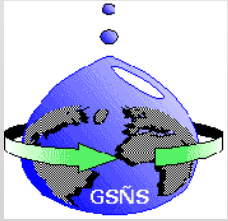
Unsaturated Soil Mechanics
Lesson 1

Prof. Fernando A. M. Marinho

Universidade de São Paulo

2020



sns.org.br

Unsaturated Soil Mechanics

- **Basic Concepts**
  - **Effective stress principle**
  - **Mohr-Coulomb and Tresca failure criteria**
- **Meteorological aspects and soil water balance**
  - **Rain and evaporation**
  - **Infiltration**
  - **Retention**
- **Soil as a particulate media**
  - **Mass and volume relations**
  - **Pore size distribution**
- **Capillary and suction concepts**
  - **Matrix suction**
  - **Osmotic suction**
  - **Total suction**
- **Soil suction measurement**
- **The Soil Water Retention Curve - SWRC**
  - **Interpretation of the SWRC**
  - **Fitting models for the SWRC**
- **Shear strength for unsaturated soils**
  - **Shear strength parameters**
    - **Laboratory tests**
  - **Bishop´s concepts**
  - **Fredlund´s concepts**
  - **Models using the SWRC**
- **Applications**

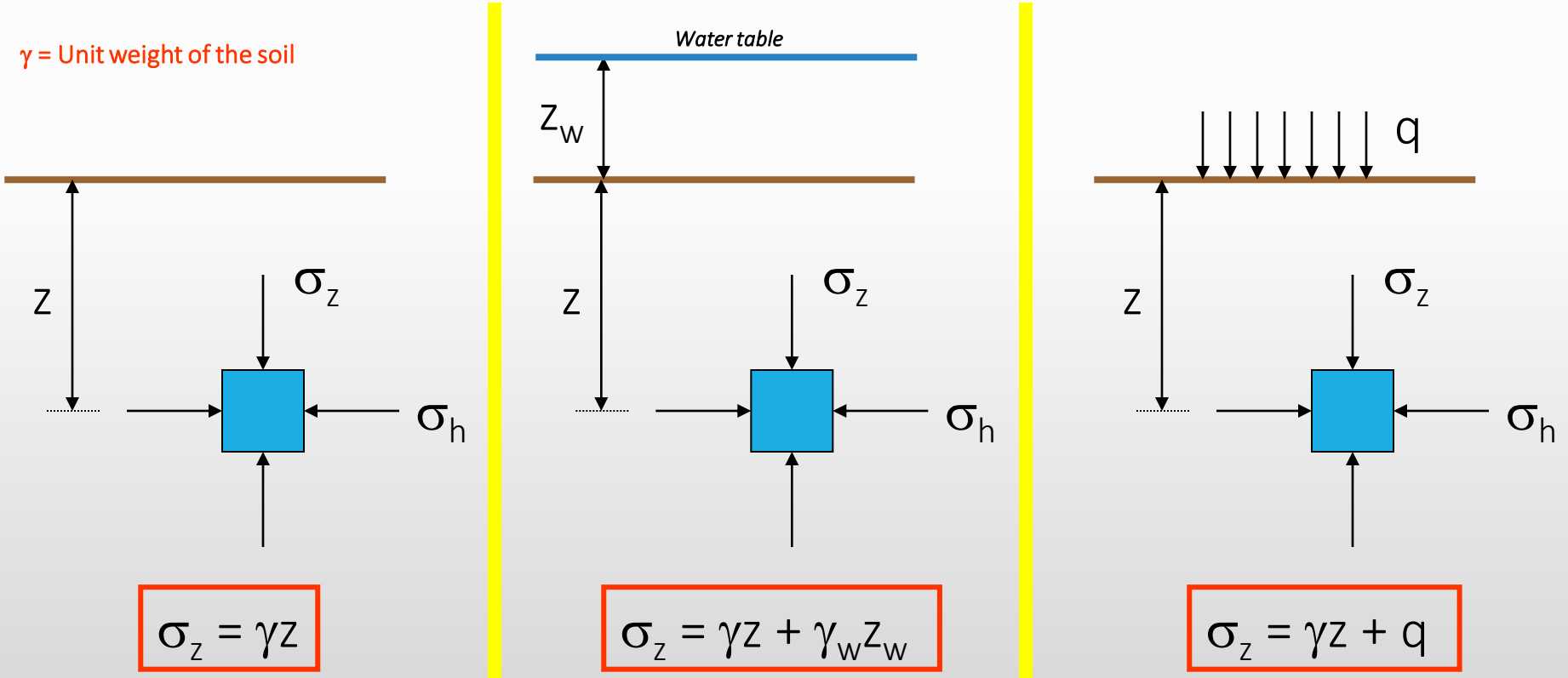
Unsaturated Soil Mechanics
Lesson 1

- **Basic Concepts**
  - **Effective stress principle**
  - **Mohr-Coulomb and Tresca failure criteria**
- **Meteorological aspects and soil water balance**
  - **Rain and evaporation**
  - **Infiltration**
  - **Retention**

- **Basic Concepts**
  - **Effective stress principle**
  - **Mohr-Coulomb and Tresca failure criteria**

Stresses in Soil

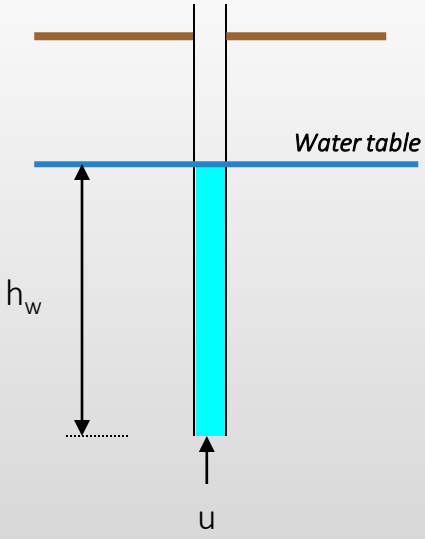
- The vertical stress at a certain depth is due to the weight of everything that is above that depth.
- What is that? Soil grain, water, any structure, etc.
- In this way, stress increase with depth.



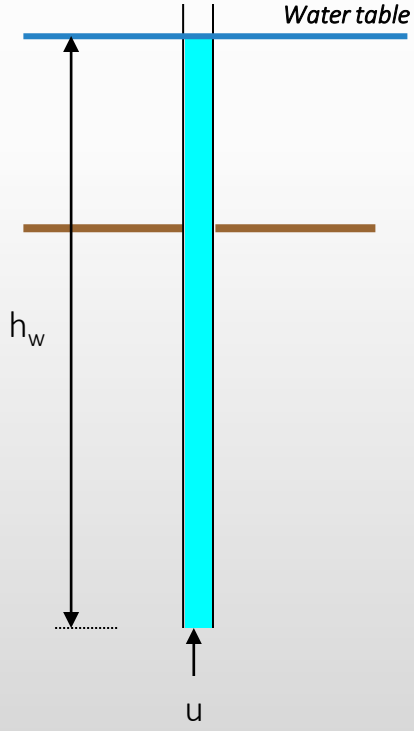
Stresses in Soil

Water in the soil and the water pressure

- The water within the pores of a soil has a pressure called pore-water pressure (u).



$$u = \gamma_w h_w$$



Stresses in Soil

Effective Stress

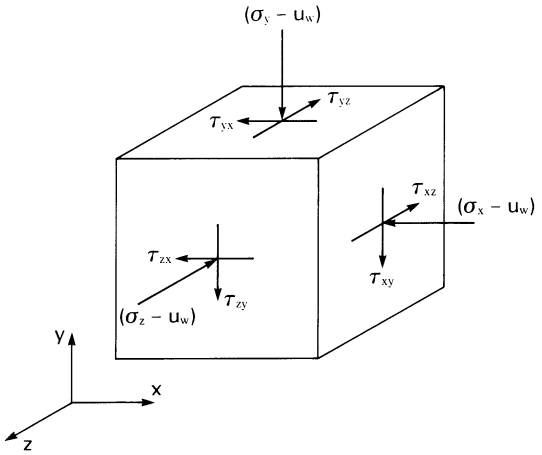
- The effective stress principle was established by Terzaghi in 1923.

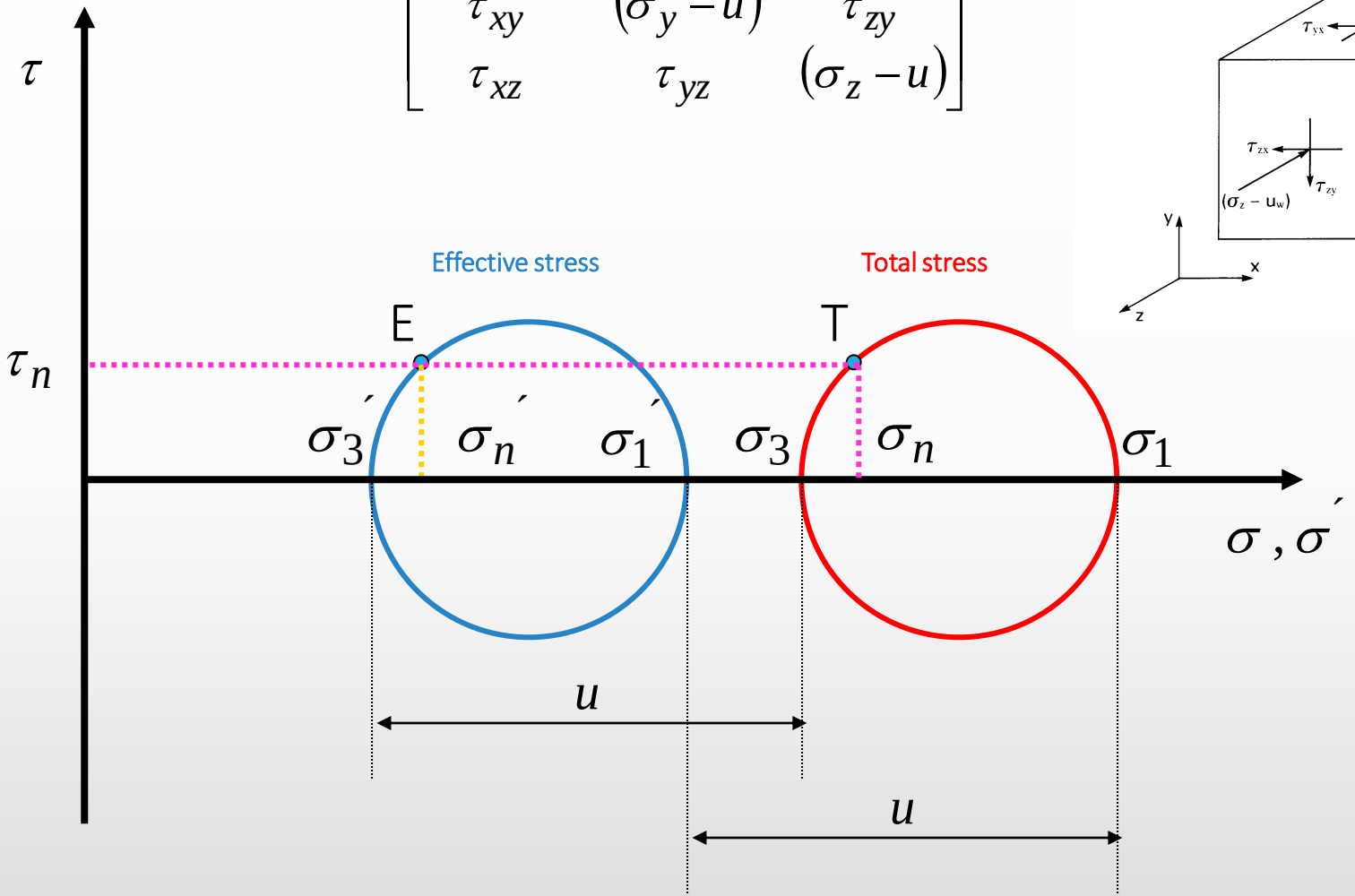
$$\sigma' = \sigma - u$$

Stress tensor for a saturated soil

$$\begin{bmatrix} (\sigma_x - u) & \tau_{yx} & \tau_{zx} \\ \tau_{xy} & (\sigma_y - u) & \tau_{zy} \\ \tau_{xz} & \tau_{yz} & (\sigma_z - u) \end{bmatrix}$$

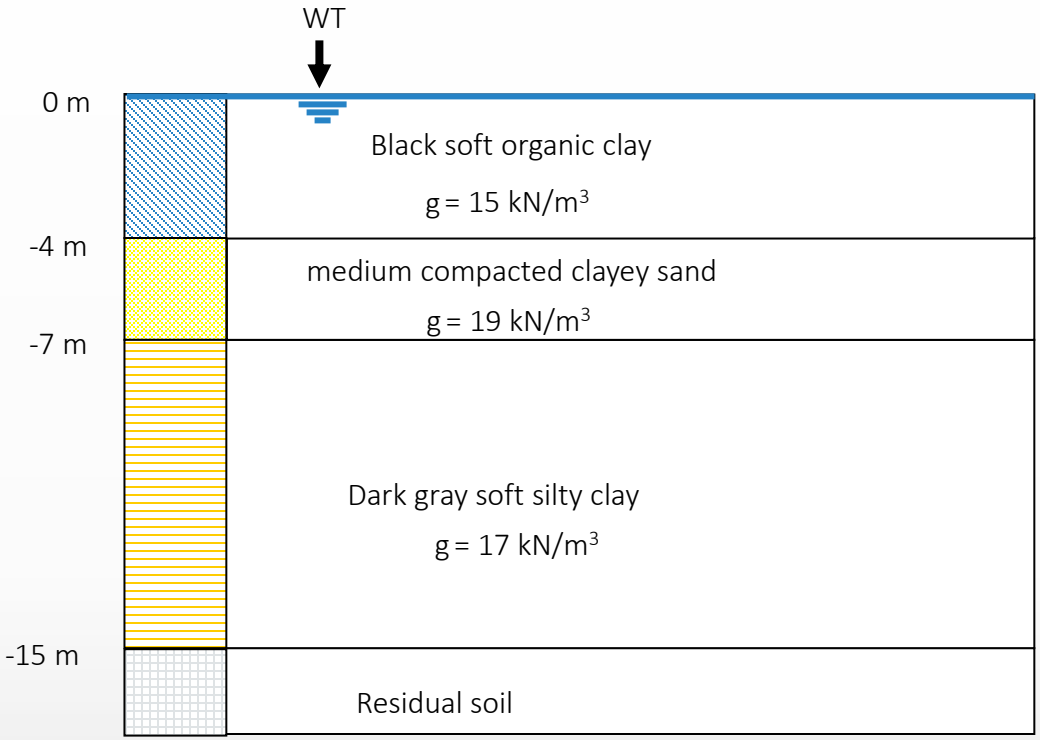
Effective stress principle



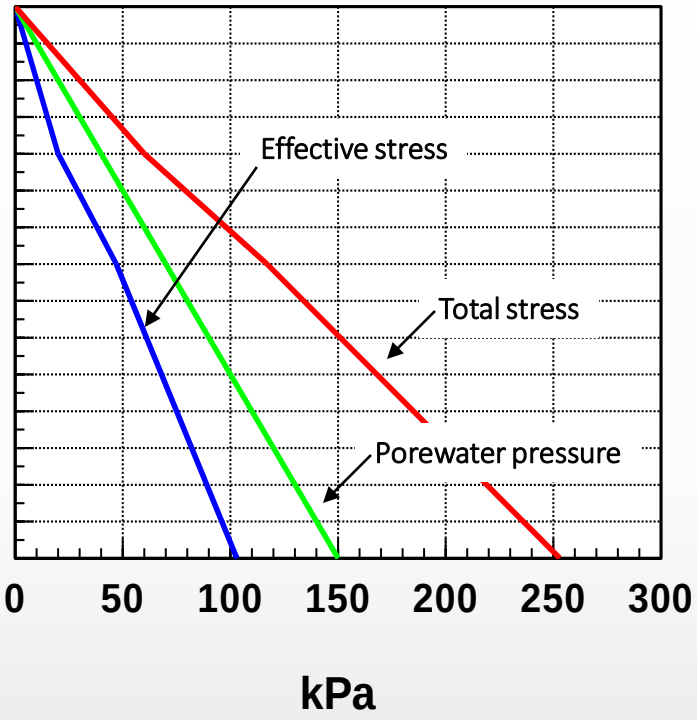


$$\sigma' = \sigma - u$$

Stresses in Soil



Stress diagram



Exemple at level –7m

$$\sigma = 15*4+19*3 = 117kPa$$

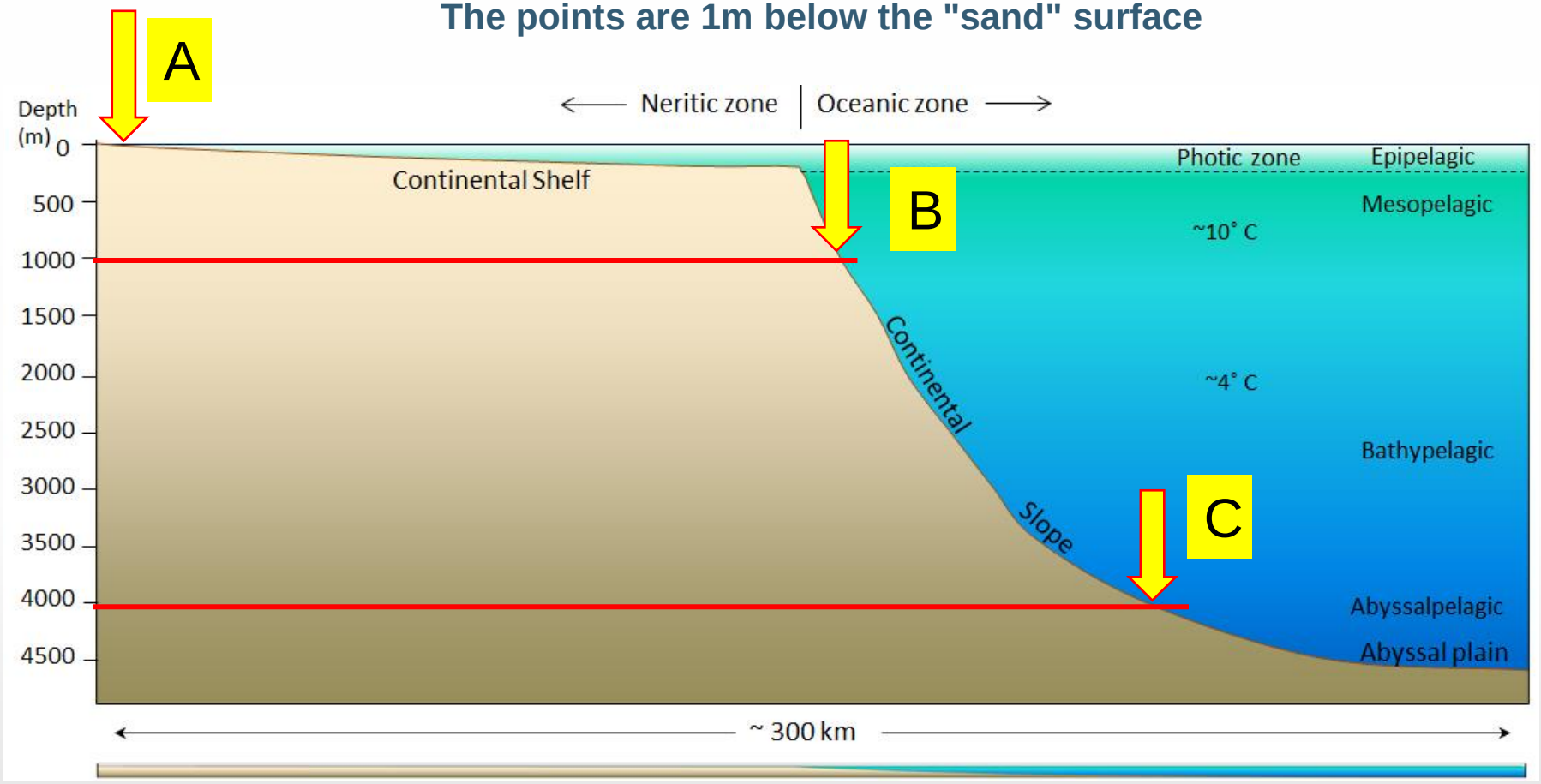
$$u = 10*7 = 70kPa$$

$$\sigma' = \sigma - u = 47kPa$$

Effective Stress

Which point has the highest effective stress?

The points are 1m below the "sand" surface



https://opentextbc.ca/geology/chapter/18-1-the-topography-of-the-sea-floor/

$\sigma = 20 * 1 + 10 * 1 = 30\ kPa$
$u = 10 * 2 = 20\ kPa$
$\sigma' = \sigma - u = 10\ kPa$

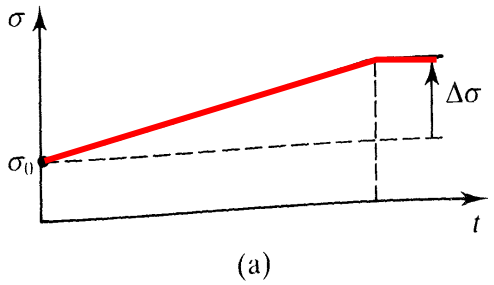
A

$\sigma = 20 * 1 + 10 * 1000 = 10020\ kPa$
$u = 10 * 1001 = 10010\ kPa$
$\sigma' = \sigma - u = 10\ kPa$

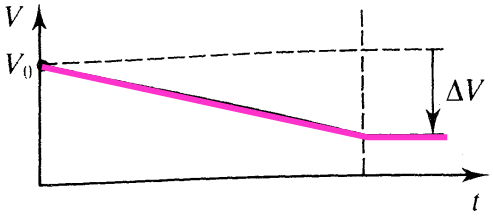
B

$\sigma = 20 * 1 + 10 * 4000 = 40020\ kPa$
$u = 10 * 4001 = 40010\ kPa$
$\sigma' = \sigma - u = 10\ kPa$

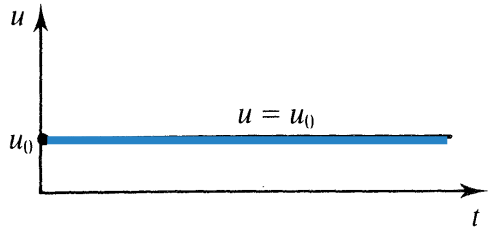
C



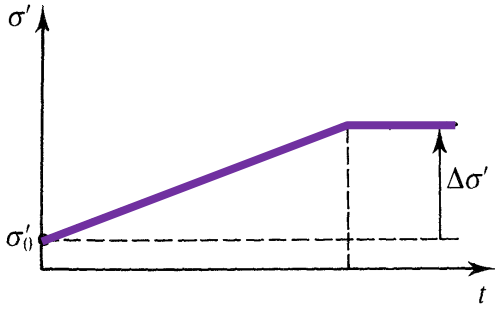
(a)



(b)



(c)



(d)

Atkinson (1993)

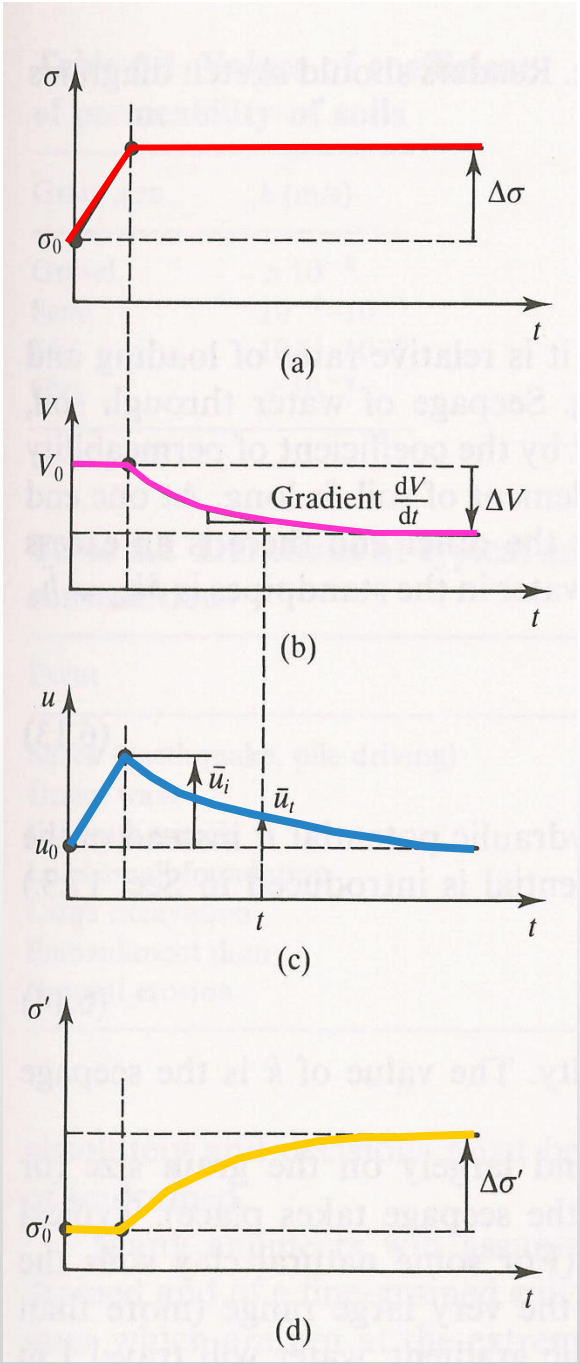
Loading – total stress

Volume change

Porewater pressure development

Effective stress change

Drained Behaviour



Atkinson (1993)

Loading – total stress

Volume change

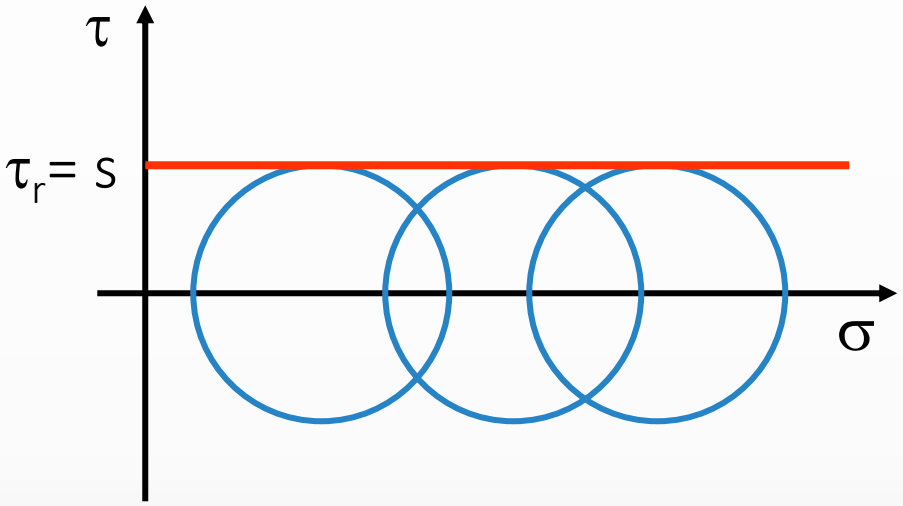
Porewater pressure development

Effective stress change

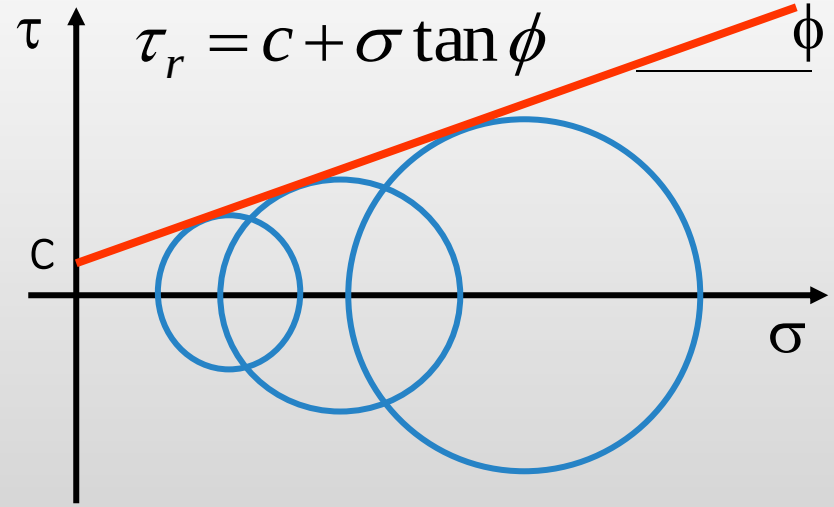
Undrained Behaviour

Mains failure criteria for soils:

- Tresca



- Mohr-Coulomb

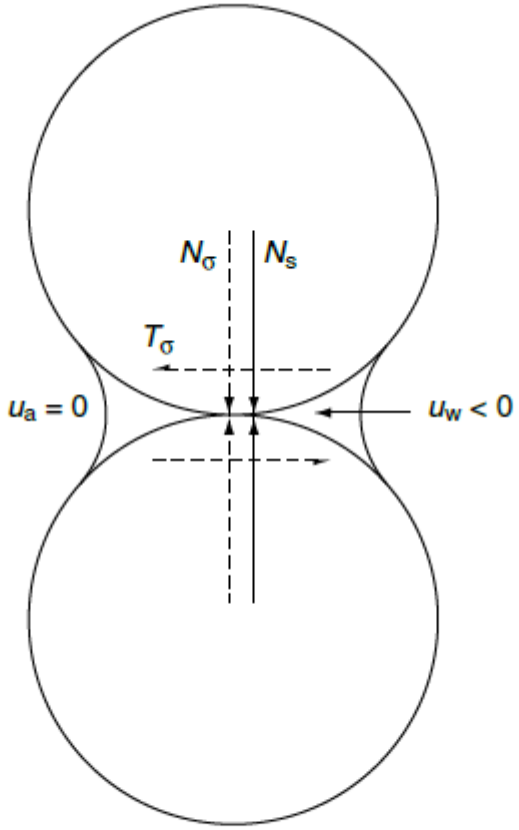


Although it is relatively easy to relate the shear strength of unsaturated soil to a single stress parameter involving σ, u_a and u_w the volumetric behaviour is not controlled by the same stress parameter or by any other single stress variable.

Table 1.2 Proposed effective stress equations for unsaturated soils (Fredlund, 1987)

$\sigma' = \sigma - u_a + \chi(u_a - u_w)$	χ = parameter related to degree of saturation u_a = the pressure in gas and vapour phase	Bishop (1959)
$\sigma' = \sigma - \beta' u_w$	β' = holding or bonding factor which is measure of number of bonds under tension effective in contributing to soil strength	Croney, Coleman and Black (1958)
$\sigma = \bar{\sigma} a_m + u_a a_a + u_w a_w + R - A$	a_a = fraction of total area that is air–air contact $\bar{\sigma}$ = mineral interparticle stress a_m = mineral particle contact area a_w = water phase contact area R = repulsive pore fluid stress due to chemistry A = attractive pore fluid stress due to chemistry	Lambe (1960)
$\sigma' = \sigma + \psi p''$	ψ = parameter with values ranging from zero to one p'' = pore-water pressure deficiency	Aitchison (1961)
$\sigma' = \sigma + \beta p''$	β = statistical factor of same type as contact area; should be measured experimentally in each case	Jennings (1960)
$\sigma' = \sigma - u_a + \chi_m(h_m + u_a) + \chi_s(h_s + u_a)$	χ_m = effective stress parameter for matric suction h_m = matric suction h_s = solute suction χ_s = effective stress parameter for solute suction	Richards (1966)

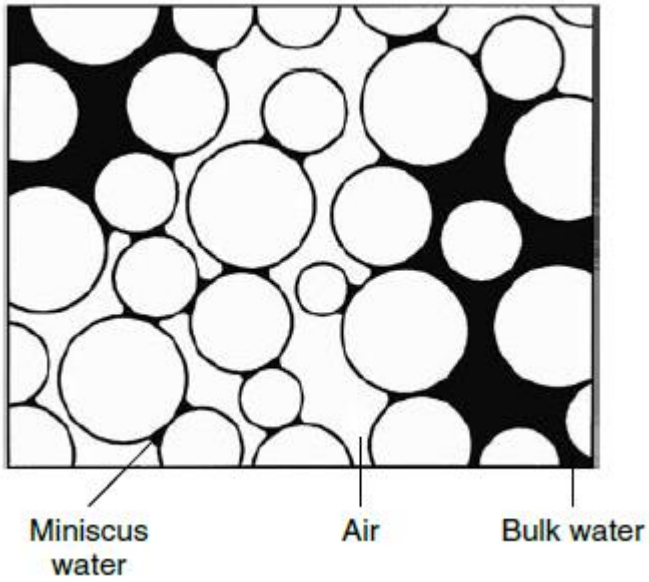
Influence of external stress and suction on inter-particle forces



N_σ = normal component of inter-granular force due to external stress
T_σ = tangential component of inter-granular force due to external stress
N_s = inter-granular force due to suction

Wheeler and Karube (1995)

Two forms of liquid water in an unsaturated soil



- Suction modifies the skeleton stresses both normal and tangential of an unsaturated soil through changing the average bulk pore fluid pressure inside its pores;
- Suction provides an additional normal bonding force (stabilising effects) at the particle contacts, attributed to capillary phenomena occurring in the water menisci or contractile skin.

Ng and Manzies (2007)

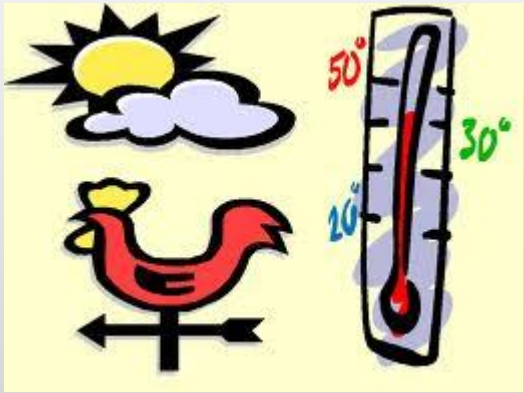
In 1977, Fredlund and Morgenstern suggested the use of any two of three possible stress variables, $\sigma - u_a$, $\sigma - u_w$ and $u_a - u_w$, to describe mechanical behaviour of unsaturated soils. The possible combinations are:

1. $\sigma - u_a$, and $u_a - u_w$,
2. $\sigma - u_w$ and $u_a - u_w$
3. $\sigma - u_a$ and $\sigma - u_w$

The most common choice is to use net stress $\sigma - u_a$ and matric suction $u_a - u_w$, as the two independent stress state variables.

Ng and Manzies (2007)

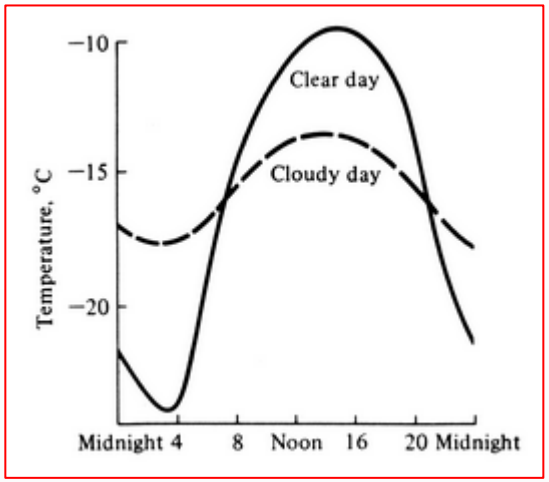
- **Meteorological aspects and soil water balance**
  - **Rain and evaporation**
  - **Infiltration**
  - **Retention**



What is the difference between weather and climate?

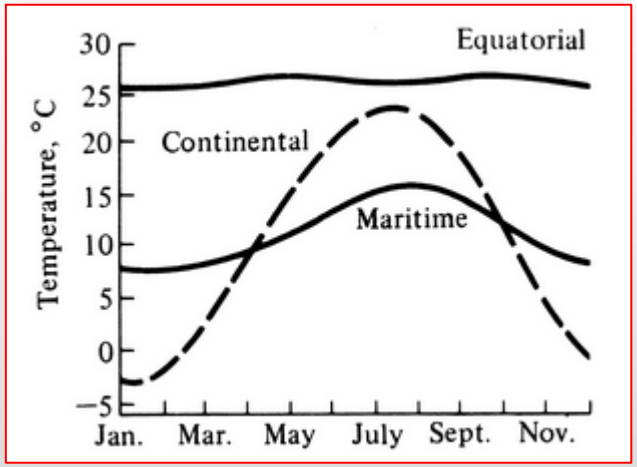
Weather

Is the day-to-day state of the atmosphere, and its short-term variation in minutes to weeks.



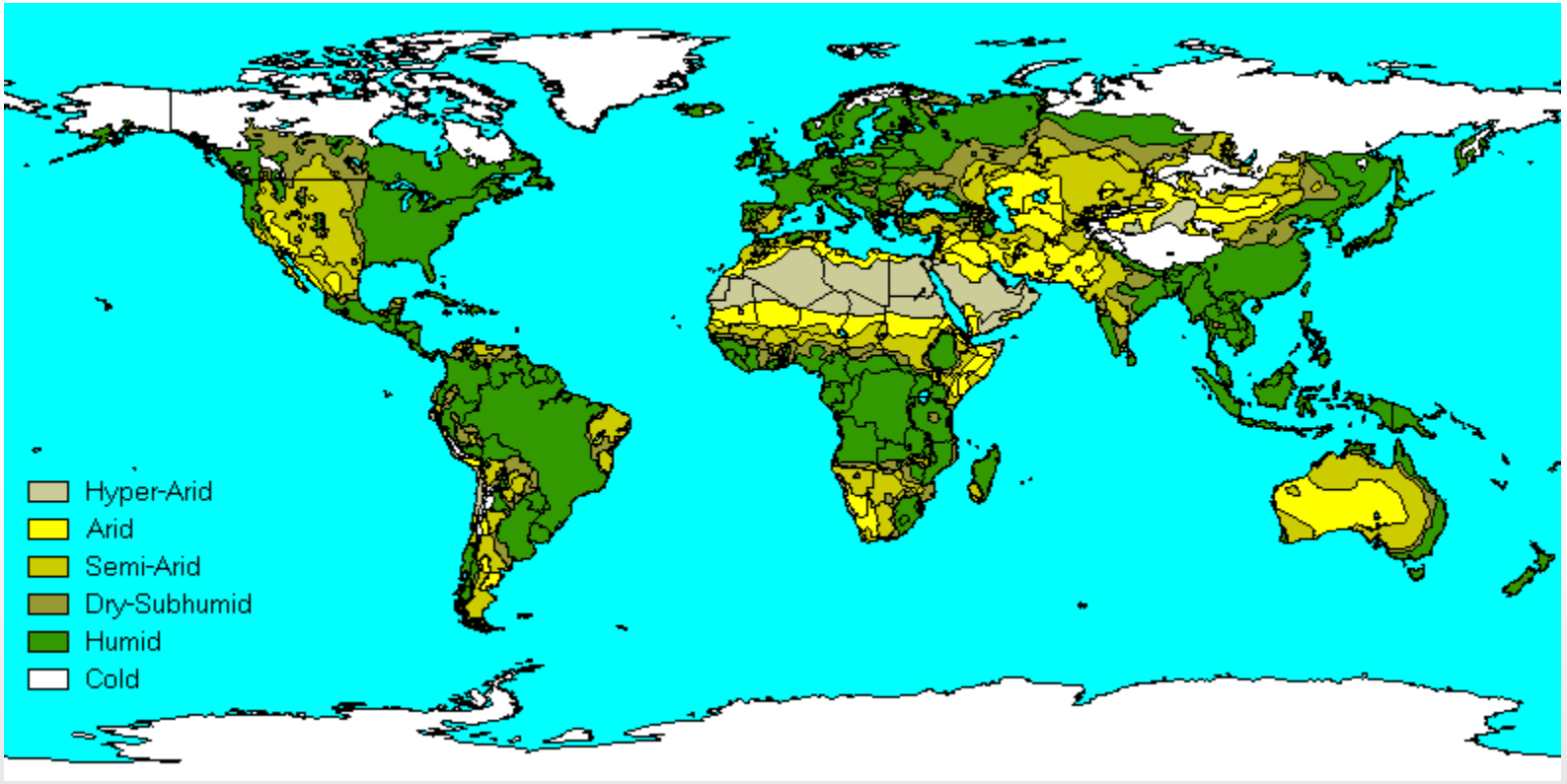
Climate

Is the weather of a place averaged over a period of time, often 30 years. Climate information includes the statistical weather information that tells us about the normal weather, as well as the range of weather extremes for a location.

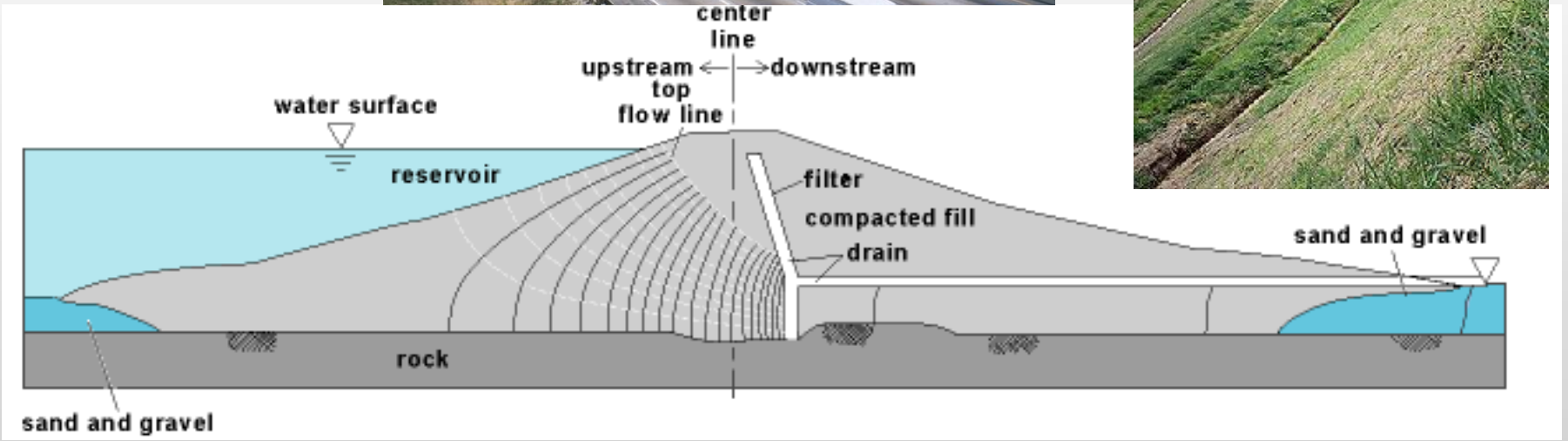


https://nsidc.org/cryosphere/arctic-meteorology/climate_vs_weather.html

Climates of the Earth



What is saturated and what is not?



The Unsaturated Region of the Soil

The region above the water level is commonly known as unsaturated zone, vadose zone or aeration zone.

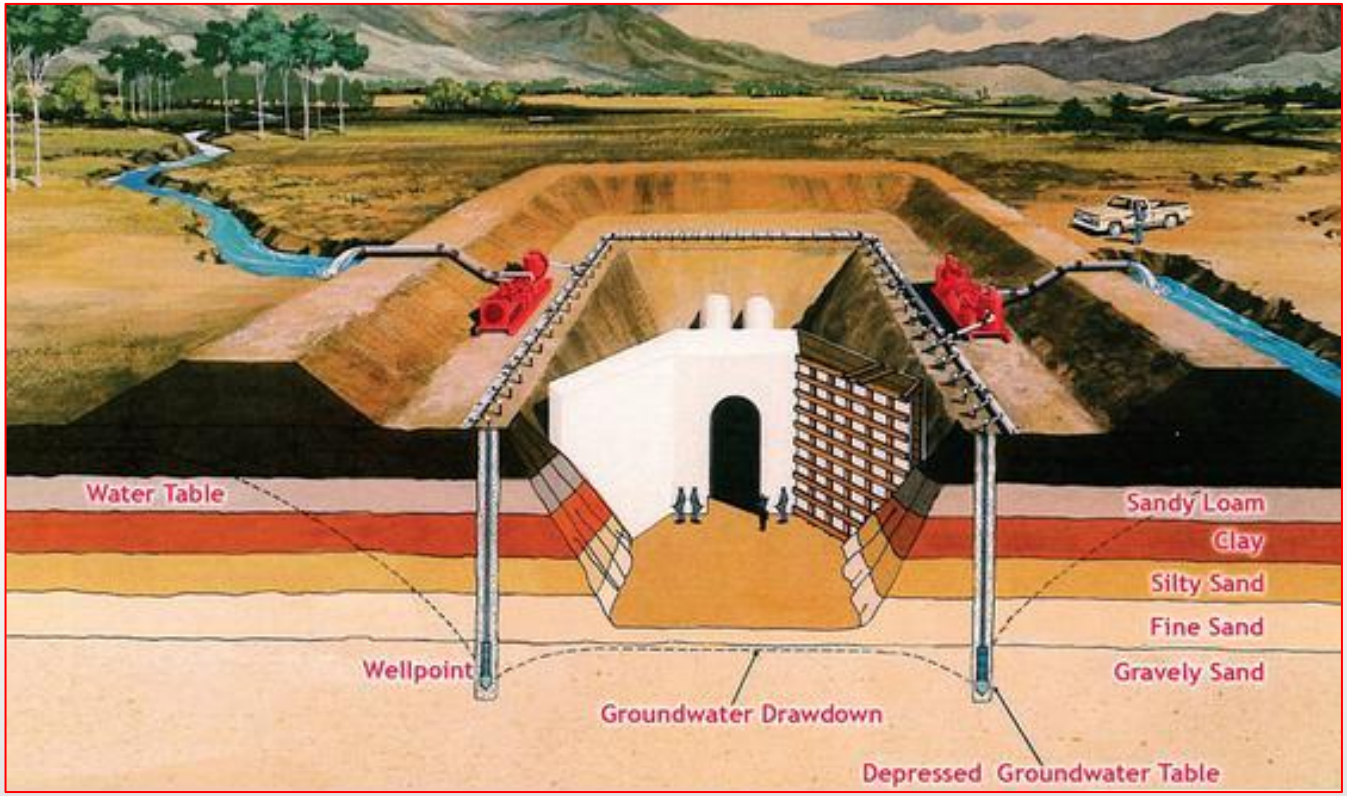
HOWEVER

Not always this region is unsaturated.

The capillary phenomenon also saturates the soil.

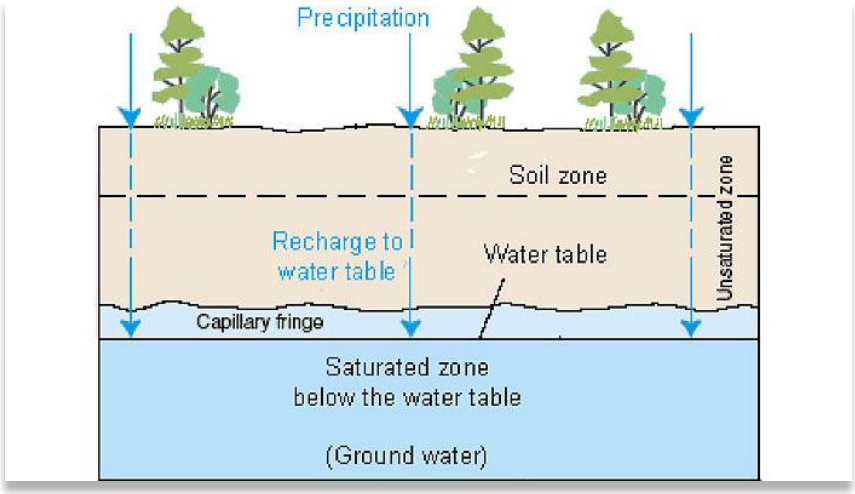
In these cases the mechanics of saturated soils is usually applied.

What is saturated and what is not?



http://civil-engg-world.blogspot.com.br/2012/12/What-Responsibilities-Engineers-Foundation-Excavation.html

Unsaturated Zone
Vadose Zone
Aeration Zone



The thickness of the unsaturated zone can vary from a few centimeters to hundreds of meters depending on the soil and region.

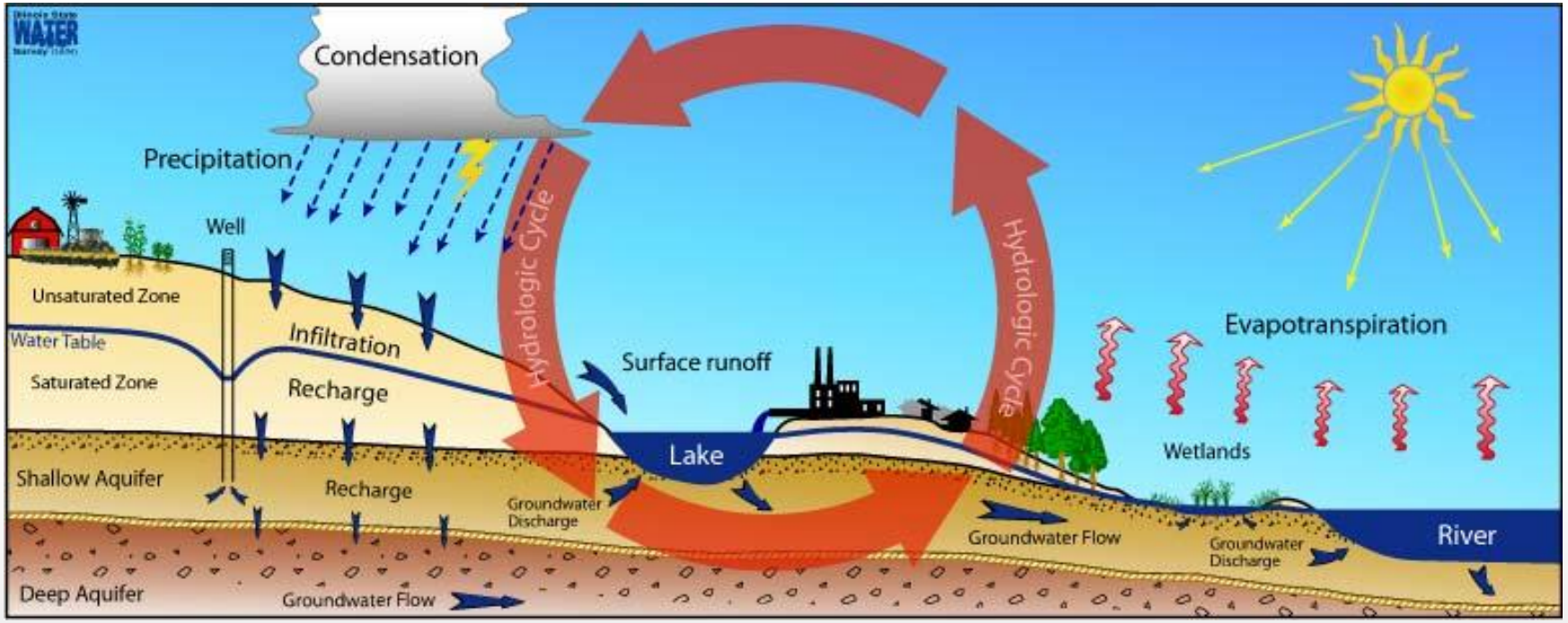
In the same region the thickness of the vadose zone can vary seasonally.

Capillary Rise Test

See also.

https://youtu.be/o8TssbmY-GM

Hydrologic cycle



www.sws.uiuc.edu

The soil at the unsaturated zone (vadose zone) has three phases

Solid

Liquid

Gas

Solid – Mineral soil grains and organic maters or other solids.

Liquid – Pure water or solutes

Gas - Air or other gás apart from water vapour

Relation Soil/Atmosphere

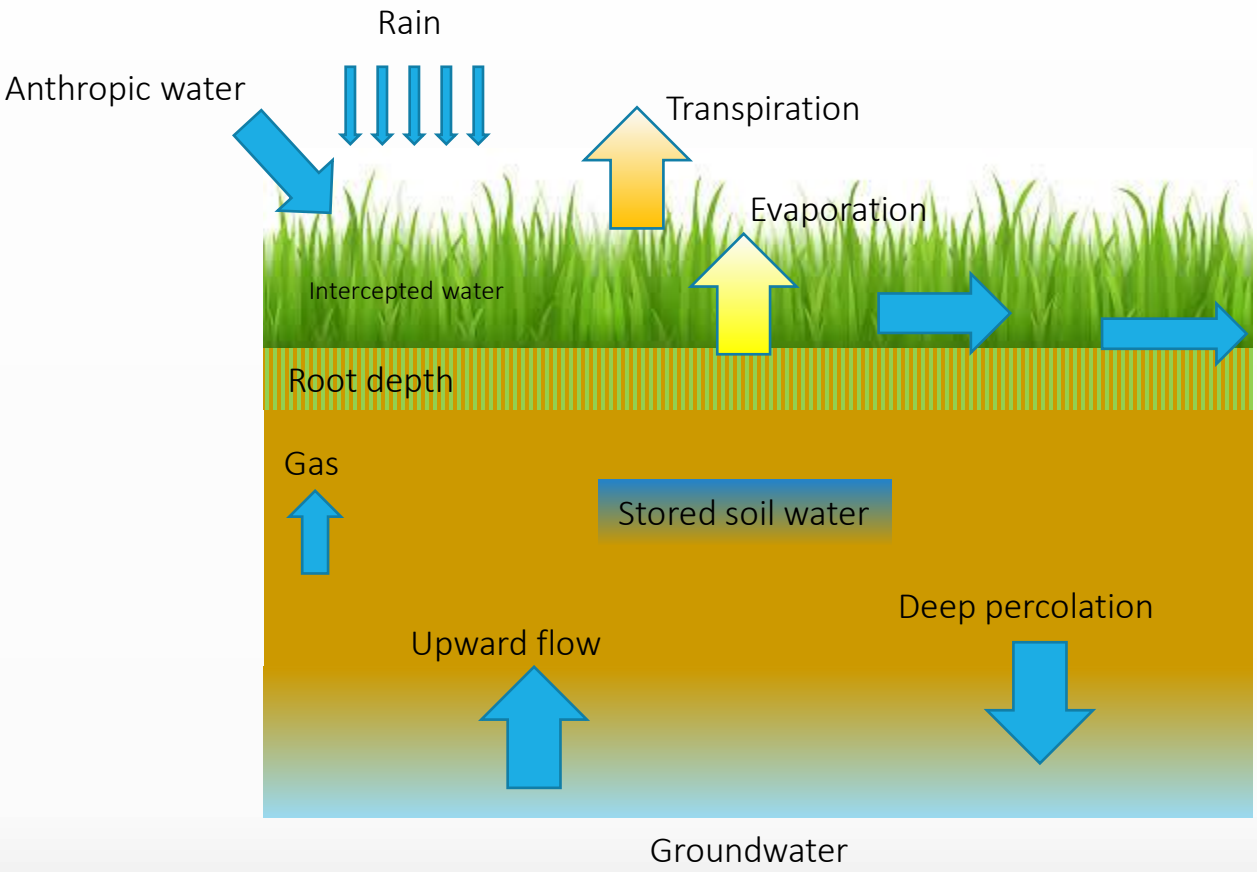
Atmospheric water balance
Soil water balance

The amount of water retained by the soil depends of factors such as:

- Topography
- Type of soil (nature and state)
- Characteristics of the soil profile
- Clime

At the interface between the soil and the atmosphere there is a water exchange that is paramount for the soil behaviour from engineering point of view (agronomy too).

Soil water balance



Atmospheric Water Balance

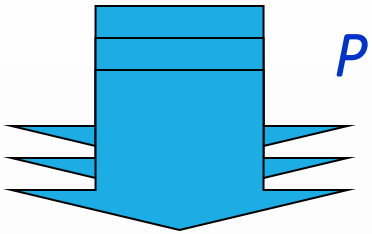
$$\mathbf{B} = P - E$$

The soil water balance is:

$$P - (I_i + R) = E + R_r + S$$

P – Precipitation
E – Evapotranspiration
I_i – Intercepted water
S – Stored water
R – Runoff
R_r – Deep water percolation

Water Balance

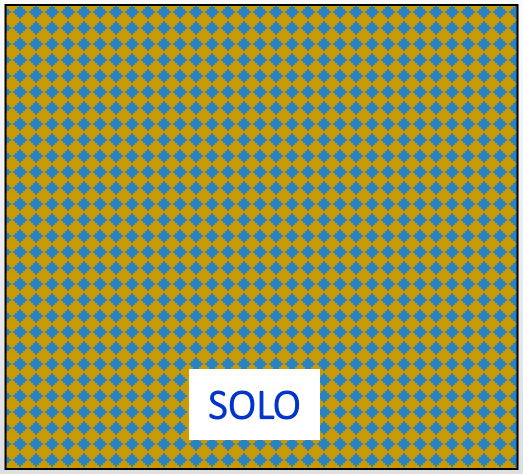


P - precipitation

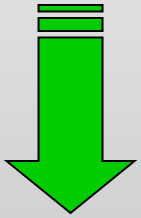
E – evapotranspiration

I_i – Intecepted water

R – runoff

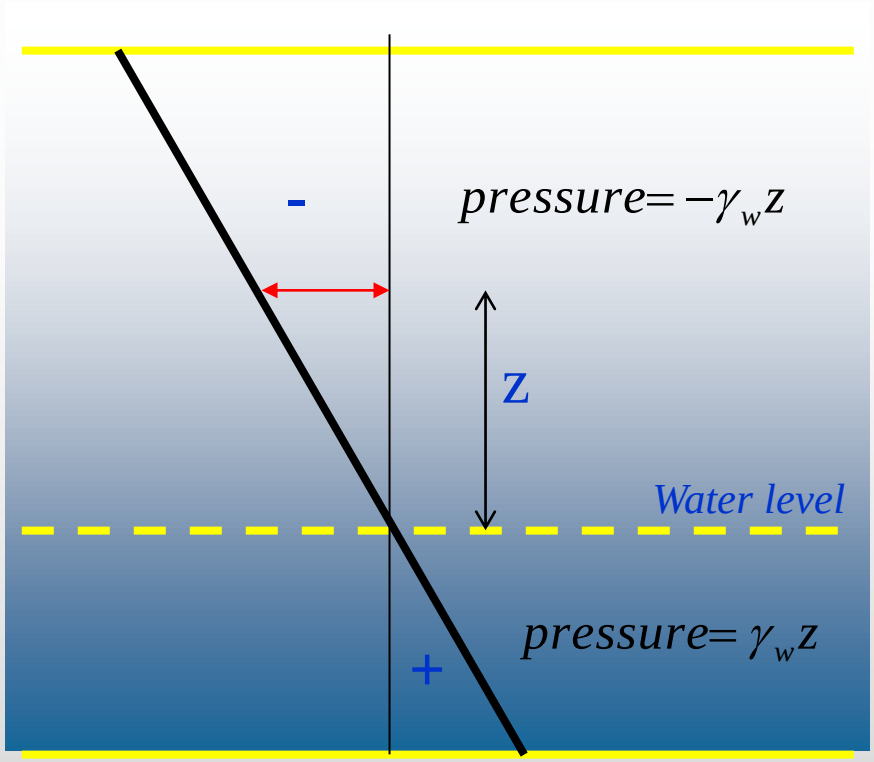


S – Stored water in the soil

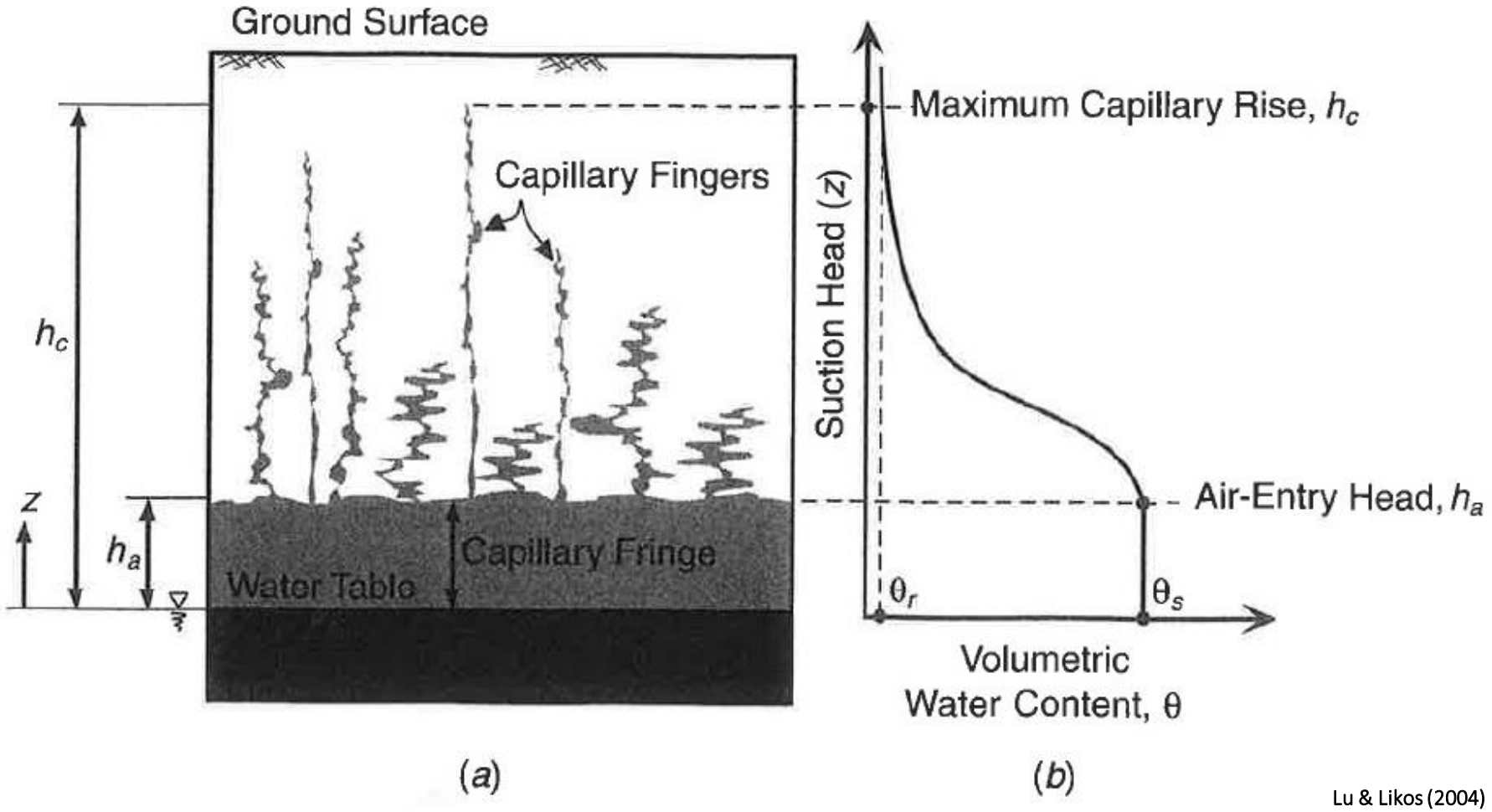


R_r – Deep water (recharge)

Equilibrium Profile
No flow

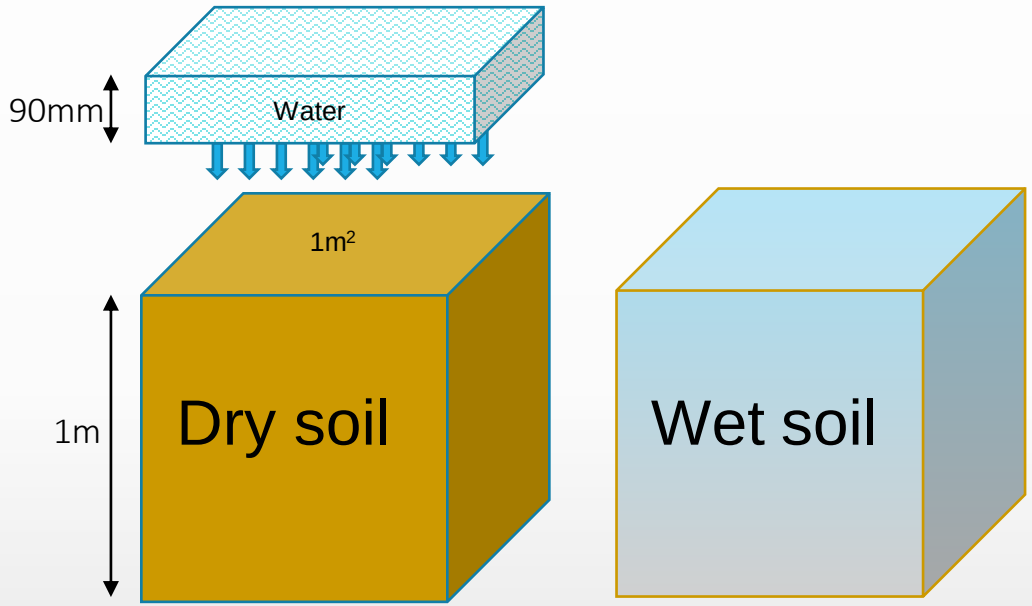


Capillary rise and associated pore water retention



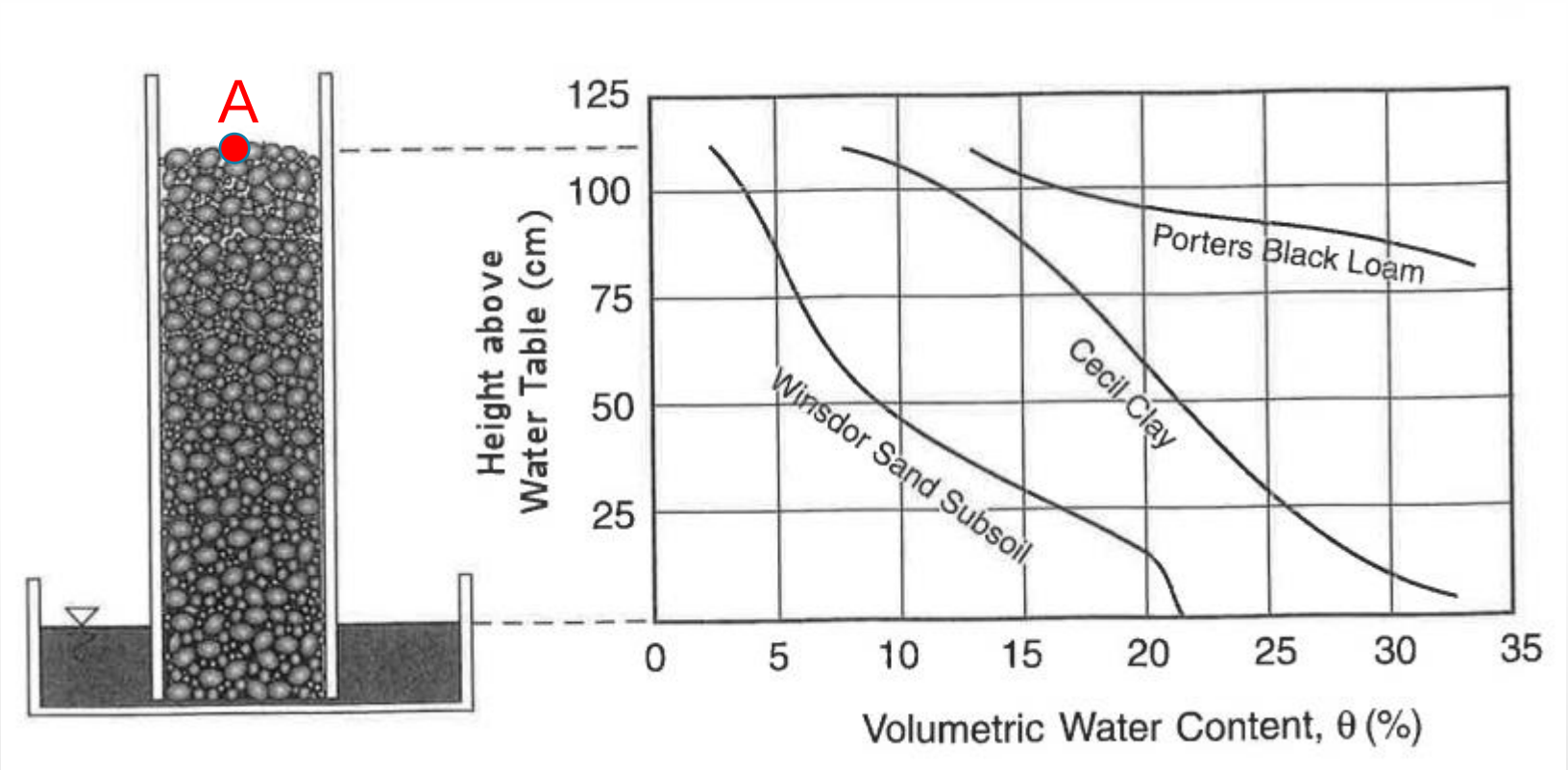
Lu & Likos (2004)

What happen if it rains?



$$\theta = \frac{0.09m^3}{1m^3} * 100 = 9\%$$

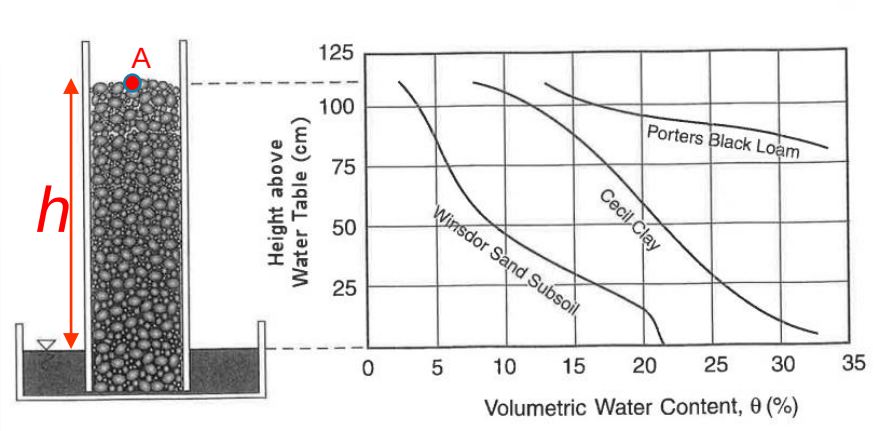
Capillary rise and equilibrium moisture content distribution in a soil column



Lu & Likos (2004) com dados de Buckingham (1907)

What can you say about the effective stress at point A?

Effective stress



$$\sigma' = \sigma - u$$

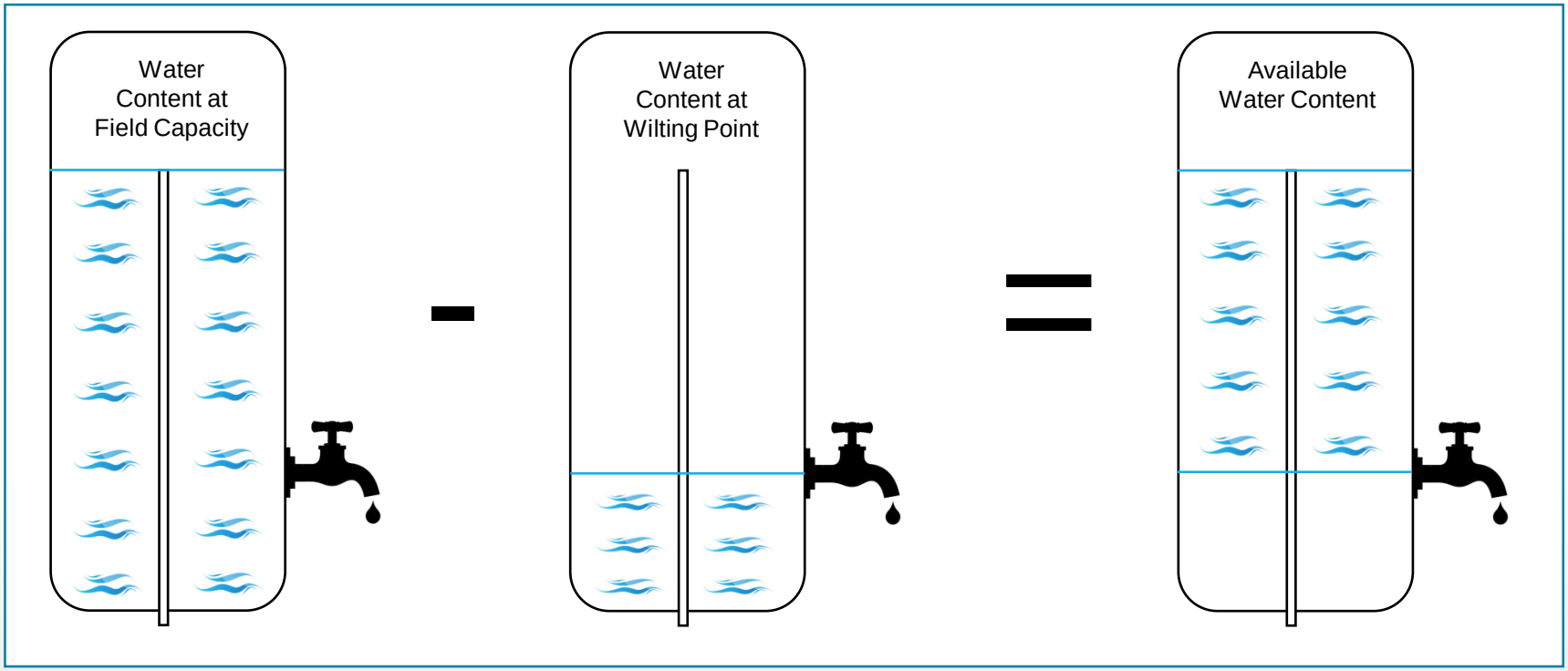
$$u_A = -\gamma_w * h$$

$$\sigma = 0$$

$$\sigma' = -(-\gamma_w * h)$$

Is it valid for all these soil?
What is the condition for this to be valid?

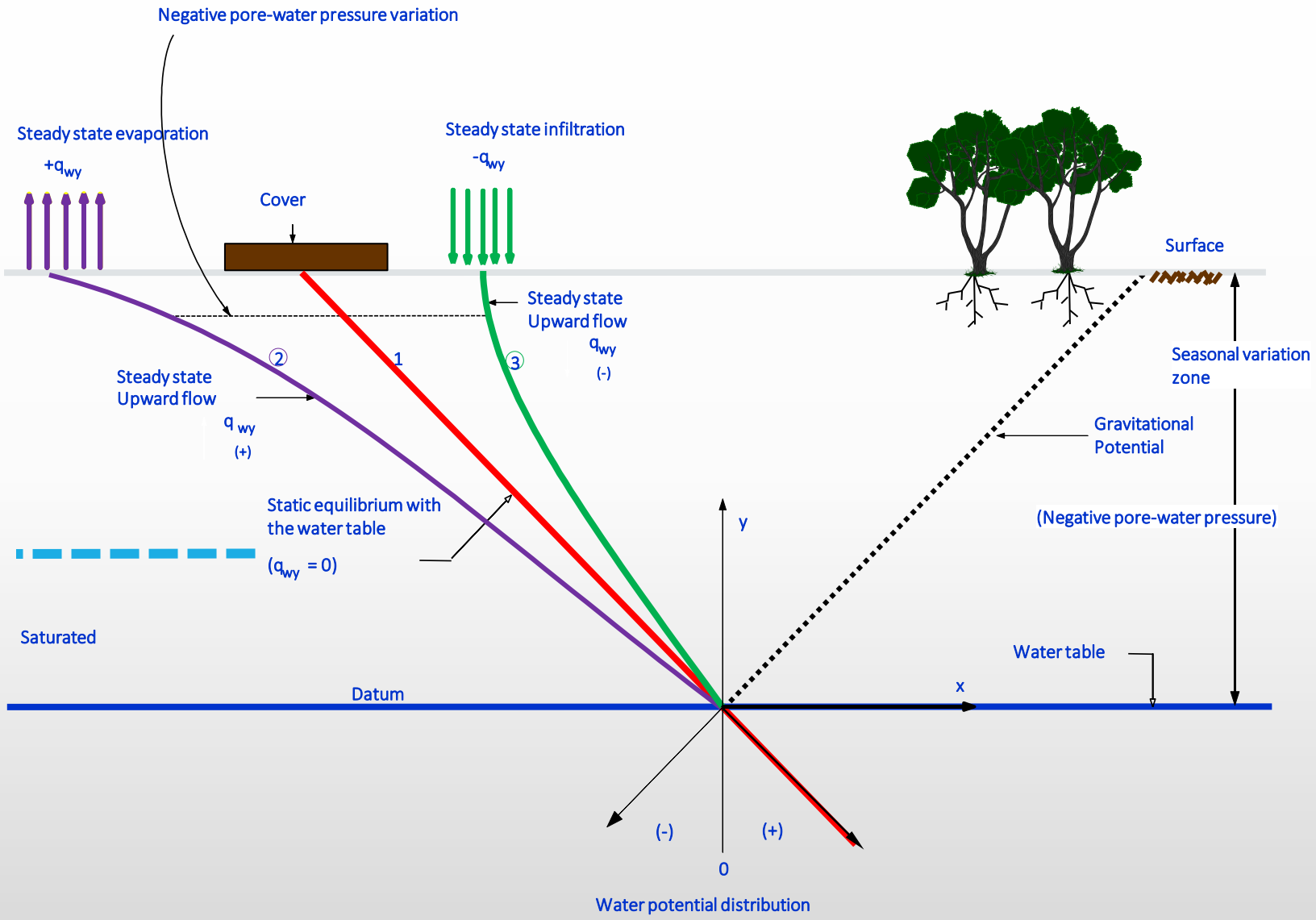
The available water content



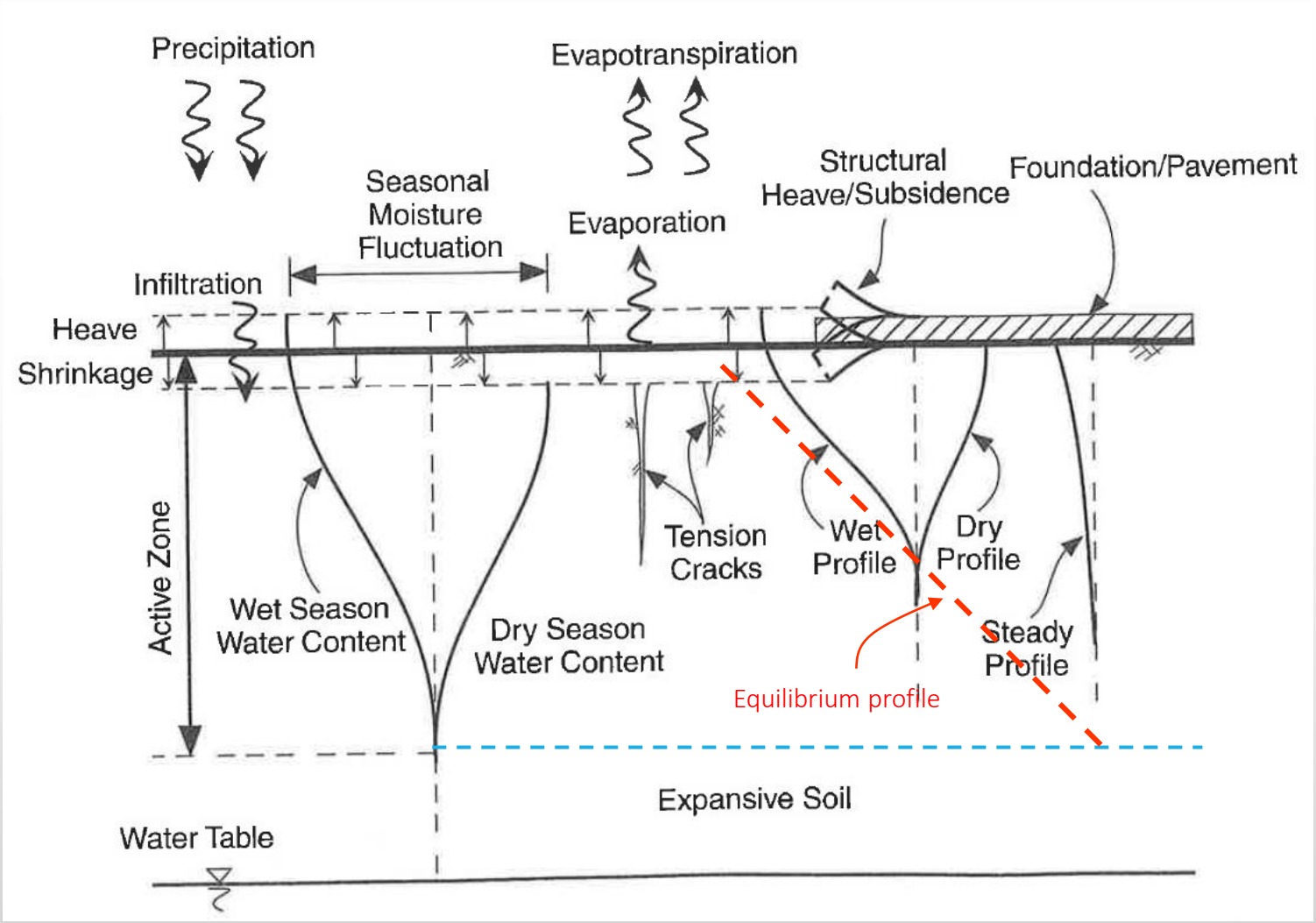
Based in http://www.fao.org/docrep/r4082e/r4082e03.htm

This concepts are from agriculture.
What analogy can be made for geotechnical engineering?

Suction profiles

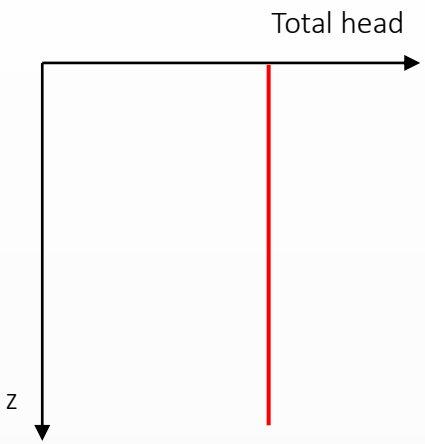


Deformation and fluid flow phenomena in near-surface deposit of unsaturated expansive soil

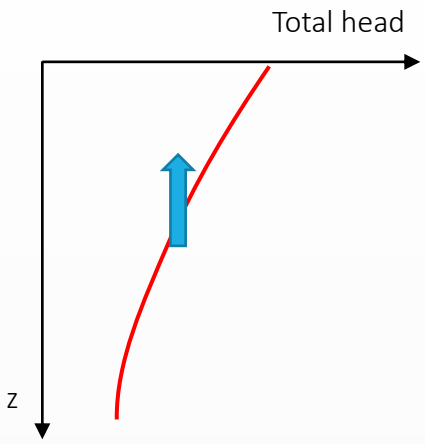


Lu & Likos (2004)

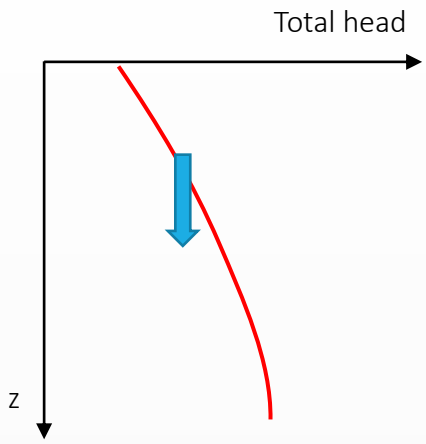
Suction profiles



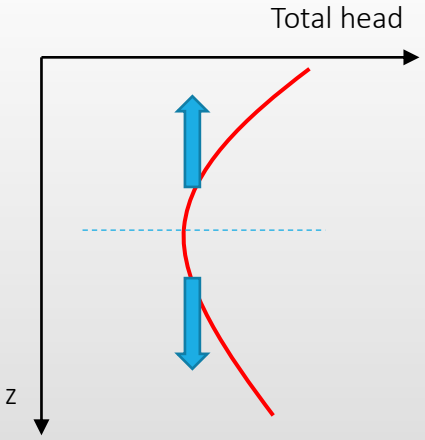
Equilibrium



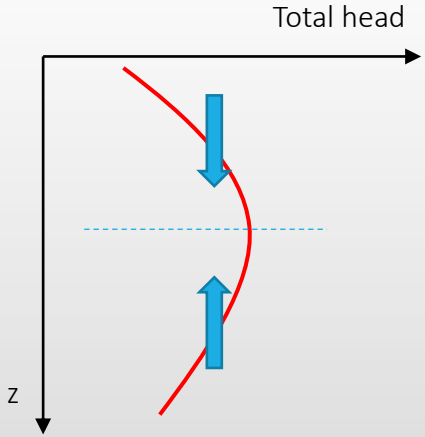
Water going up



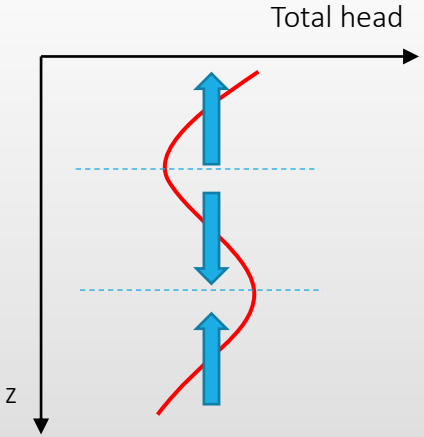
Water going down



Water going up and down in opposite direction

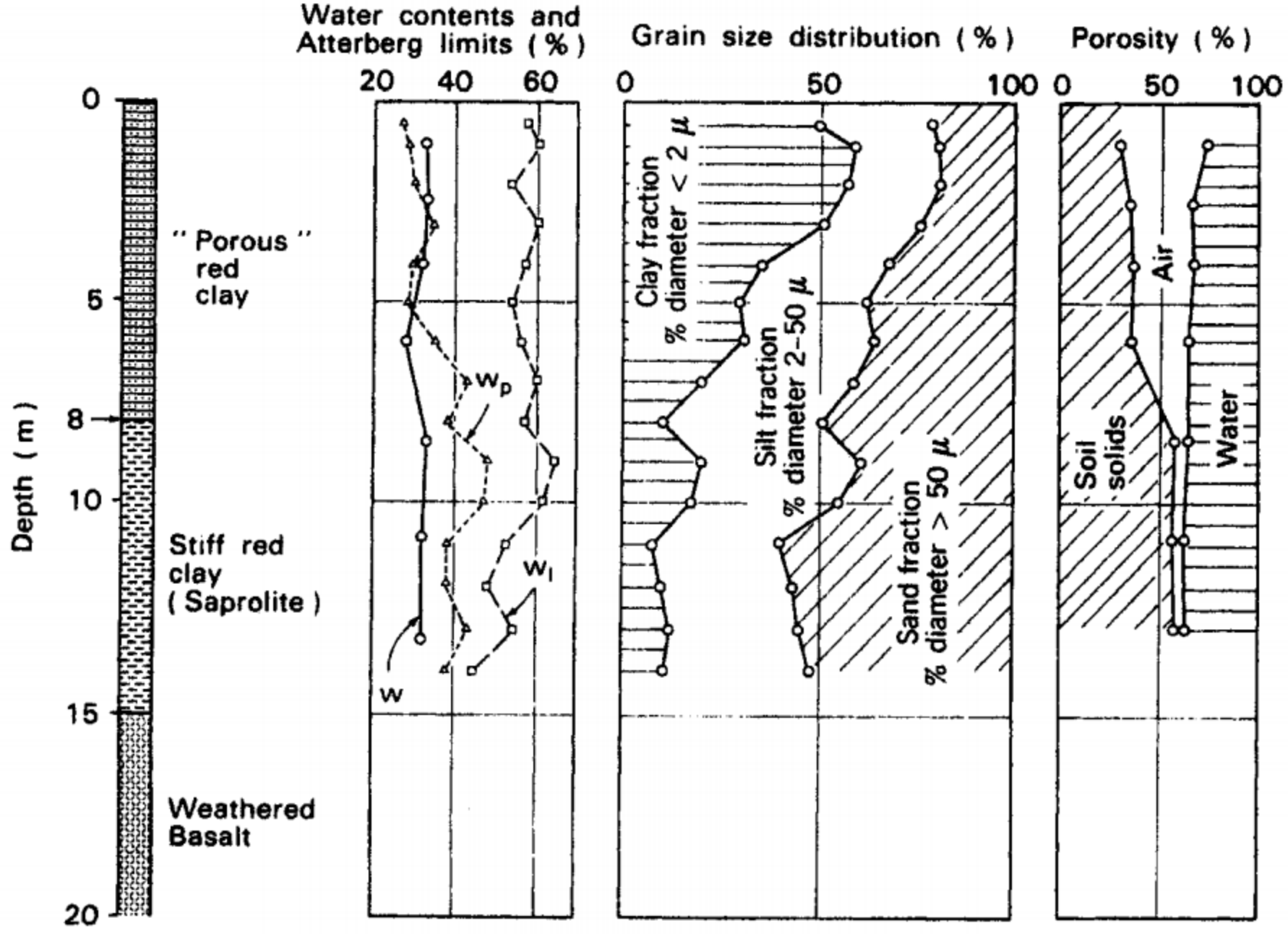


Water going up and down in the same direction

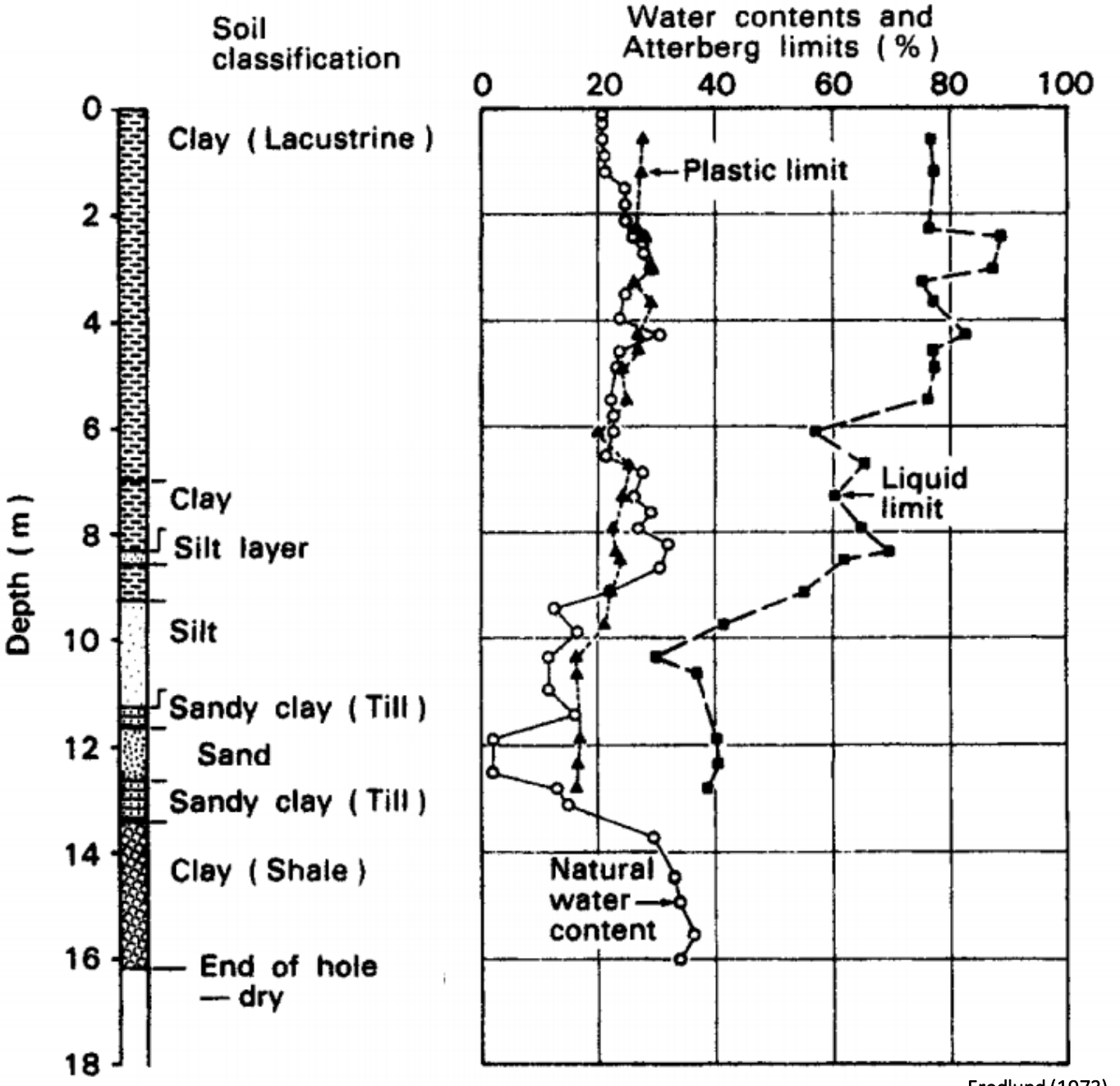


Mix movement of water

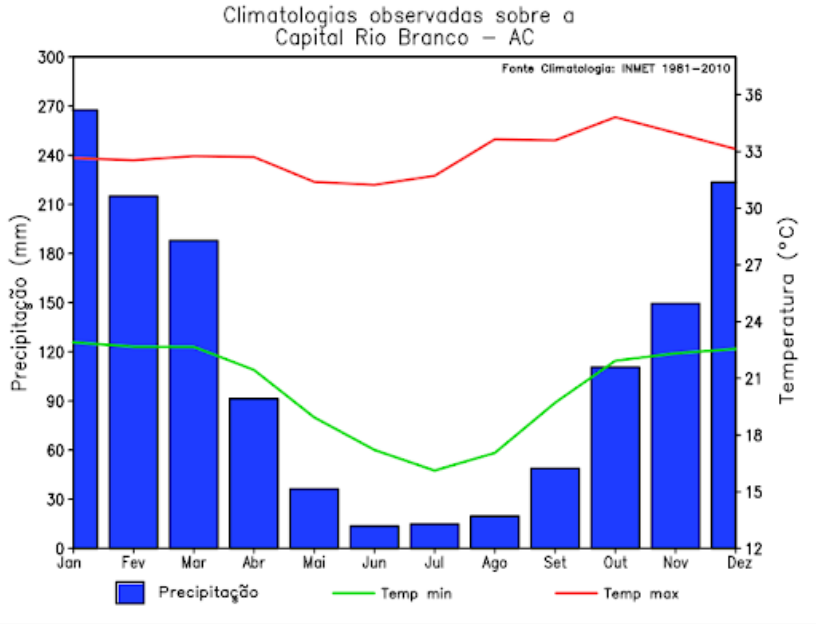
Modified from Reichardt and Timm (2004)

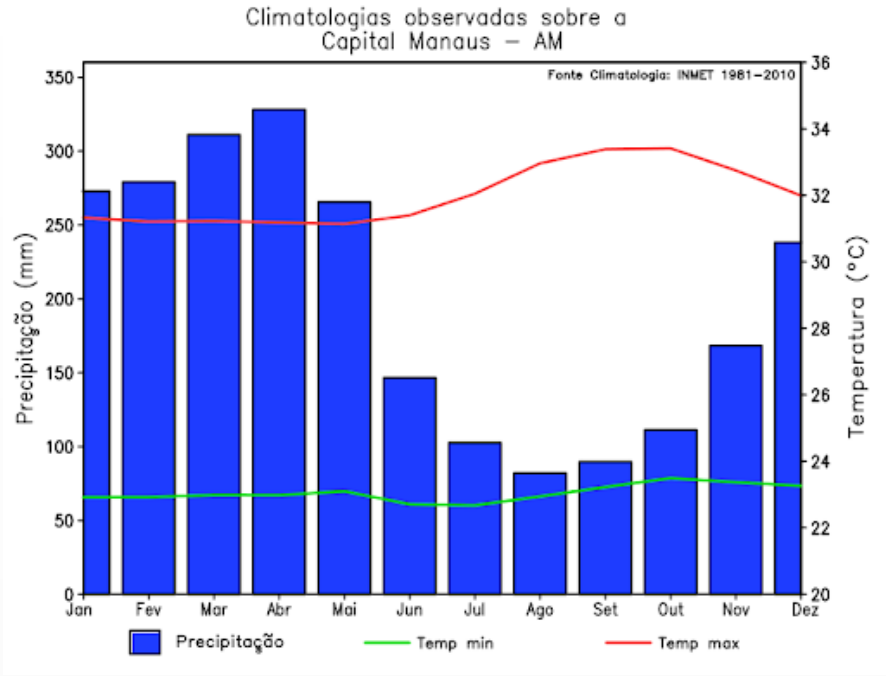

Water contents and Atterberg limits (%)
20 40 60
Grain size distribution (%)
0 50 100
Porosity (%)
0 50 100
Depth (m)
0
5
8
10
15
20
" Porous " red clay
Stiff red clay (Saprolite)
Weathered Basalt
w_p
w_l
w
Clay fraction % diameter < 2 μ
Silt fraction % diameter 2–50 μ
Sand fraction % diameter > 50 μ
Air
Soil solids
Water

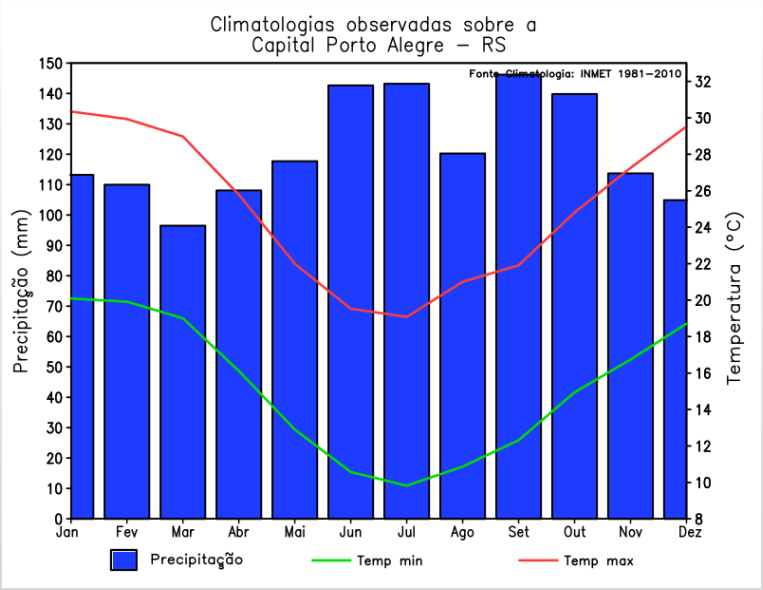
Vargas (1985)

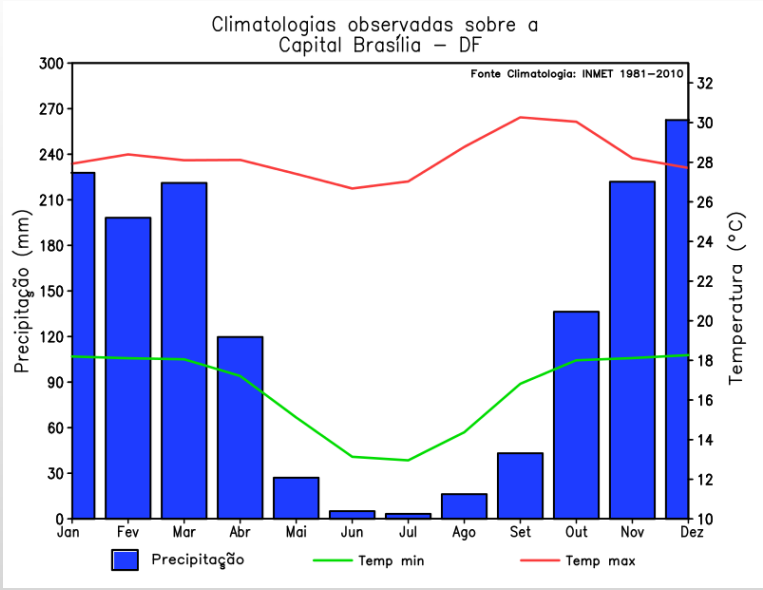


Fredlund (1973)



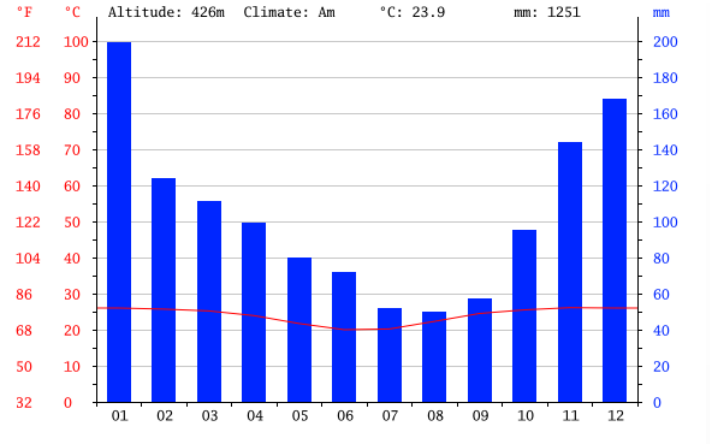




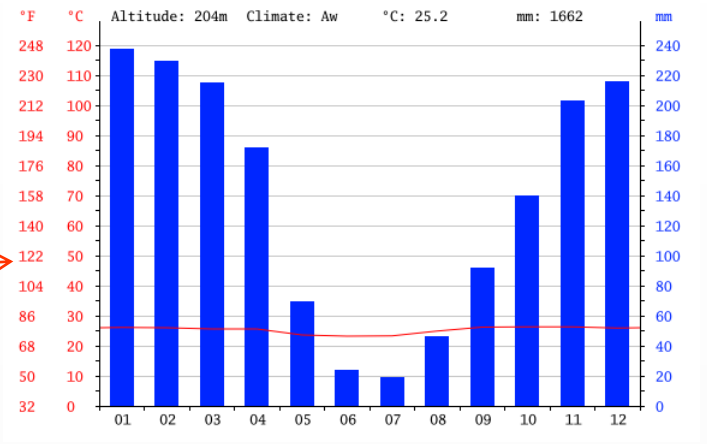


https://clima1.cptec.inpe.br/

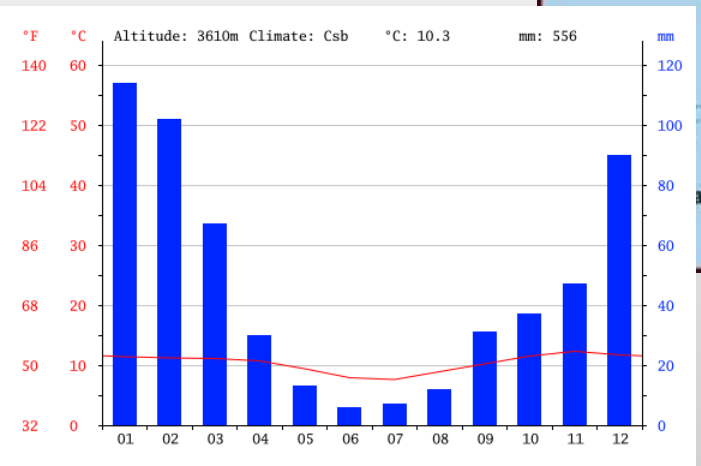
Santa Cruz de La Sierra



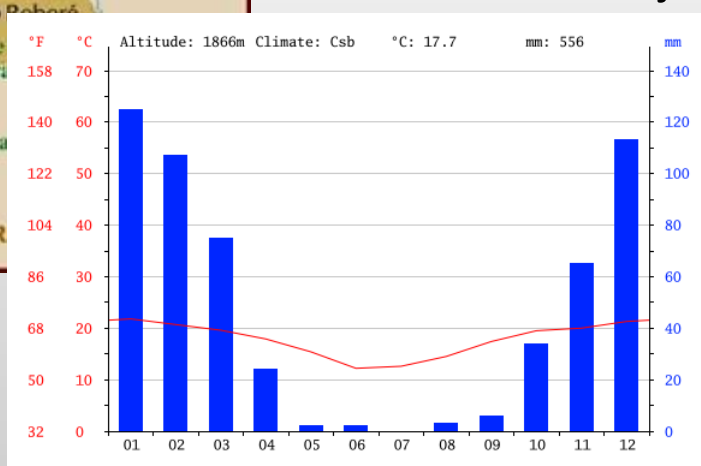
Cobija



La Paz



Tarija



Exercises

1. Describe and illustrate the Mohr-Coulomb failure criterion.
2. What do you think is the influence of the unsaturated condition on the Mohr-Coulomb envelope?
3. Where are the regions in Bolivia where unsaturated soils are likely encountered to significant depth below the ground surface? Explain and Illustrate your response.
4. Do you consider that the concept of unsaturated soils are important to design in Santa Cruz de la Sierra or Bolivia in general?
5. Consider the soil profile below and discuss the following aspects:
    a. If the water table is at 6m, what do you expect in terms of degree of saturation for a covered area? What may change if the W.T. is at 3m?
    b. If a SPT test is performed during the rain season and another during the dry season, what do you expect for the results?
    c. What the implication you may have?