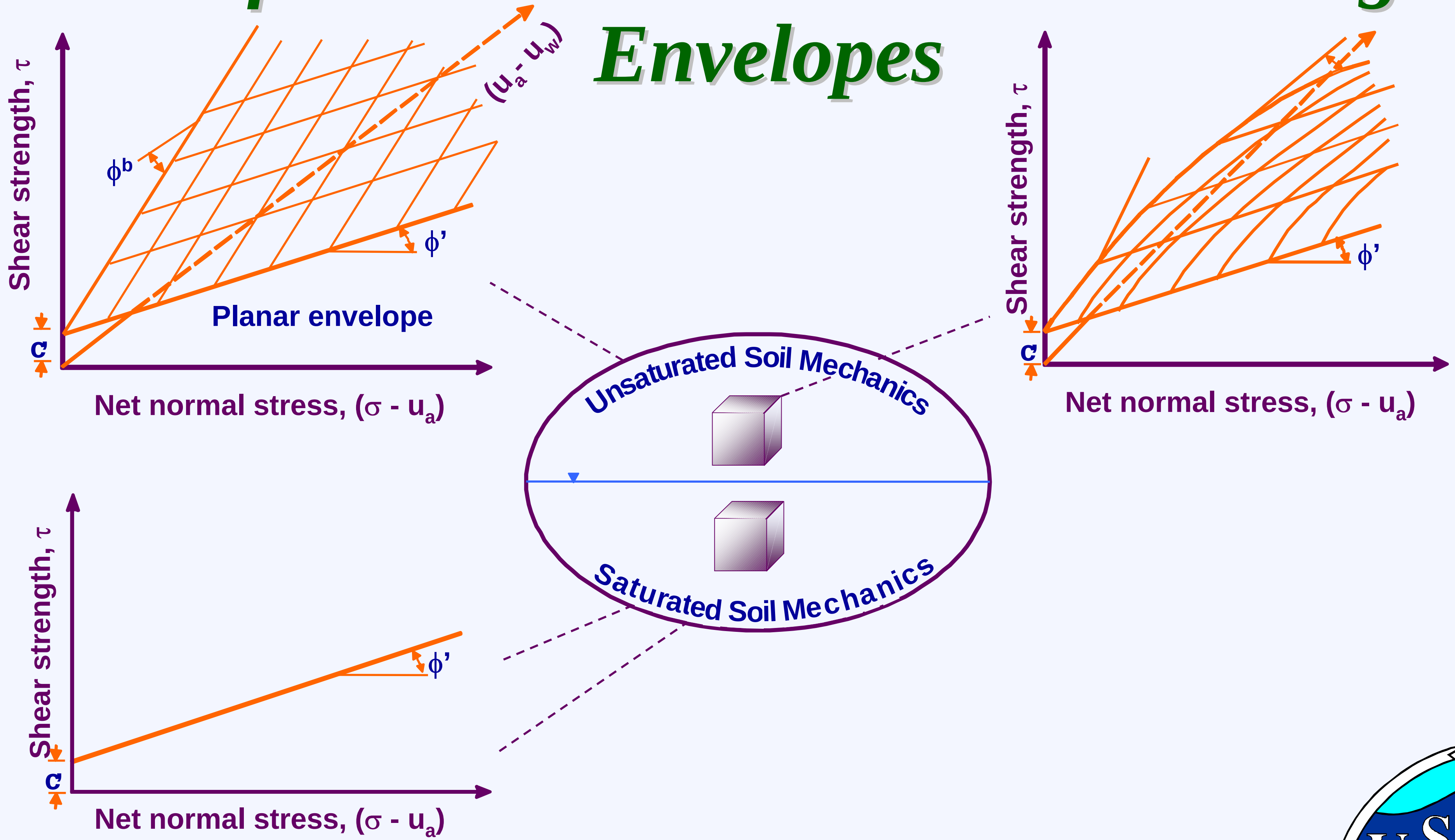
Boundary conditions and formulation



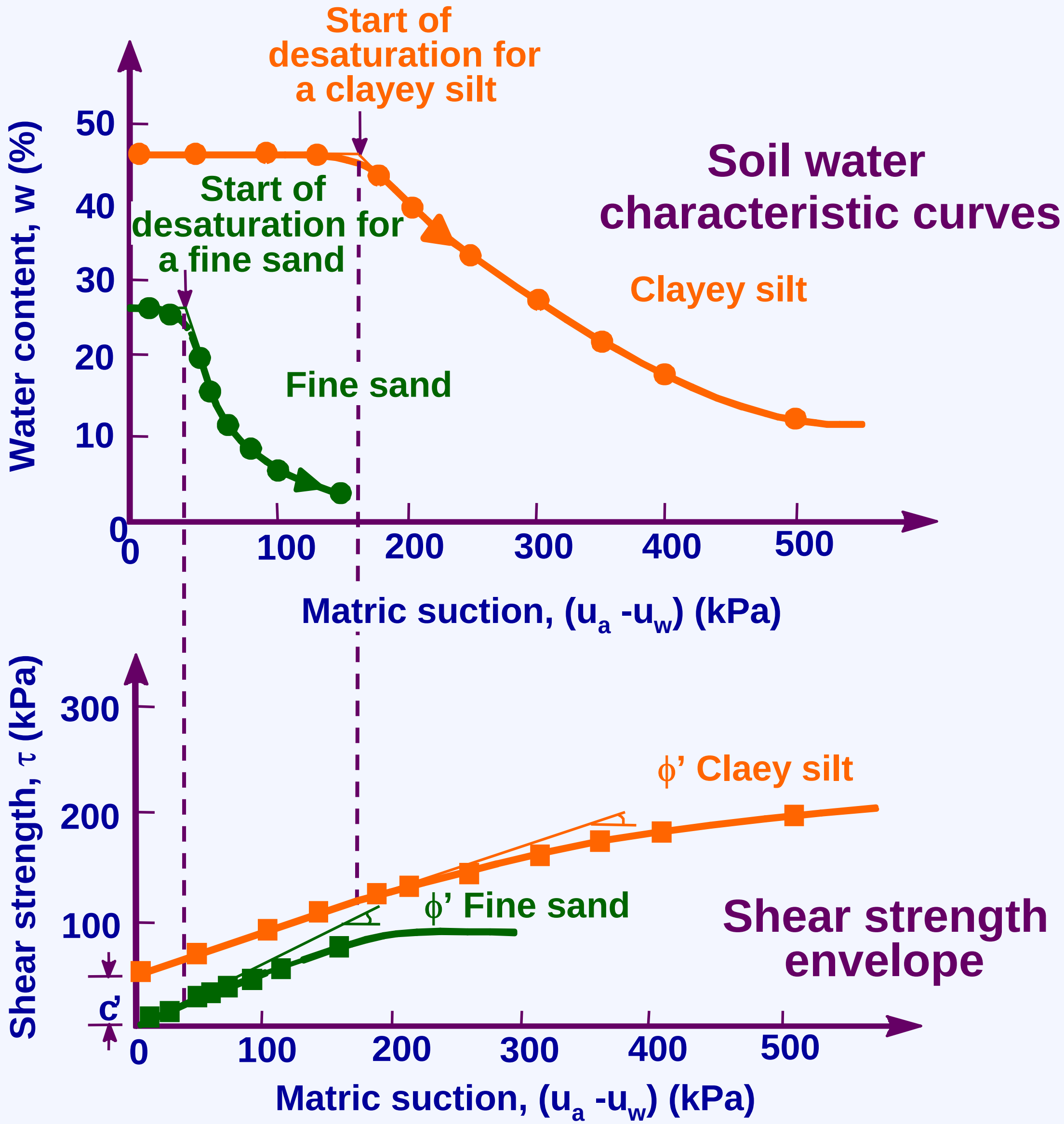
Engineered solution to ‘real’ problem

Solution

Modified Mohr-Coulomb Shear Strength Envelopes

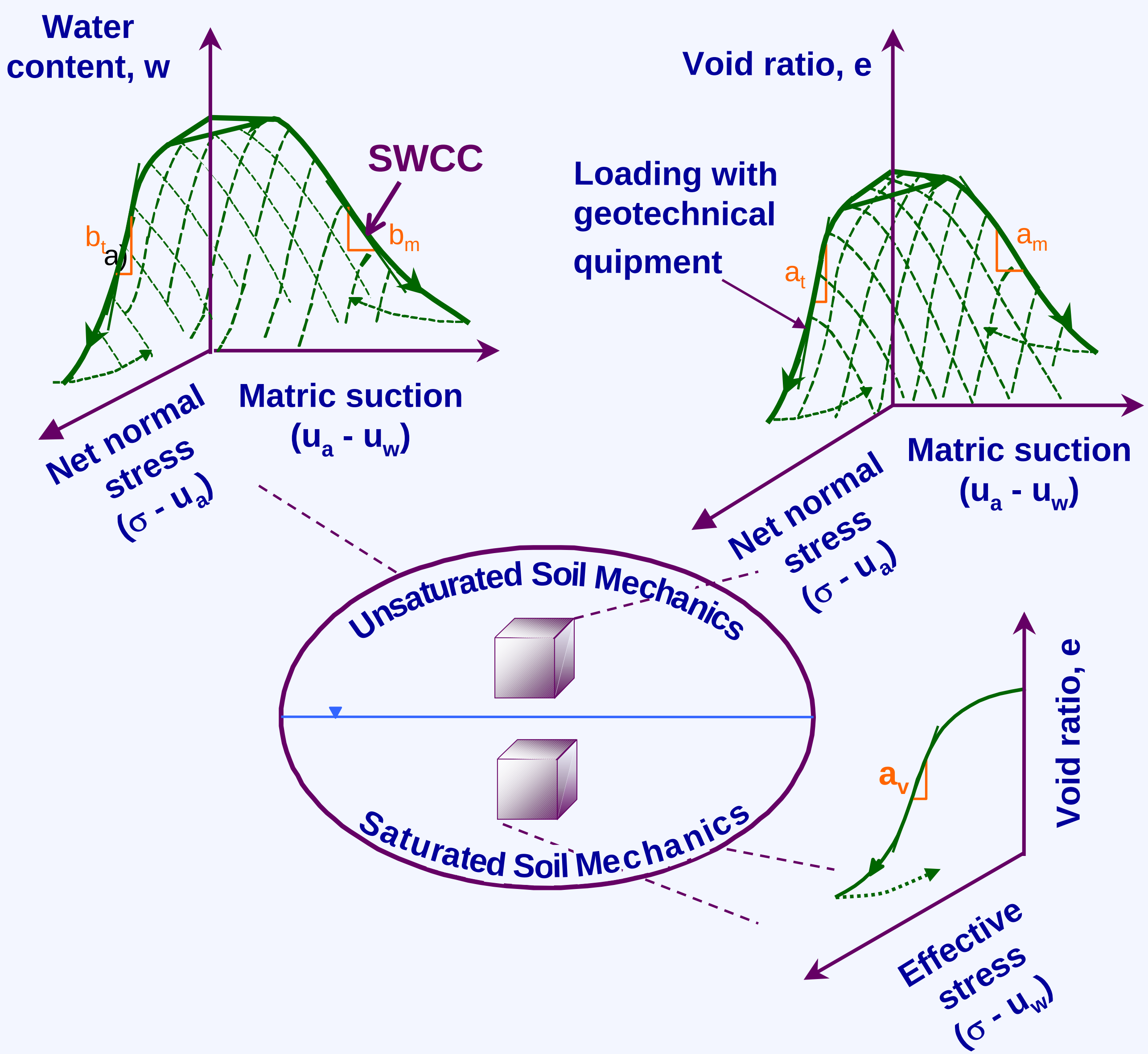


Relationship between SWCC and Shear Strength for a Fine Sand and a Clayey Silt



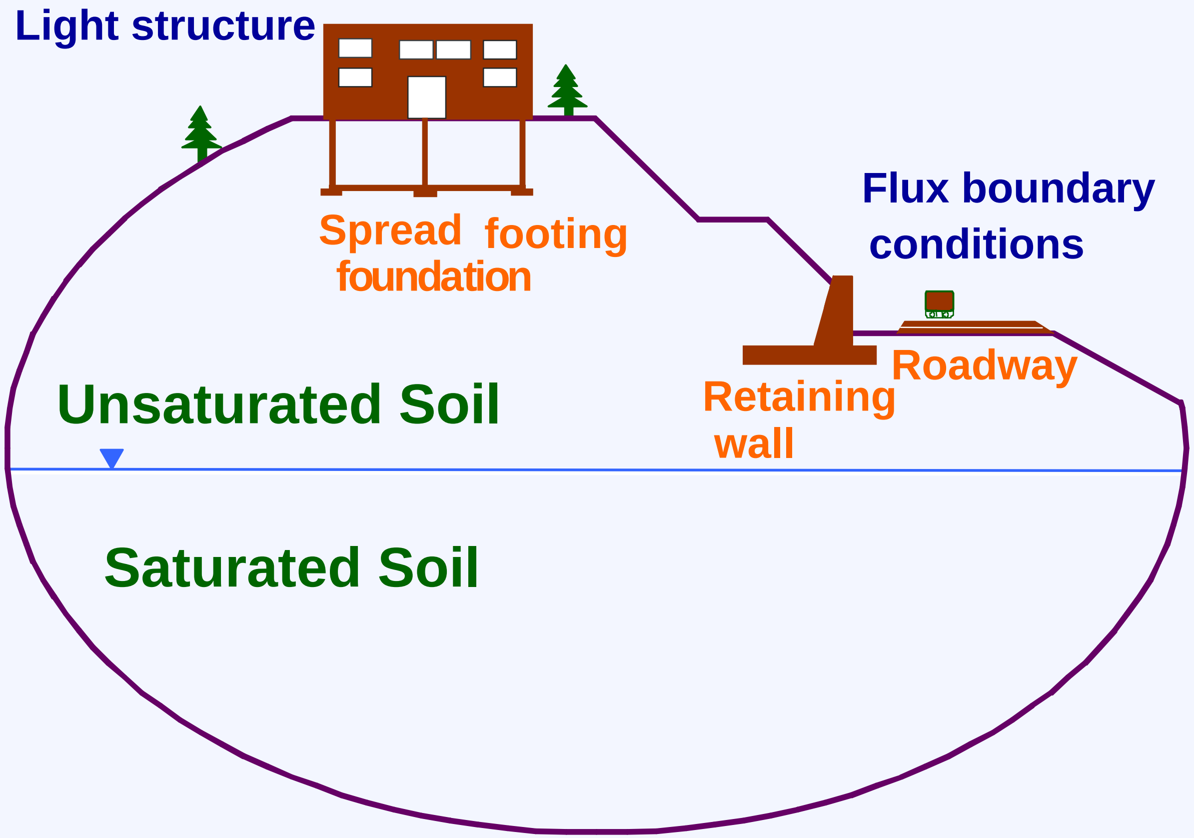
Volume-Mass Changes for an Unsaturated Soil

- Two three-dimensional plots are required to visualize volume-mass behavior
- Volume-mass change problems involving unsaturated soils are difficult to solve



Void Ratio and Water Content Constitutive Surfaces

Examples of Engineered Structures Commonly Placed above the Water Table

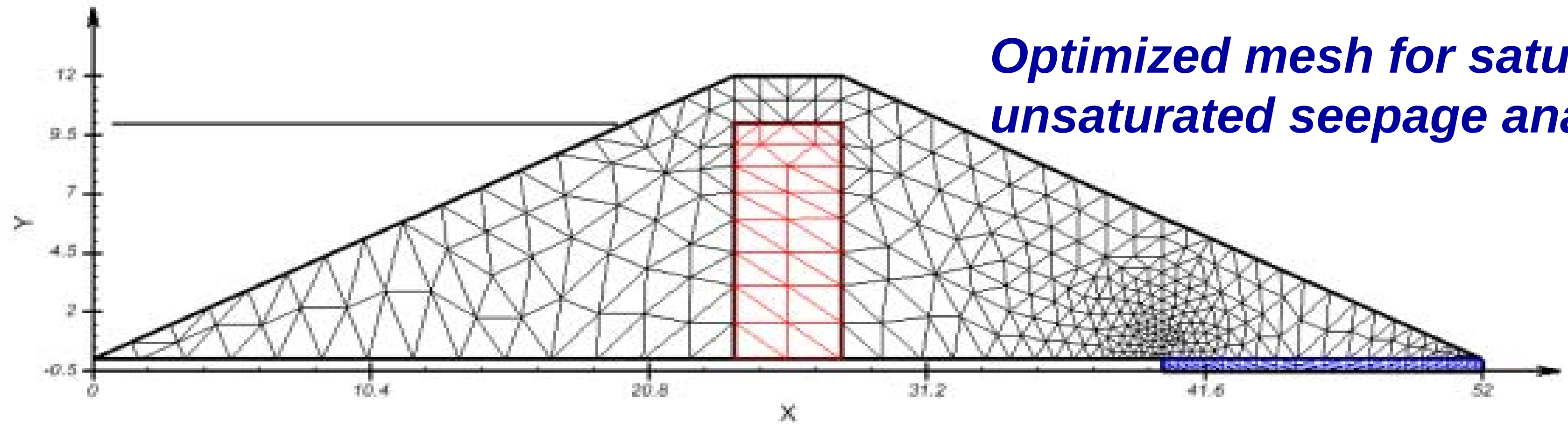


Examples of Seepage Problems Involving Unsaturated Soils

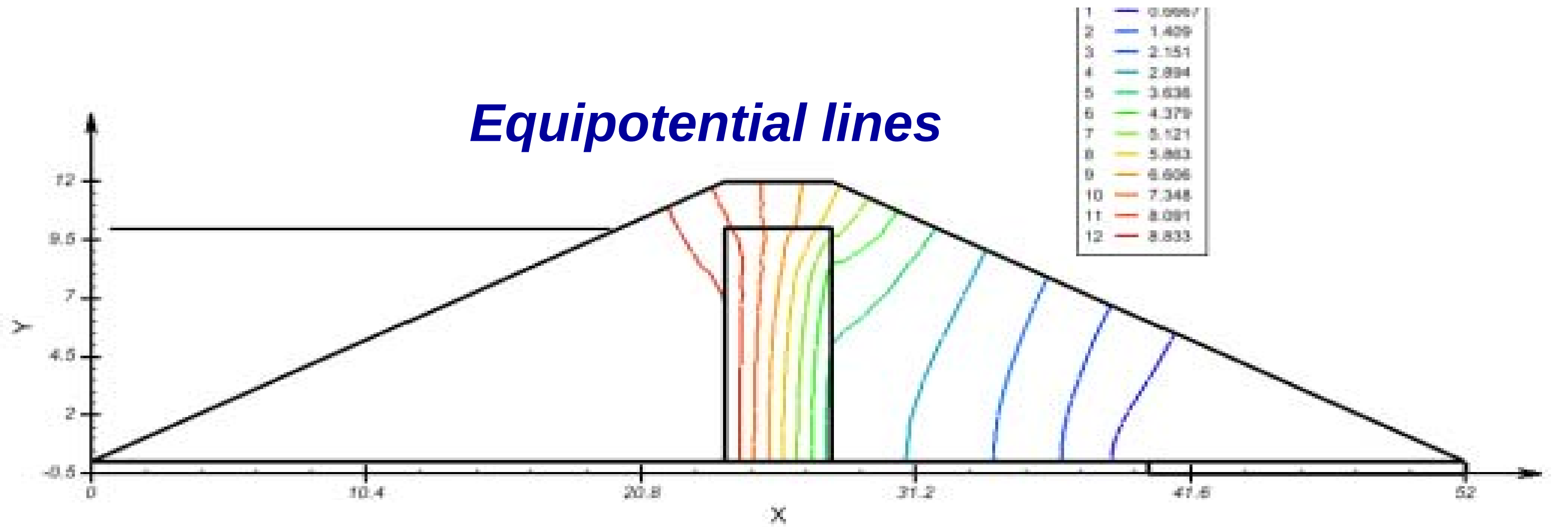
- Structures can suffer distressed from infiltration of water into an expansive or collapsible soil
- Moisture flux at ground surface influences the movement of contaminants
- Covers designs involve an analysis of the transmission and storage of water
- Extended infiltration on the surface of an earth dam may cause the instability
- Predictions related to "Closure" of mining operation are controlled by the surface flux

Two-dimensional seepage analysis through an earthfill dam with a clay core.

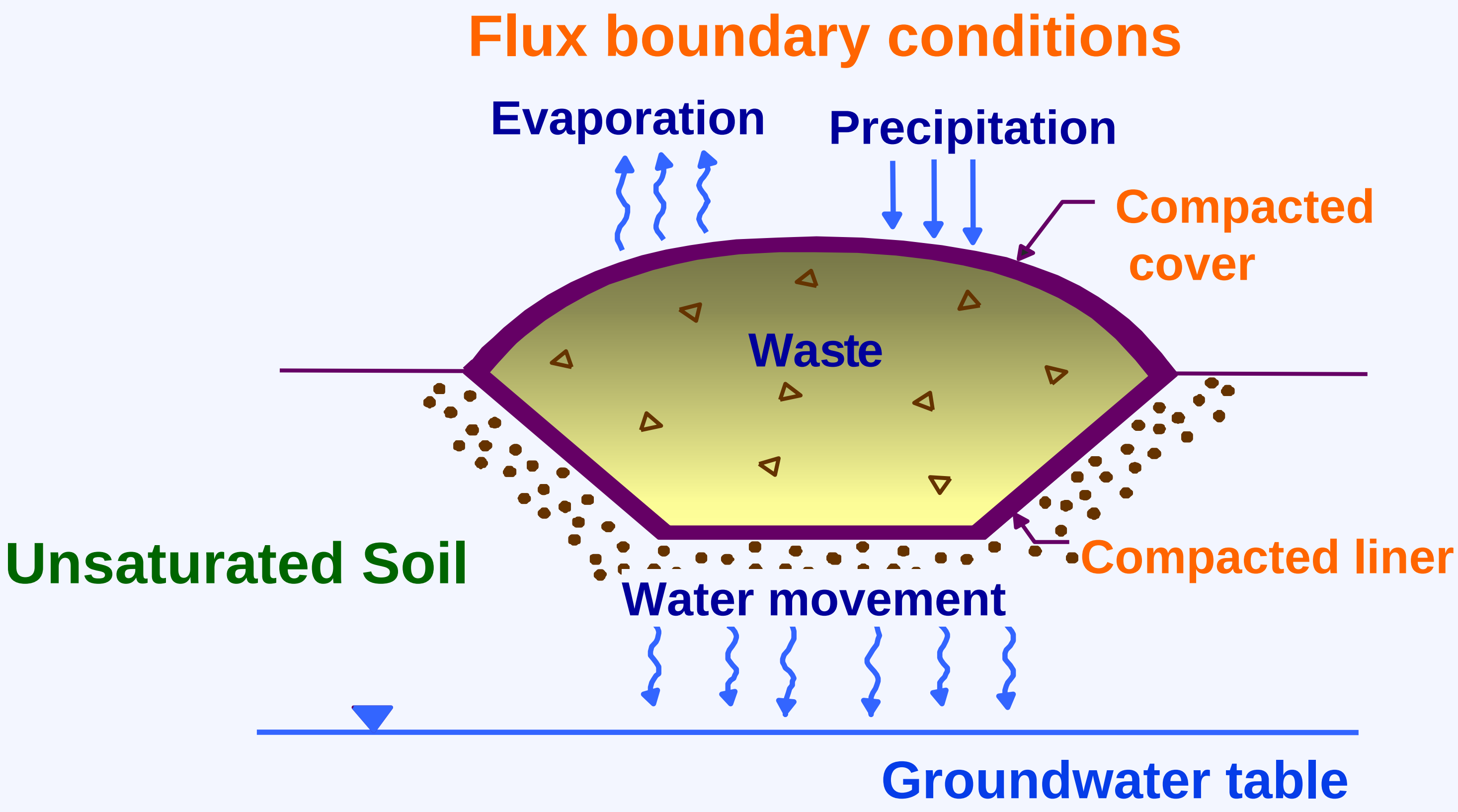
Optimized mesh for saturated-unsaturated seepage analysis



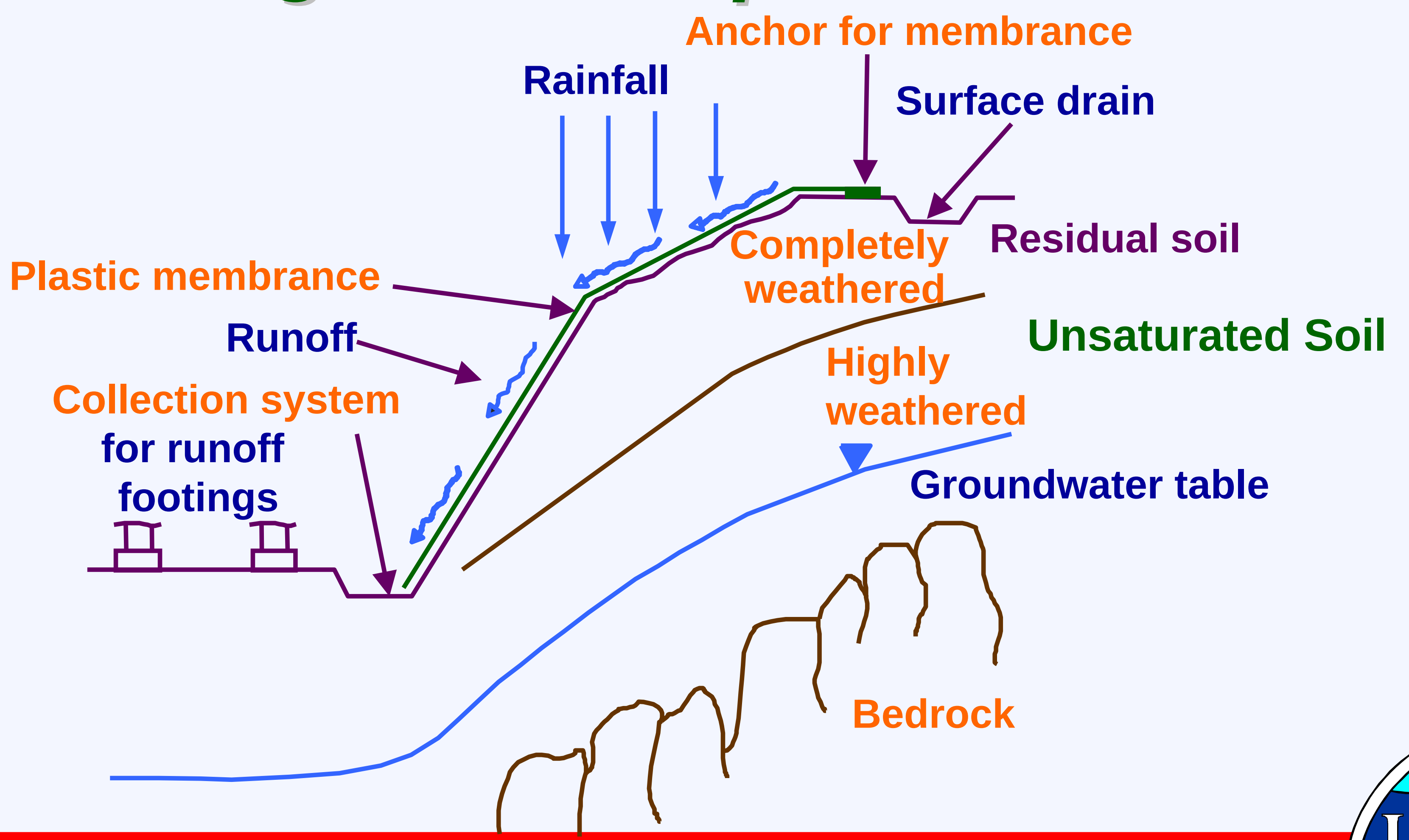
Equipotential lines



Examples of the Movement of Water through a Cover and Flow in the Unsaturated Zone below a Liner



Examples of the Control of Infiltration through the use of Geomembrances



Examples of Shear Strength Problems

- *Natural slopes often fail following extended levels of precipitation.*
- *Loosely compacted fills can collapse and result in high velocity mass movement upon wetting*
- *Cuts or trenches for laying pipelines can collapse*
- *Some backfill materials used behind earth retaining structures can change volume and shear strength due to the intake of water*
- *Bearing capacity of shallow footings may change significantly due to infiltration*

Examples of Volume Change Problems

- *Footings and slabs-on-ground should be simulated using realistic moisture flux conditions*
- *Shrinkage problems can occur due to drying or vegetation*
- *Collapse of the soil structure can occur as a result of a decrease in suction*
- *Predictions of the depth of cracking*
- *Volume change predictions of compacted fills and covers needs to be analyzed*

Concluding Remarks

- Undergraduate engineering students can be taught the concepts of unsaturated soil mechanics at the undergraduate level
- Once the concepts are taught, and saturated soil systems can be shown to be a special case, much of the remaining time can be spent on solving saturated soil mechanics problems

USG
Unsaturated Soils Group

Thank You

Delwyn G. Fredlund

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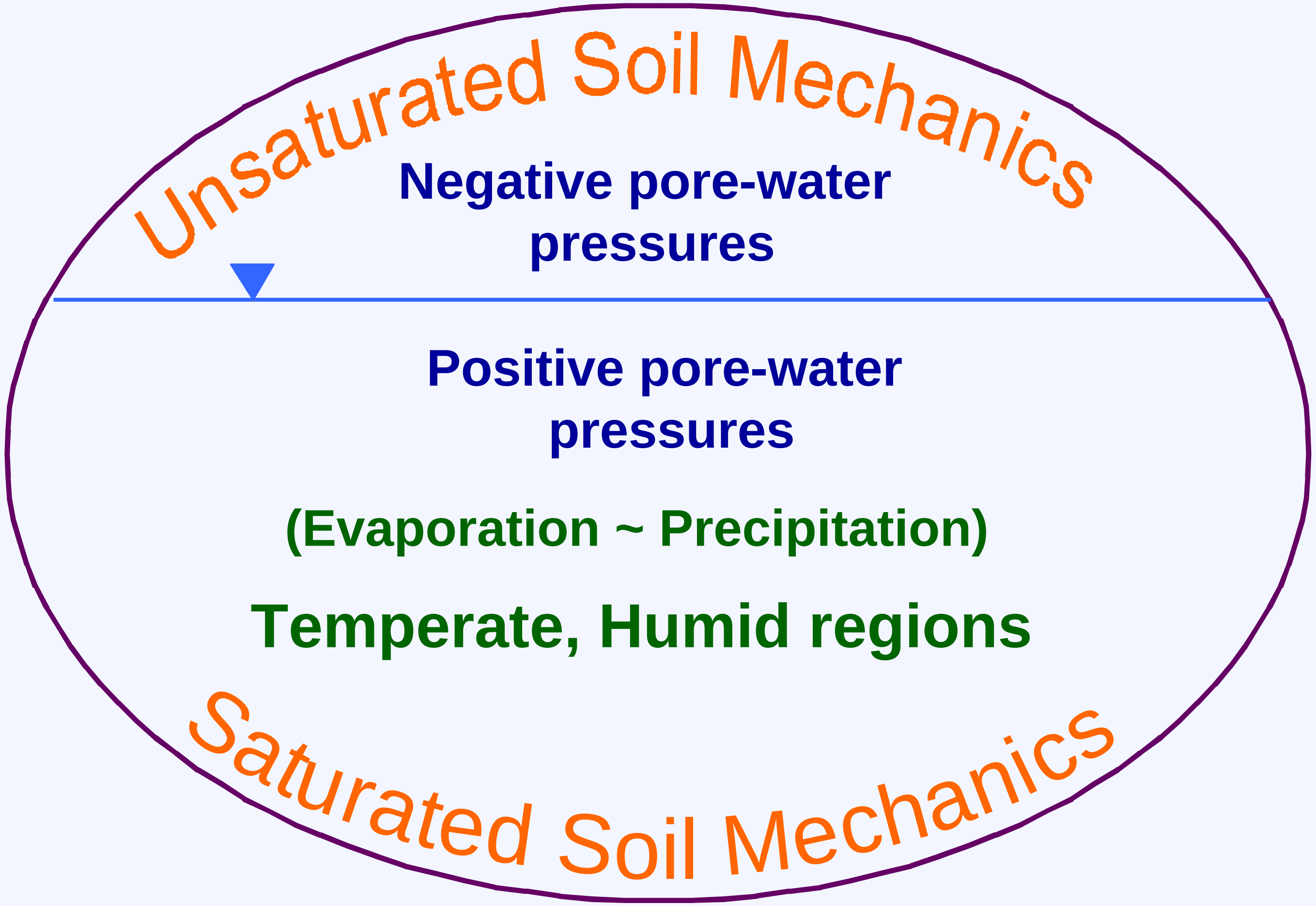
Observations from the Elliptical Geotechnical World

- *Unsaturated Soils Mechanics:*
  - *applies above the phreatic line*
  - *soil has negative pore-water pressures*
  - *pore-air pressure may or may not be atmospheric*
  - *stress state variables are:*
    - » *net normal stress,* $(s - u_a)$
    - » *matric suction* $(u_a - u_w)$
- *Saturated Soils Mechanics:*
  - *applies below the phreatic line*
  - *soil has positive pore-water pressures*
  - *stress state variable is effective stress,* $(s - u_w)$

The Need to Quantify "Real-World" Moisture Flux Boundary Condition

- *Changes in matric suction causes serious distress to the light engineered structures*
- *Climate influences the location of the groundwater table and pore-water pressures*
- *Climate "Drives" many geotechnical engineering problems*

Long Term Response of the Water Table to a Temperate, Humid Climate



Teaching within the New Paradigm

- *A new attitude and mindset must be adopted by the geotechnical engineer when considering unsaturated soil behavior. The estimation of unsaturated soil property functions is done largely with the assistance of SWCCs.*

- *It can be said that geotechnical engineering for unsaturated soils must operate in a new paradigm of estimations and approximations*

- *The new protocols do not nullify the importance of modeling unsaturated soils; rather, these estimations add a new and improved understanding of the behavior of saturated-unsaturated soil systems.*

Zones of Unsaturation

- There are three zones of unsaturation:
  - occluded air bubbles in the capillary zone
  - the zone where both air and water phases are continuous
  - the zone where the water phase become discontinuous
- There can be continuity or discontinuity of the air and water phases under various levels of soil suction and this makes unsaturated soil mechanics complex

Relationship of Seepage to the SWCC

- Coefficient of permeability (or hydraulic conductivity) of the soil is:
  - constant throughout the capillary zone
  - decreases with increase in soil suction
  - decreases logarithmically between the air entry value and the residual condition
  - various over several orders of magnitude
- Hydraulic flow continues until the residual suction is reached
- Water flows only where there is water in the soil!

Relationship of Coefficient of Permeability and the SWCC

- Coefficient of permeability responds logarithmically to an arithmetic change in water content
- Air Entry Value and Residual Conditions become the most important parts of a SWCC
- It is possible for a sand to have a lower coefficient of permeability than a clay

Shear Strength of an Unsaturated Soil

- Shear strength envelope is three-dimensional
- Shear strength is linear over a limited soil suction range
- Shear strength becomes nonlinear over a wide range of soil suctions
- Shear strength increases in accordance with the effective angle of internal friction below the air entry value of the soil
- Shear strength remains constant after residual condition

Illustration of the Potential for Swelling Versus Depth and Soil Suction

Swelling = *f* (suction change, overburden)