Convegno

‘SCARTI MINERARI: DA RIFIUTO A RISORSA

6-7 ottobre 2022

Comportamento idraulico e meccanico dei terreni non saturi: Ruolo nella progettazione e gestione dei depositi di sterili minerari

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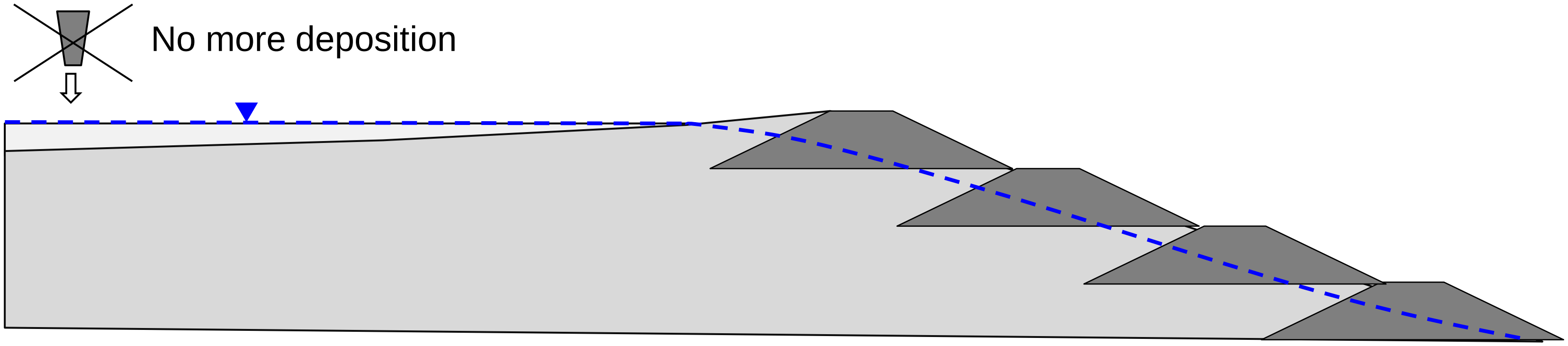
Post-closure failure hazard of Tailing Storage Facilities



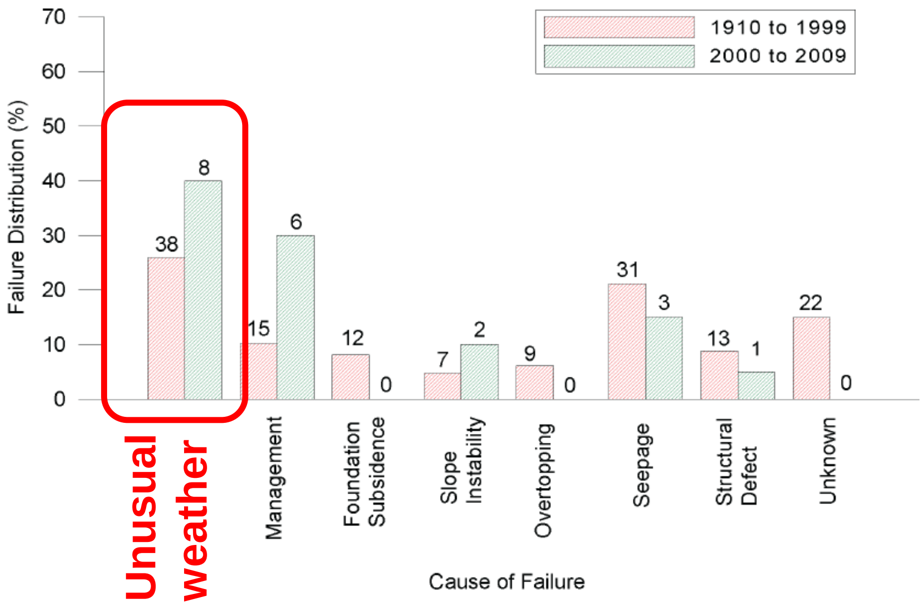
LIQUEFACTION

- Excessive rate of loading due to dam rising $\Rightarrow$ NO
- Excessive rate due to increase of recharge $\Rightarrow$ NO
- Seismic loading $\Rightarrow$ Low risk in Europe
- Transit of machinery $\Rightarrow$ Low risk
- Failure of the drainage system $\Rightarrow$ Medium risk
- **Other?**

Review of causes of failure

Rico et al 2008

Azam and Li 2010



In Europe, the most common cause of failure is related to unusual rain

Failures due to unusual rain increased from 25% pre-2000 to 40% post-2000

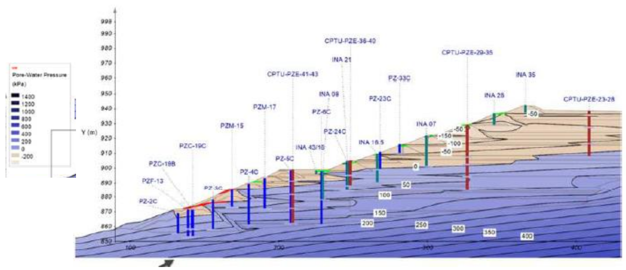
Failure of Feijão Dam I

(Report of the Expert Panel, Robertson et al. 2019)

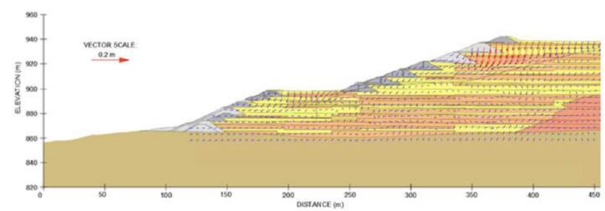
July 2016 → Cessation of tailings deposition

January 2019 → Sudden failure

Simulated pore-water pressure



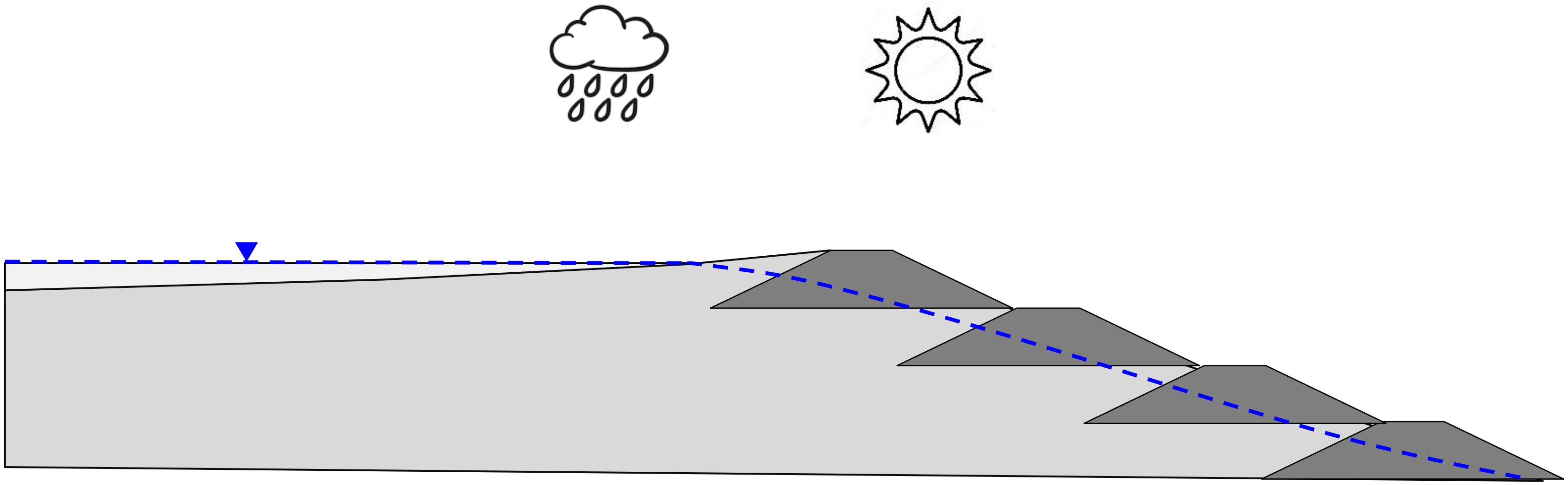
Simulated deformations



'Loss of suction from cumulative rainfall over the years following the cessation of tailings deposition, culminating in the intense rainfall recorded towards the end of 2018, would lead to a small strength reduction in the previously unsaturated zone (i.e., the zone above the water level)'

'This analysis showed that a significant loss of suction could potentially have contributed to the observed failure mechanism'

Effect of climatic loading on mechanical behaviour of tailing slopes



- Why rainwater infiltration may affect slope instability
- Why suction (negative pore-water pressure) and partial saturation play a key role

OUTLINE

Part 1: ‘Lay’ audience (no special or expert knowledge)

- Elementary surface physical phenomena
- Capillary pressure / suction
- Sandcastles
- Rainfall-induced tailing slope instability

Part 2: (Geo)Technical audience

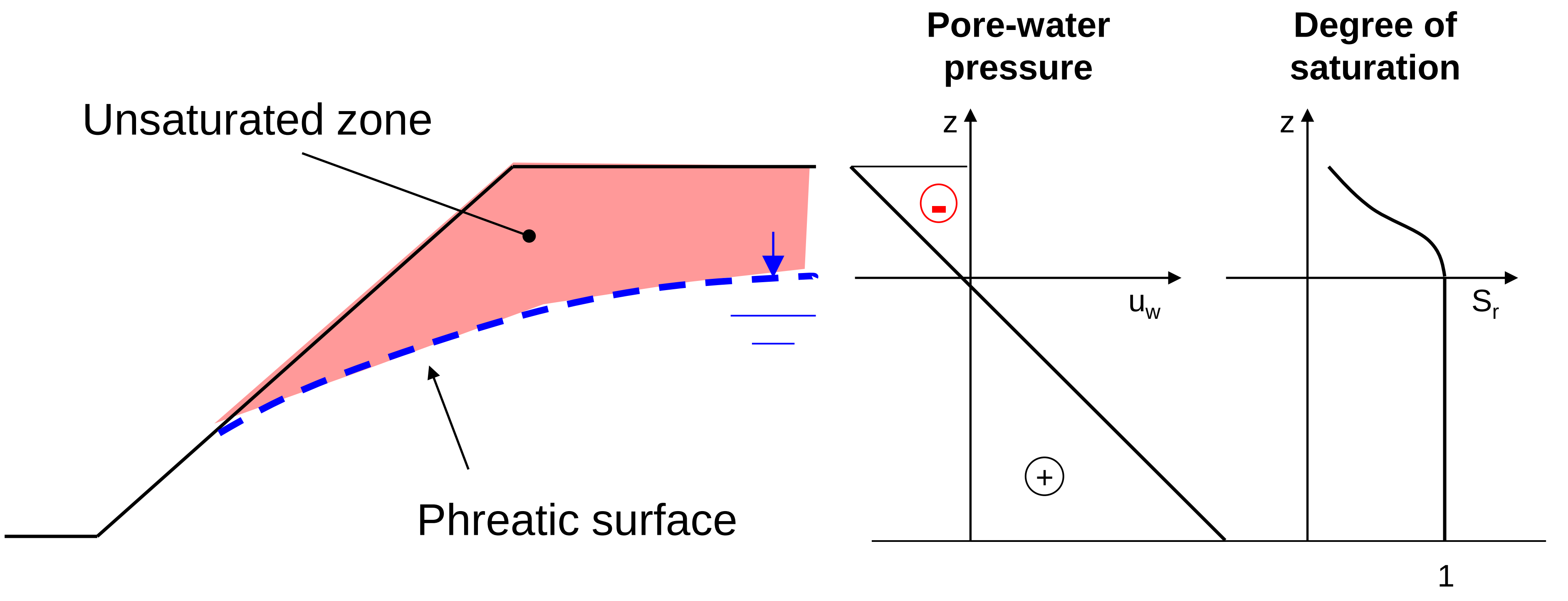
- Water retention behaviour of unsaturated soils
- Shear strength of unsaturated soils
- Loss of shear strength due to rainwater infiltration
- Monitoring precursors variables
- Possible mitigation strategies

Part 1

‘Lay’ audience

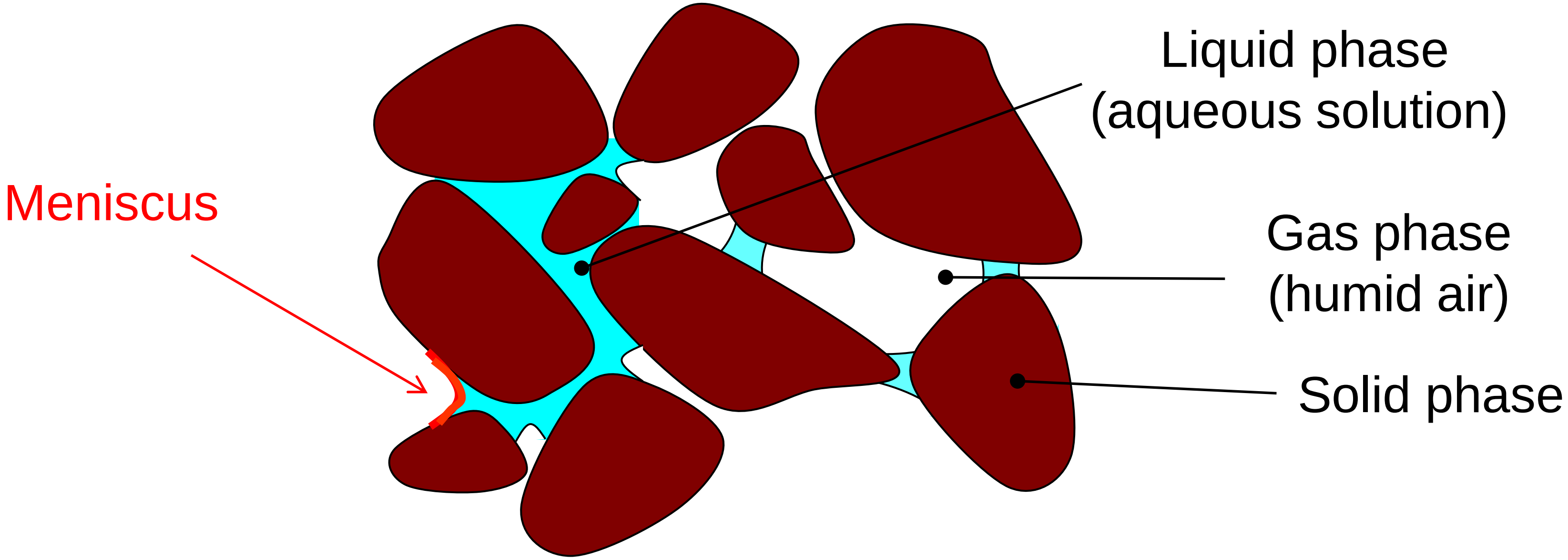
(no special or expert knowledge)

Geomaterials above the water table are unsaturated and have negative pore-water pressures



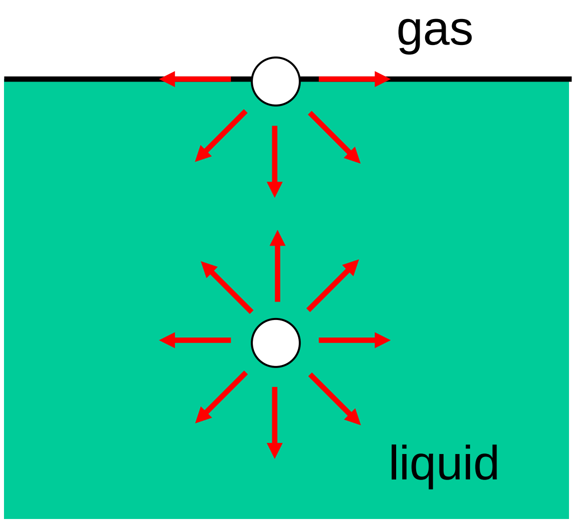
Unsaturated state

Pore space is filled by two fluids,
a wetting and a non-wetting one



Cohesion and surface tension

Cohesion = Attraction force between molecules of the same type

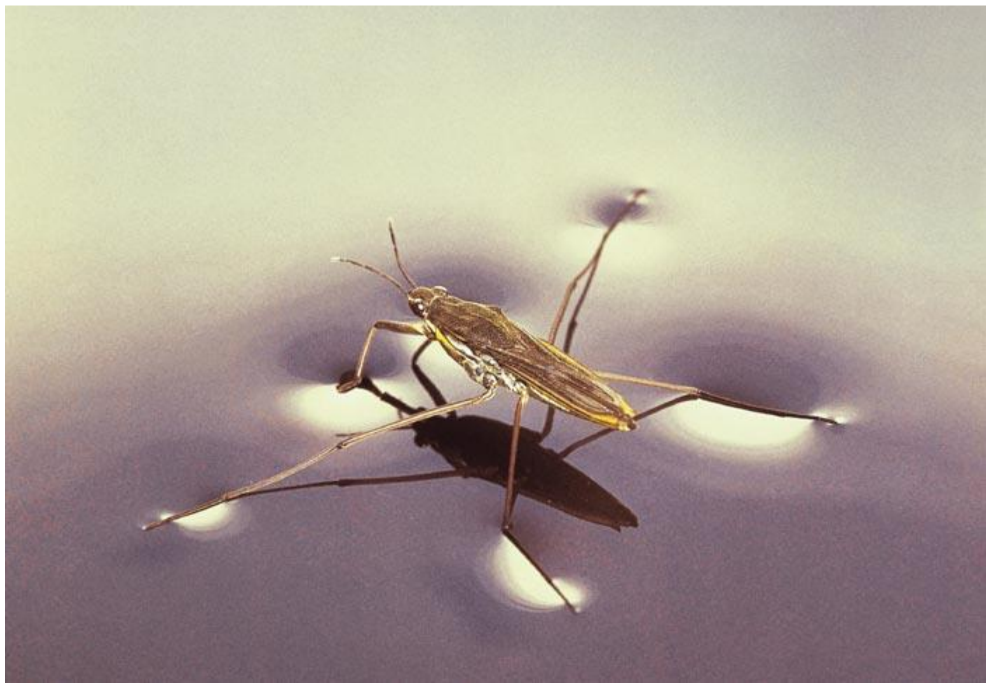


At the surface, the resultant force is directed downward

The gas-liquid interface behaves like a membrane subject to a uniform tensile stress

This stress is termed surface tension

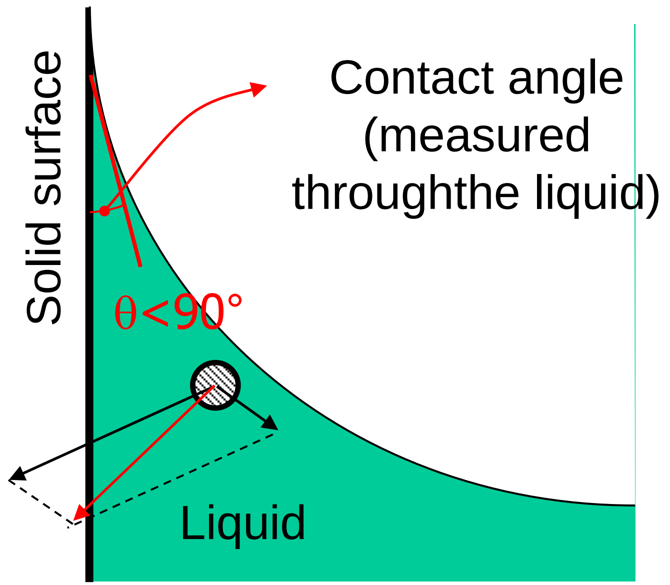
Real life example of surface tension: insect walking on water



Adhesion

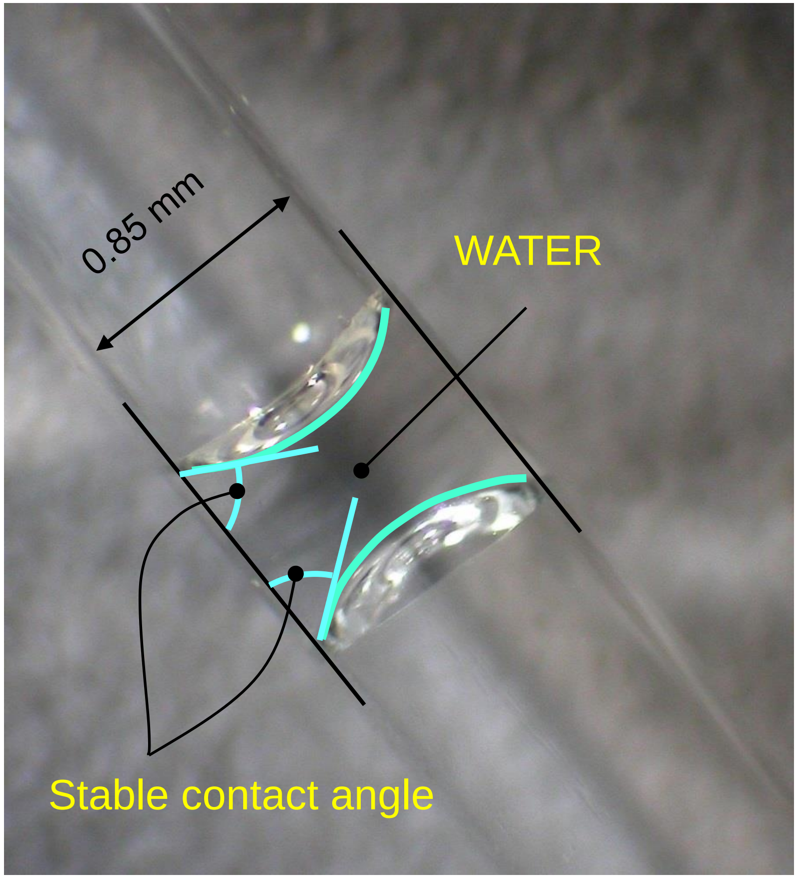
Adhesion = Attraction force between molecules of different type

Adhesion < Cohesion

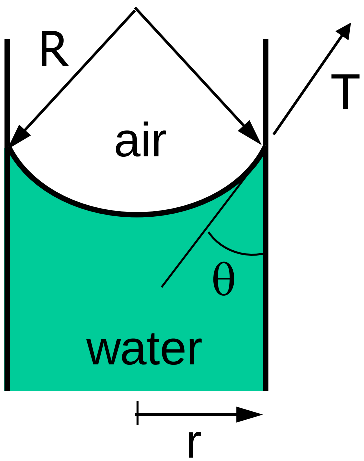


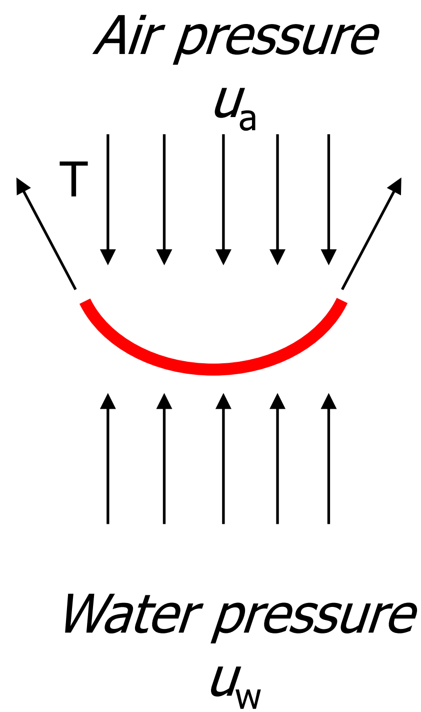
The liquid ‘wets’ the surface

Real life example of adhesion: water in small diamater (capillary) tube



Effect of curvature of the liquid-gas interface





u_a = air pressure [F/L^2]

u_w = water pressure [F/L^2]

θ = contact angle

T = surface tension [F/L]

r = radius of capillary tube [L]

R = radius of curvature of spherical cup [L]

Mechanical equilibrium

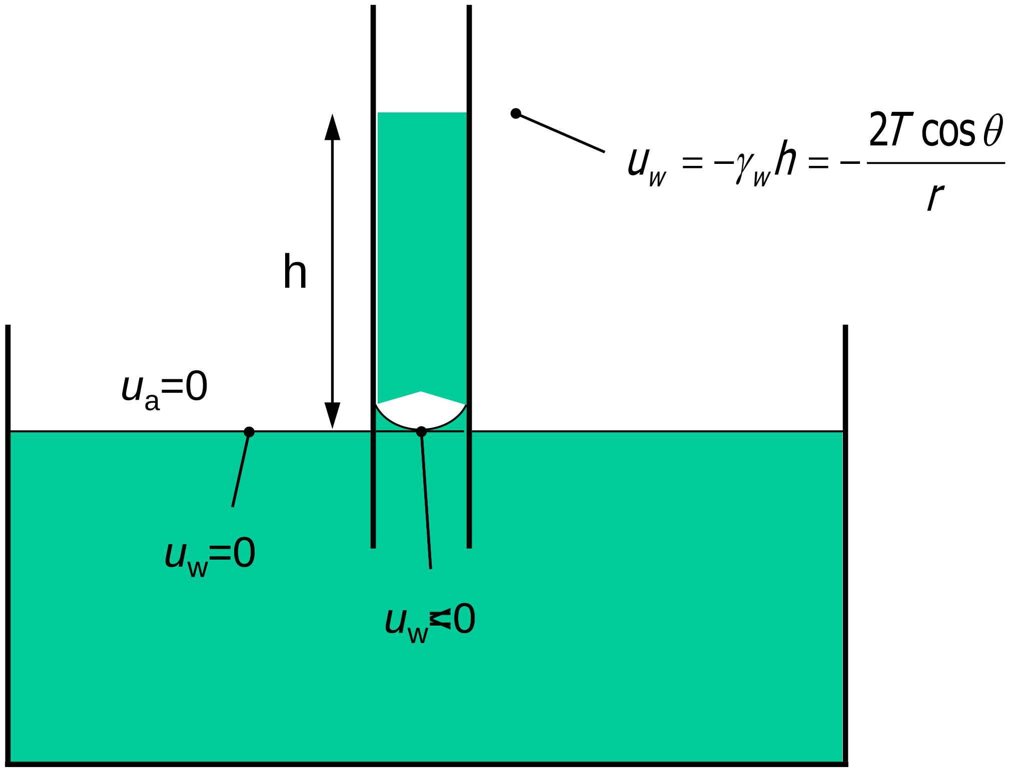
$$\boxed{u_w - u_a = -\frac{2T\cos\theta}{r} = -\frac{2T}{R}}$$

if $\theta < 90°$

Water pressure is NEGATIVE

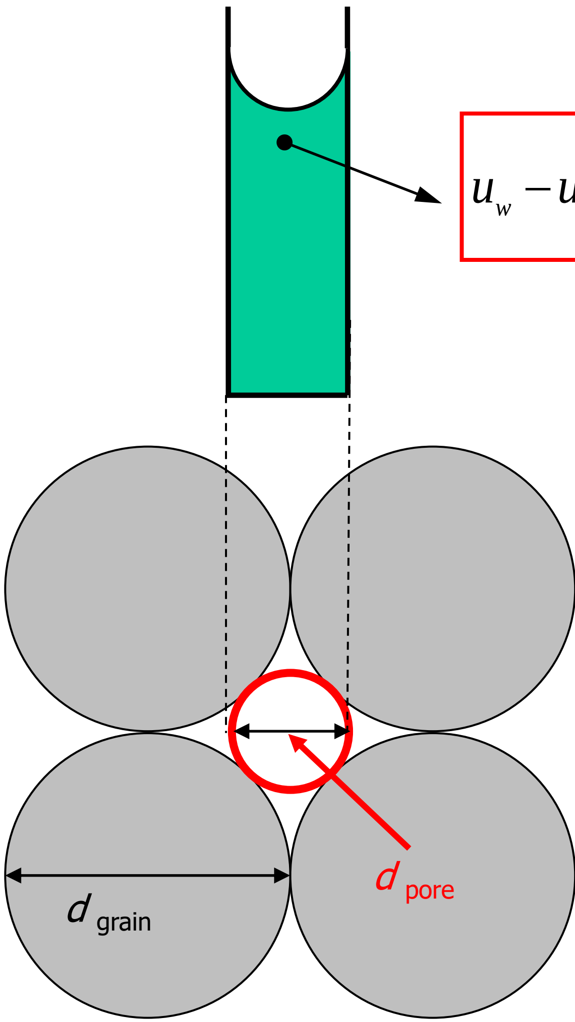
$$\boldsymbol{u_w - u_a < 0}$$

Real life example of surface tension: Rise in capillary tube



If θ<90°, the liquid enter the cavities in the solid surface
⇒ the liquid is said to wet the surface

Tensile stress of water in the capillary tube



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

$\theta = 0$

$T = 0.073$ N/m (20°C)

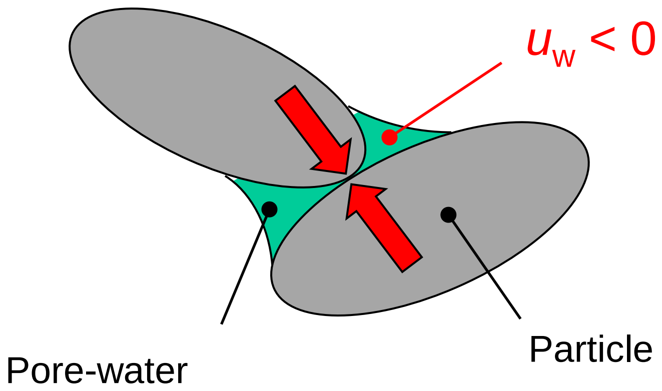
$u_a = 100$ kPa (absolute pressure)

	sand	silt	clay
d_{grain} (μm)	300	30	3
d_{pore} (μm)	30	3	0.3
u_w-u_a (kPa)	-10	-100	-1000

$d_{pore} = 1/10\ d_{grain}$

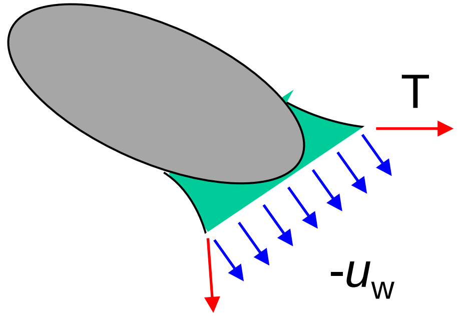
Tailings

Capillary effects in soils



The contact angle of water with the particle surface is less than 90°

The meniscus is concave toward the air side and pore water presure is negative



Particles are stuck together by surface tension and negative pressure

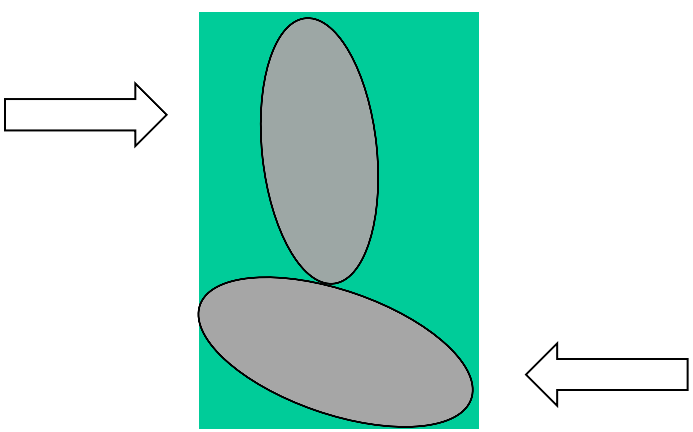
Suction

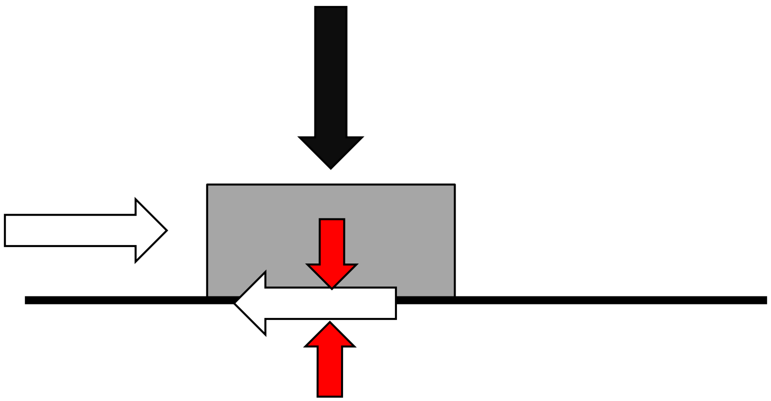
$s = -u_w$

Mechanical effects of water menisci

Saturated soil

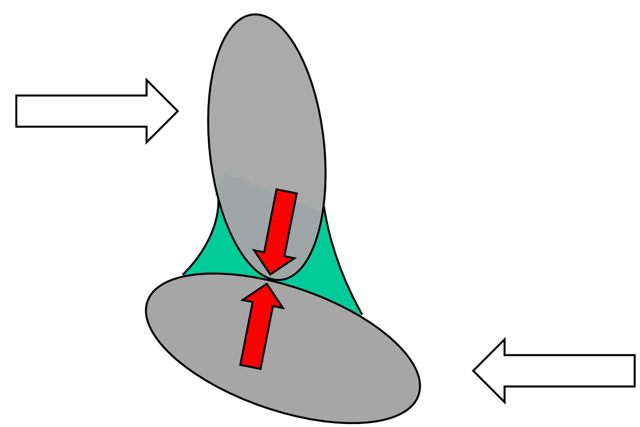
Sliding





Partially saturated soil

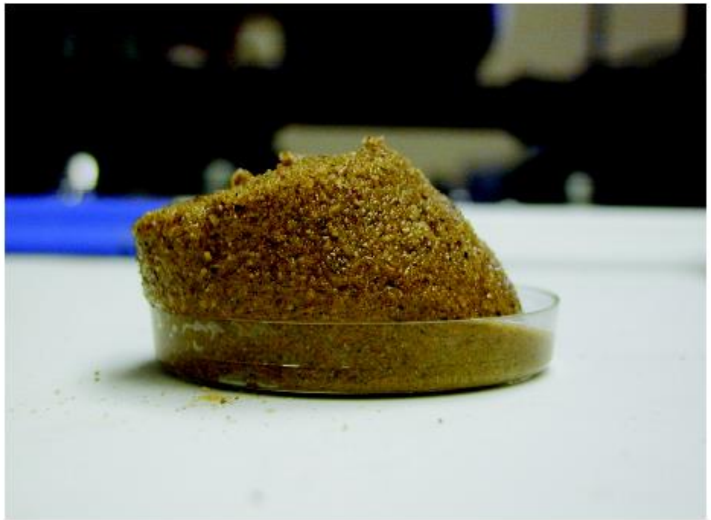
No sliding

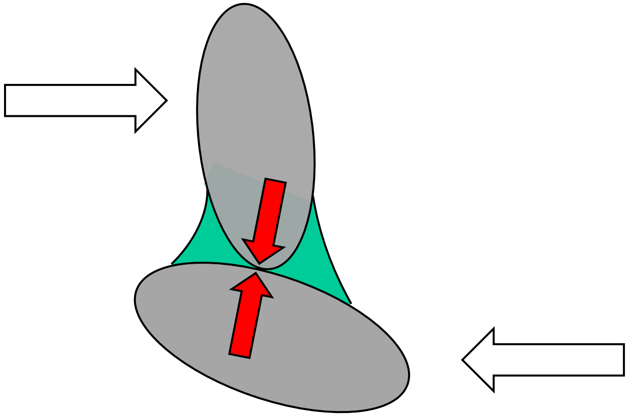


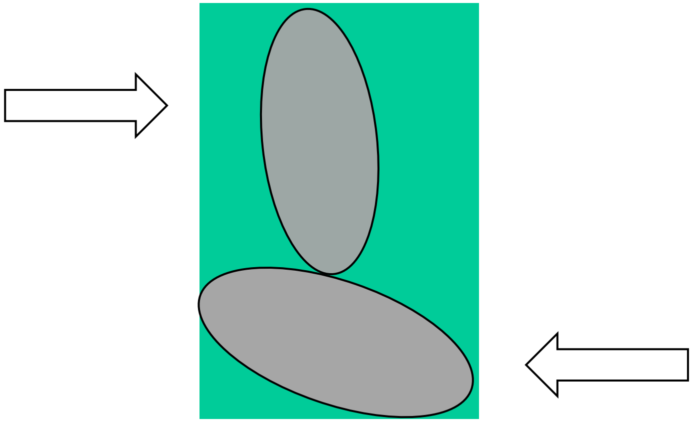
Day-to-day experience

Medium water content
(partially saturated)

High water content
(quasi-saturated)







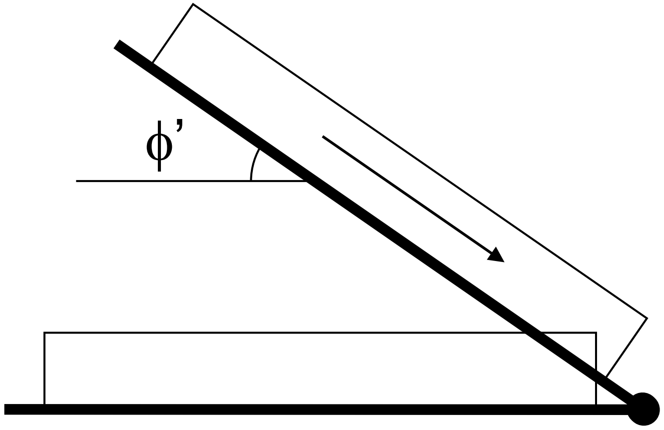
An example of the effect of partial saturation

Dry sand / Saturated sand

No negative pressure
No surface tension

⇩

No meniscus bonding

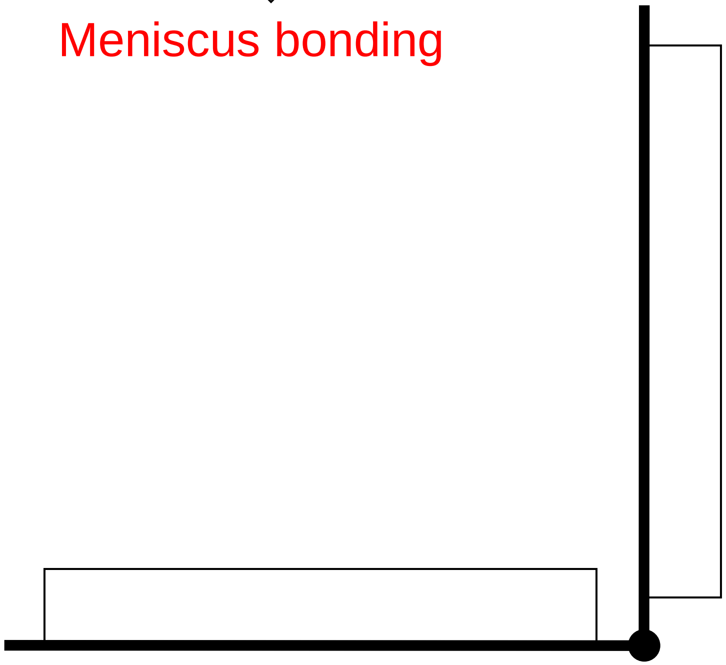


An example of the effect of partial saturation

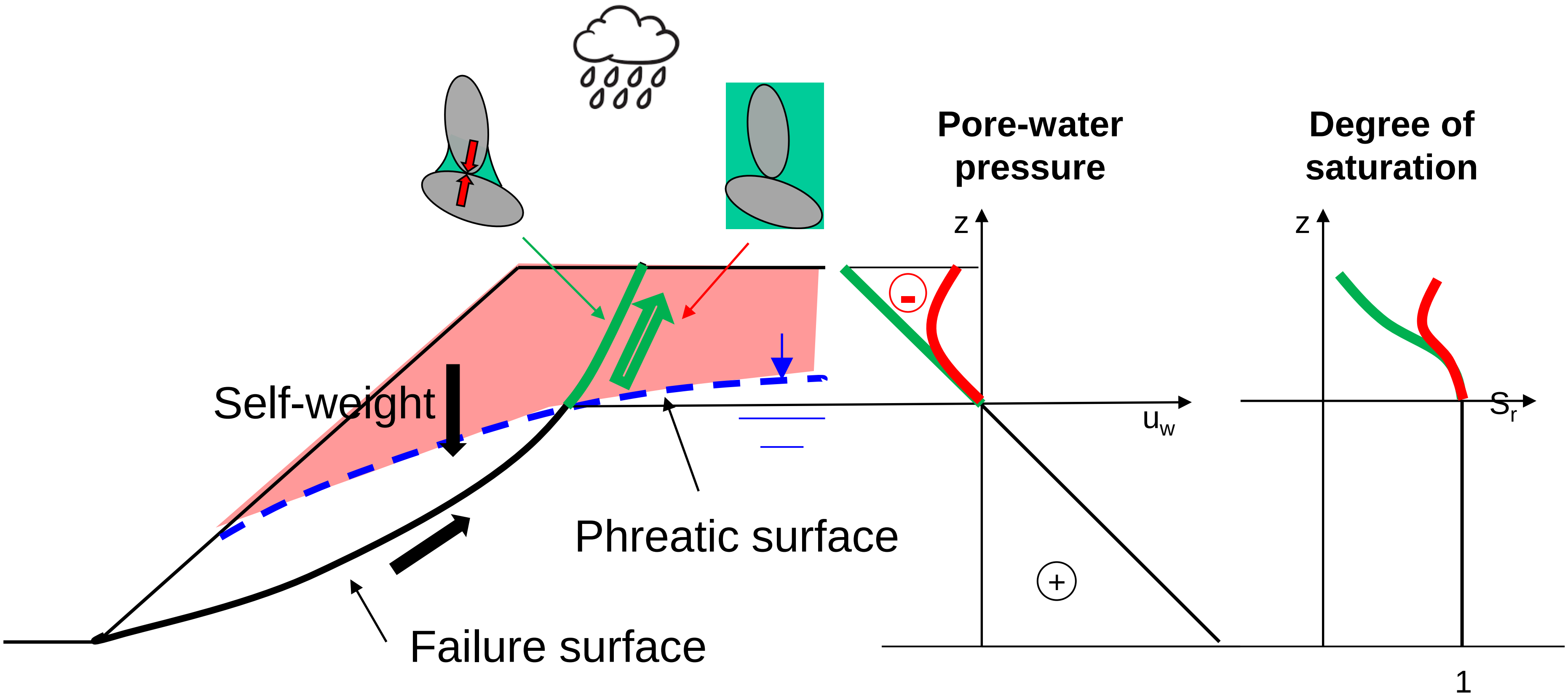
Partially saturated sand

Negative pressure
Surface tension

Meniscus bonding



Effect of rainwater infiltration on stability of slopes



One of the hypotheses of Feijão Dam failure

Part 2
(Geo)Technical audience

Tarantino A, Di Donna A (2019). Mechanics of unsaturated soils: simple approaches for routine engineering practice. Rivista Italiana di Geotecnica N. 4/2019

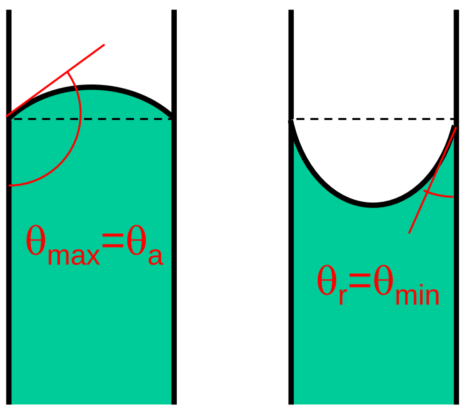
Water retention behaviour

Hysteresis of the contact angle

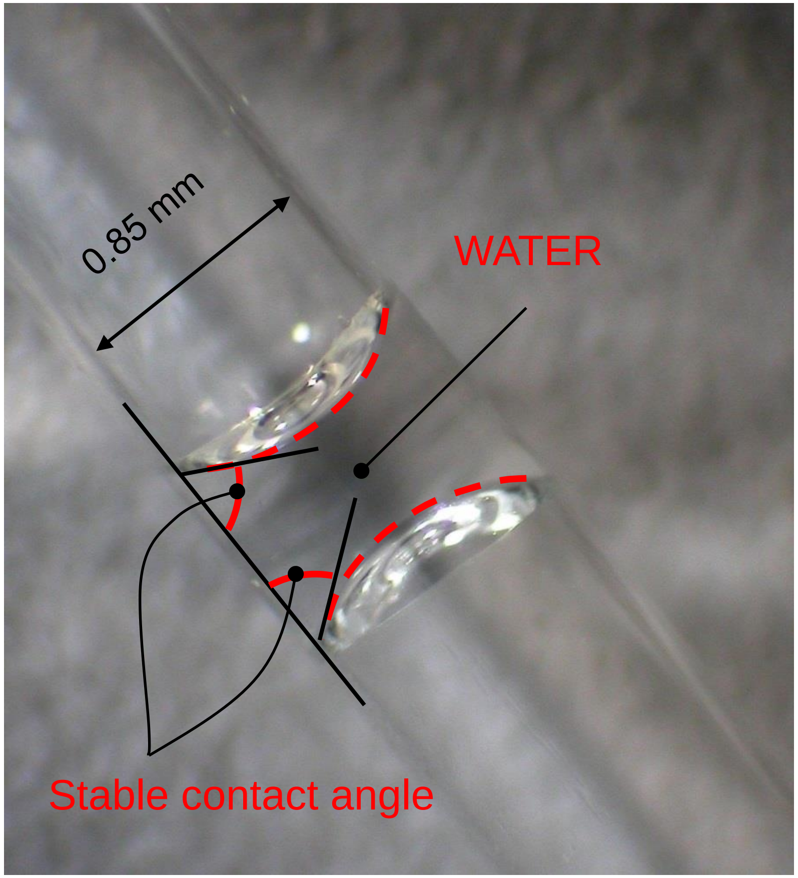
In a capilary tube, contact angle ranges from a minimum (θ_r) to a maximum (θ_a)

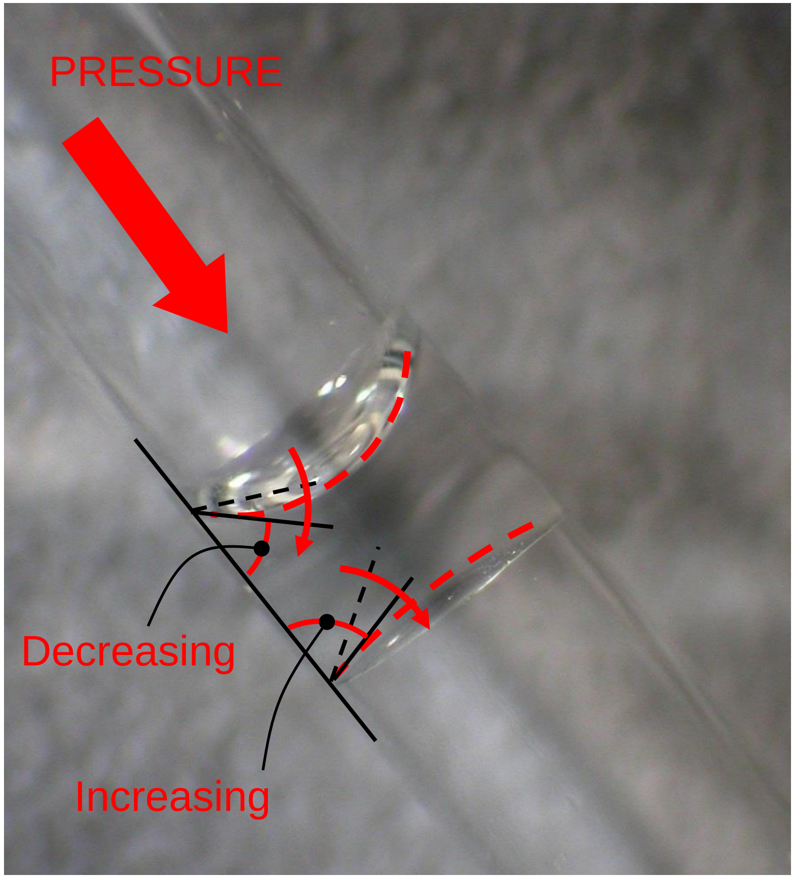
θ_r = receding angle

q_a = advancing angle

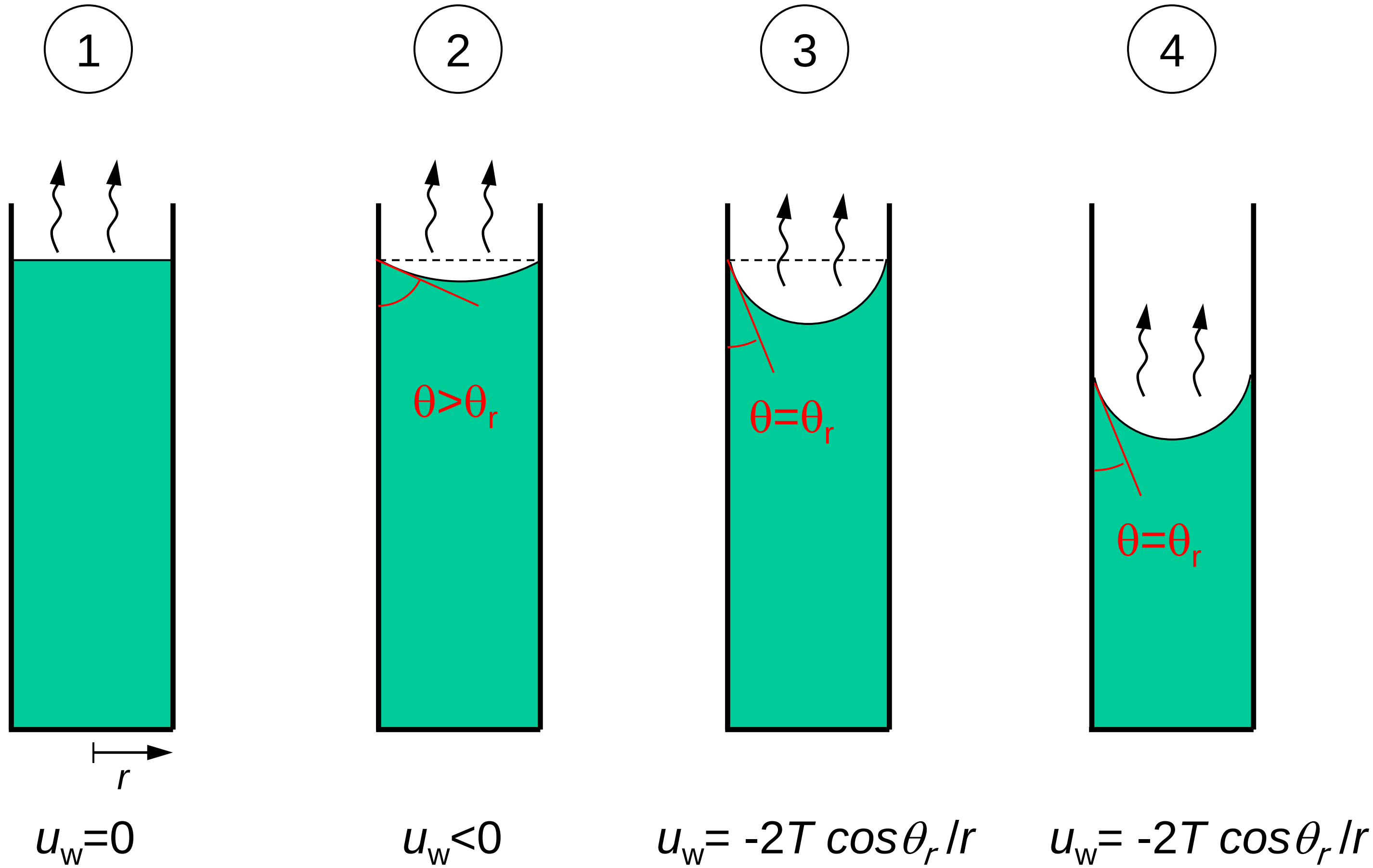


Hysteresis of the contact angle

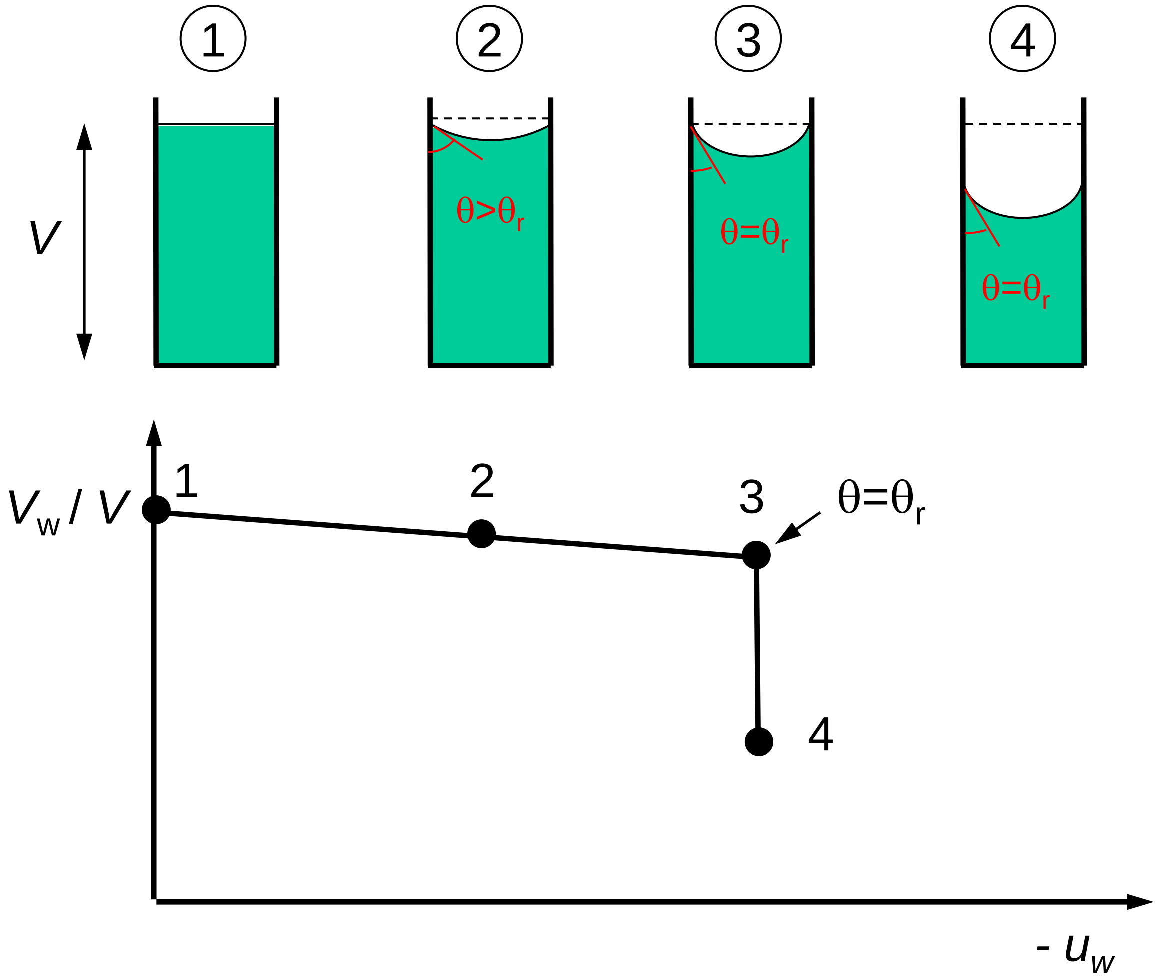




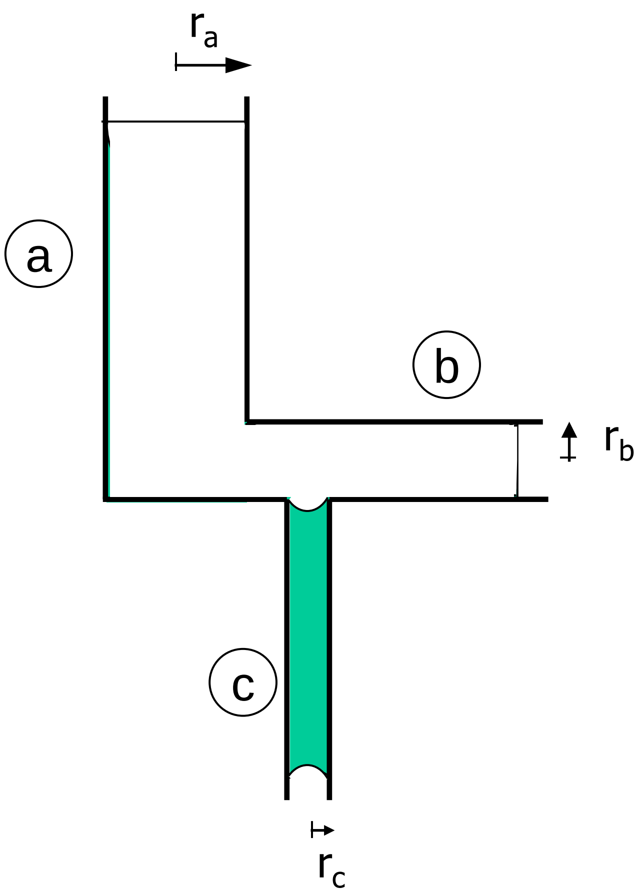
Evaporation from a capillary tube



Water retention of a capillary tube



Evaporation from a system of capillary tubes



Meechanical equilibrium

$$u_{wa} = u_{wb} = u_{wc}$$

$$\Downarrow$$

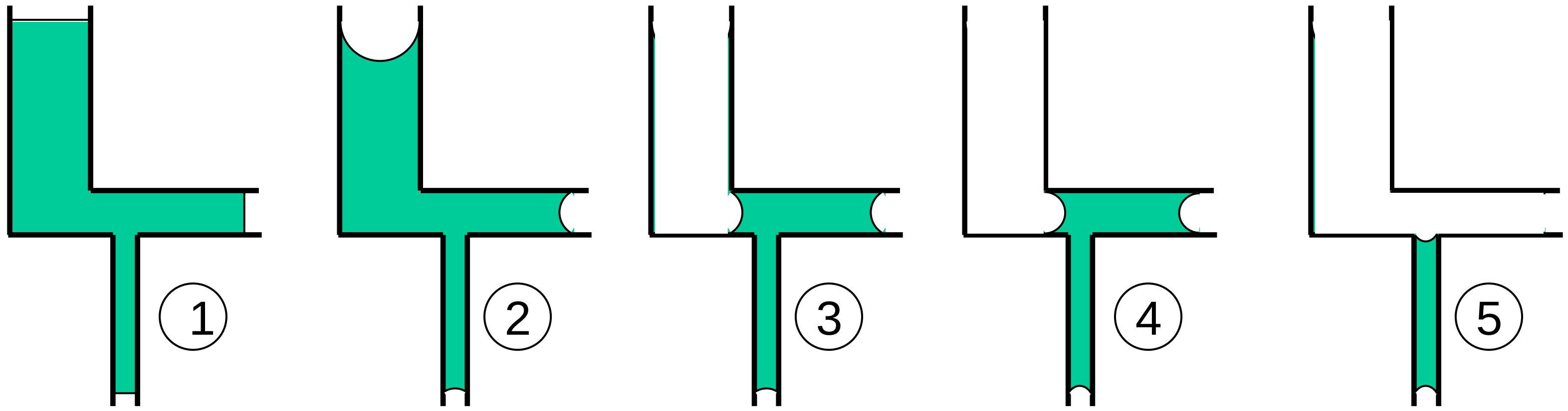
$$\frac{\cos\theta_a}{r_a} = \frac{\cos\theta_b}{r_b} = \frac{\cos\theta_c}{r_c}$$

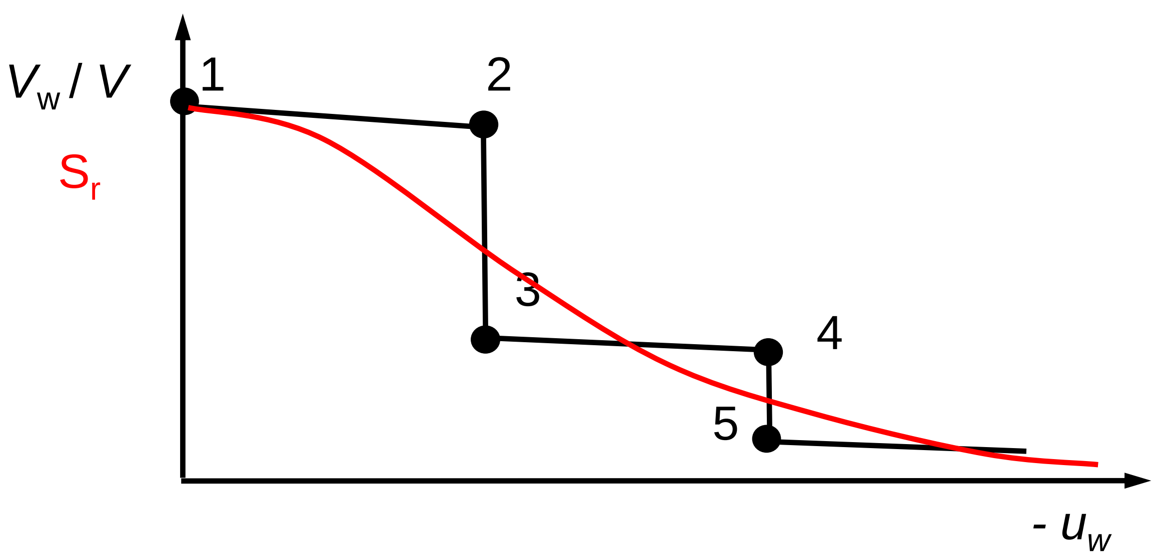
Geometry

$L_a = L_b = L_c$

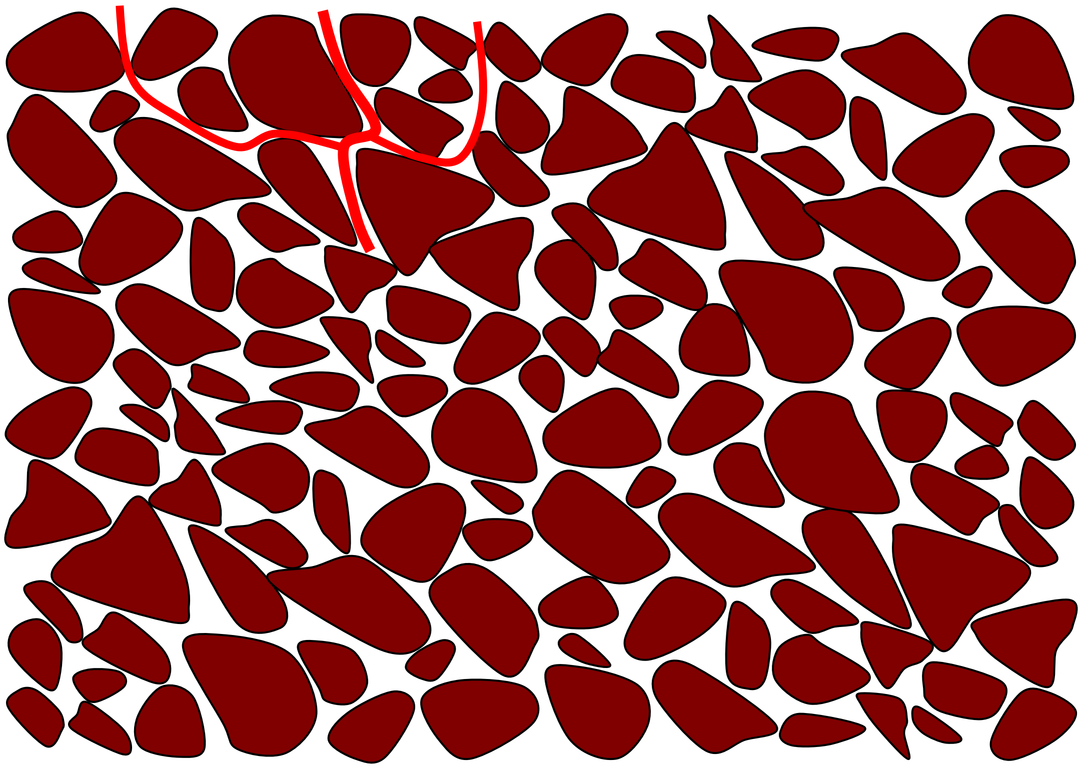
$r_a = 2\ r_b = 4\ r_c$

Water retention of a sytem of capillary tubes

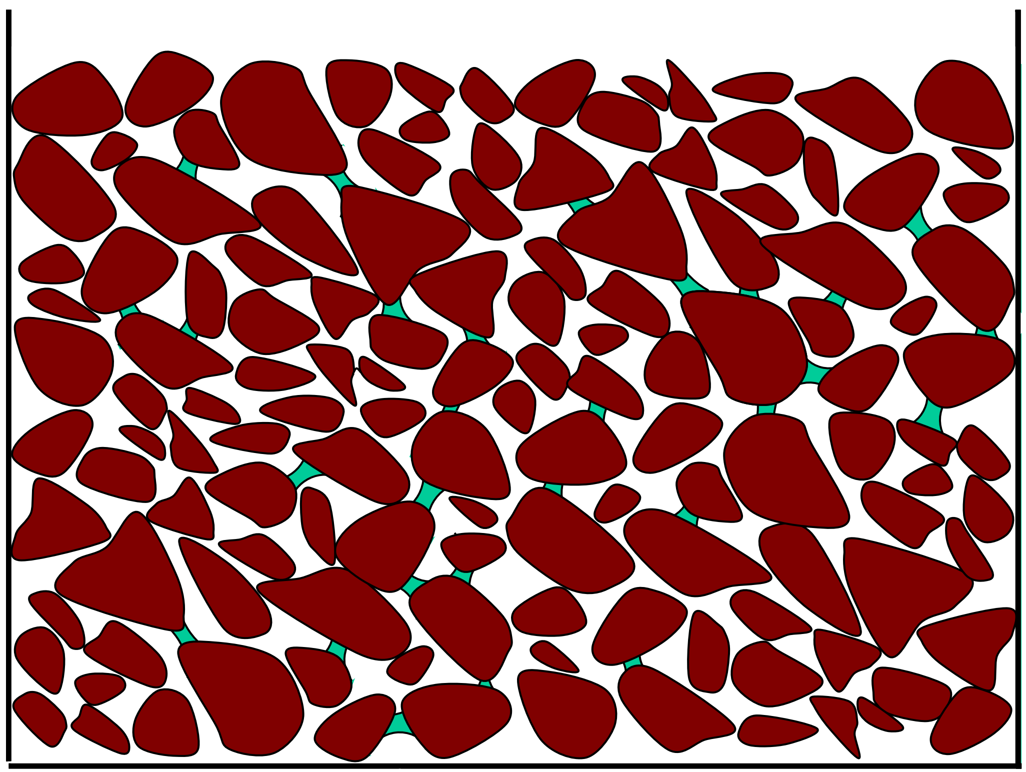




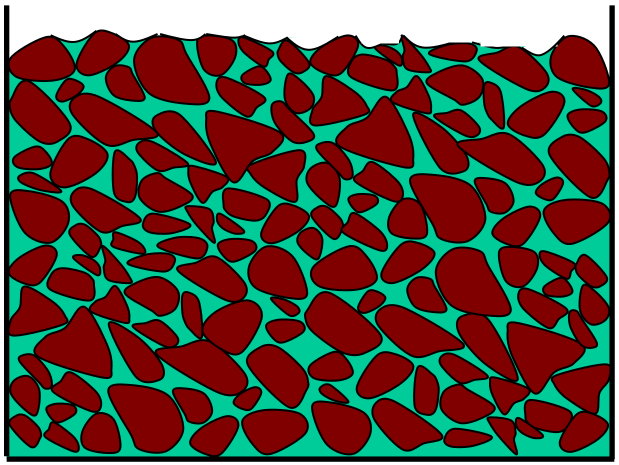
Soil as a system of capillary tubes



Evaporation from an initially saturated soil



Saturated state



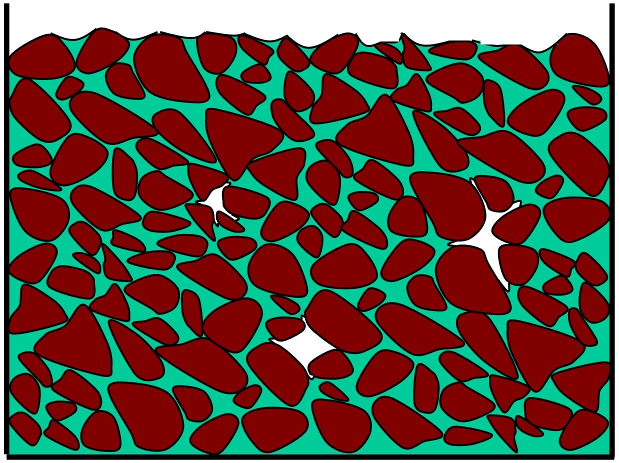
$S = 1$

$u_w < 0$

Suction is generated by the curving of menisci at the boundary

Soil is saturated, air is dissolved in water

Quasi-saturated state



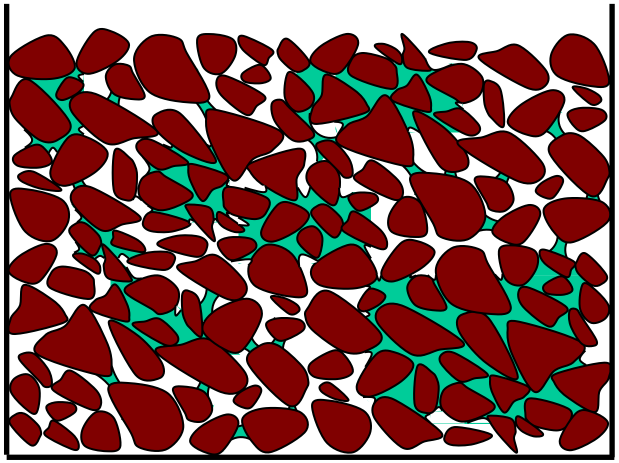
0.85-0.90 < S < 1

$u_w < 0$

Suction is generated by the curving of menisci at the boundary and cavities form in the pore water

Gas phase is discontinuous, liquid phase is continuous

Partially saturated state



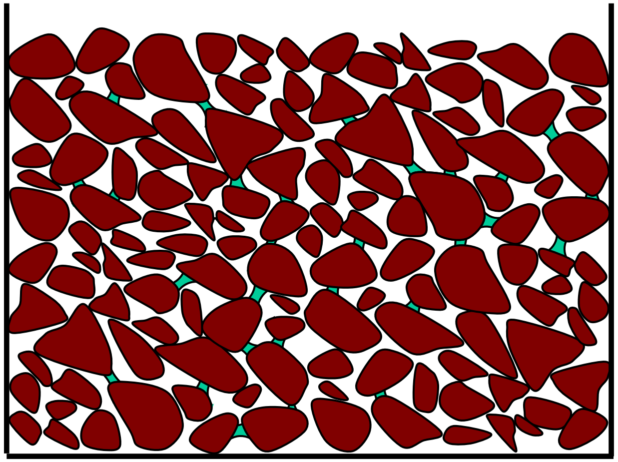
0-0.1 < S < 0.85-0.90

$u_w < 0$

Suction is generated by the curving of menisci in the pores, are saturated parts (bulk water) and part where menisci form at the interparticle contact

Gas phase is continuous, liquid phase is continuous

Residual state



S < 0-0.1

$u_w < 0$

Suction is generated by the curving of menisci in the pores, and menisci form at the interparticle contact

Gas phase is continuous, liquid phase is discontinuous

Water retention behaviour

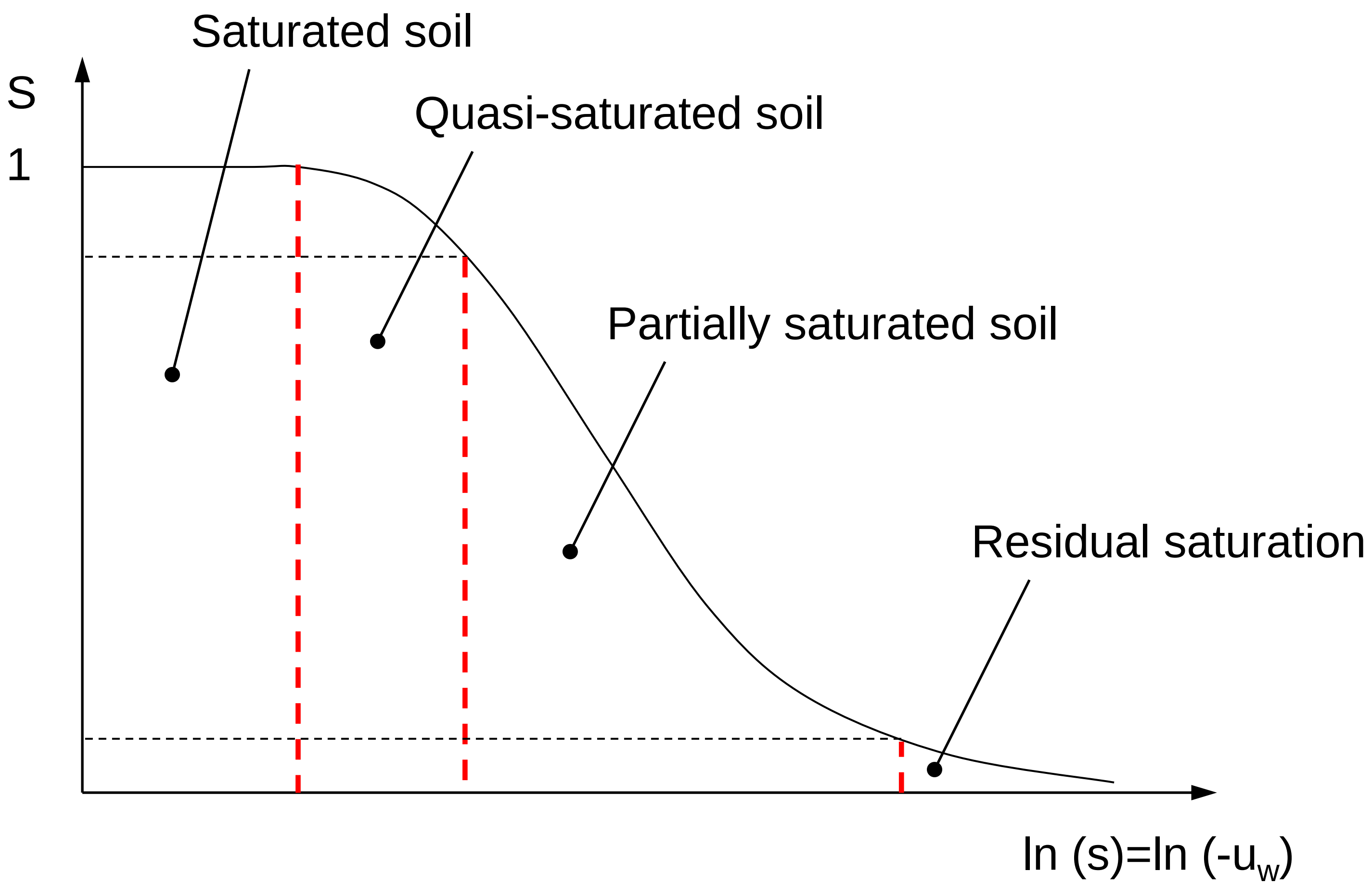
Relationship between the degree of saturation (or water content) and suction

This relationship illustates the different state of water in the soil

It is determined in the laboratory by subjecting soil specimens to drying and wetting cycles

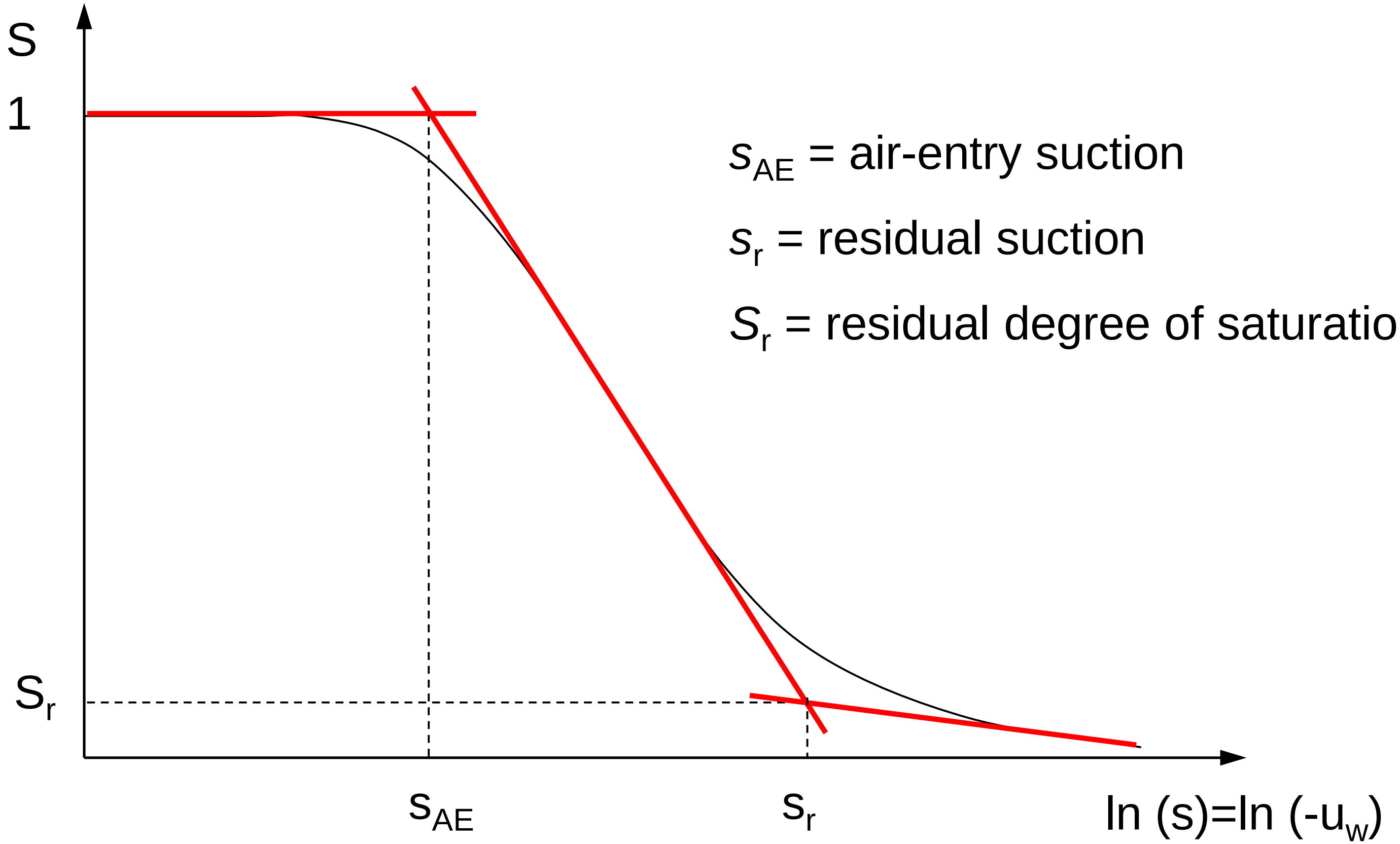
It is rarely determined in the field

Soil water rention



Suction is the opposite of pore-water pressure, $s = -u_w$

Retention curve parameters



s_{AE} = air-entry suction

s_r = residual suction

S_r = residual degree of saturation

Air-entry suction, s_{AE}

It is the suction where the soil desaturates

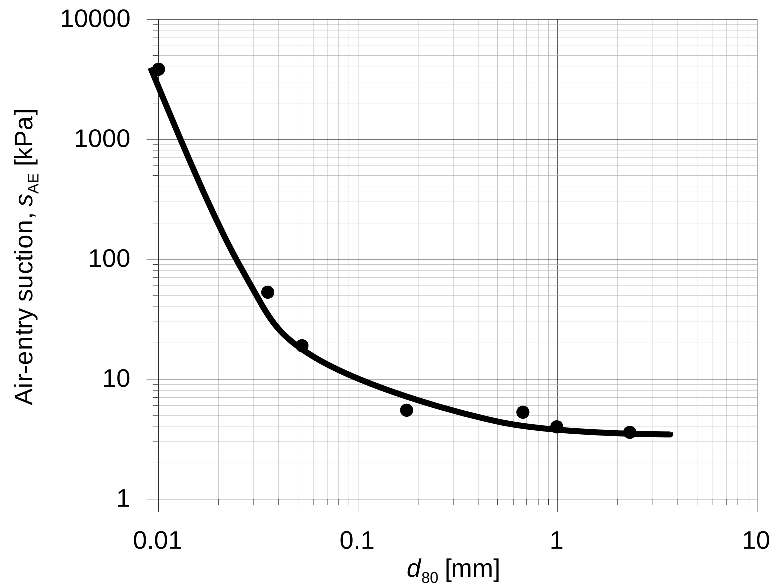
As a first approximation, the soil can be assumed saturated for suction lower than the air-entry value, s_{AE}

The air-entry suction essentialy depend on the pore size

For an order of magnitude if the air-entry suction :

sand **(d_{pore}=30 μm)**	**silt** **(d_{pore}=3 μm)**	**clay** **(d_{pore}=0.3 μm)**
10 kPa	**100 kPa**	**1000 kPa**

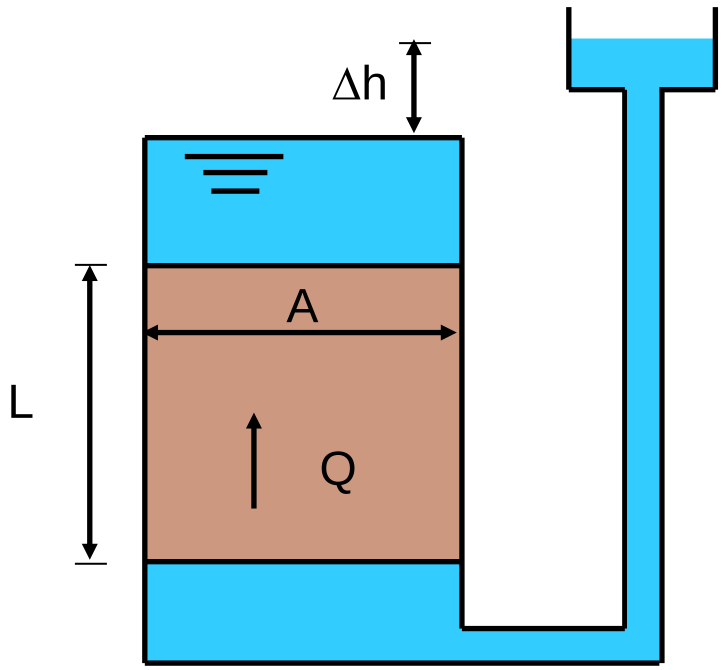
Estimating the air-entry suction



Relationship between suction at air-entry, s_{AE}, and grain size d_{80}.

Hydraulic conductivity behaviour

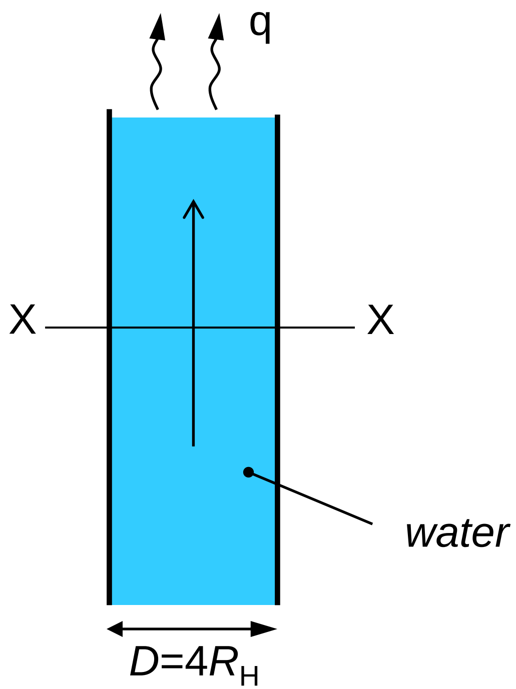
Darcy's law
(experiment)



$$v = \frac{Q}{A} = k\underbrace{\frac{\Delta h}{L}}_{i} = k \cdot i$$

v = flow velocity
Q = flow rate
A = total area
k = hydralic conductivity
Δh = hydraulic head differential
L = drainage lenght

Flow through a saturated capillary tube



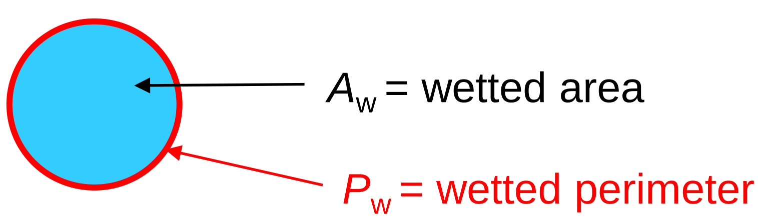
Poiseuille's law for laminar fluid flow

$$v_{act} = \frac{Q}{A_w} = \left[\frac{g}{2\eta} R_H^2\right] \cdot i$$

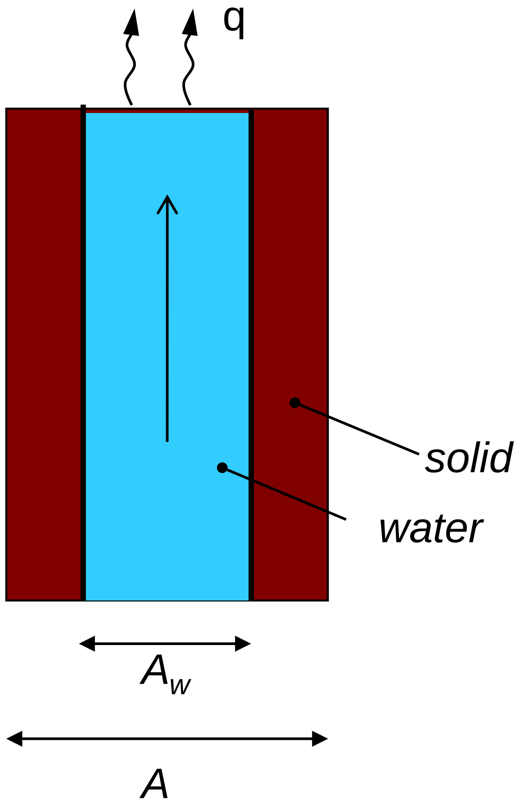
Q = flow rate
v_{act}= actual flow velocity
i = hydraulic gradient
A_w = wetted area
η = kinematic viscosity
γ = unit weight of the permeant
R = tube radius
R_H = hydraulic radius

$$R_H = \frac{\text{flow channel cross section area}}{\text{wetted perimeter}} = \frac{A_w}{P_w} = \frac{\pi \frac{D^2}{4}}{\pi D} = \frac{D}{4}$$

section X-X



Flow through a saturated capillary tube



$$v = \frac{Q}{A} = \frac{A_w}{A}\frac{Q}{A_w} = n\frac{Q}{A_w}$$

$$\left[n = \frac{A_w}{A} = porosity\right]$$

$$v = \overbrace{\left[n\frac{g}{2\eta}R_H^2\right]}^{k} \cdot i$$

Saturated hydraulic conductivity

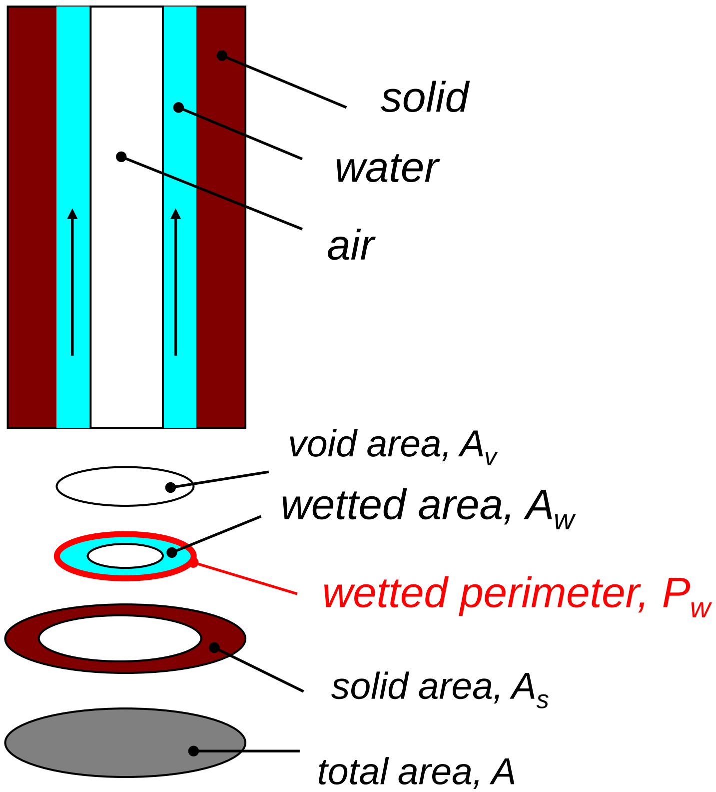
Hydraulic conductivity

$$k = n\frac{g}{32\eta}D^2 = n\frac{9.8\,\frac{m}{s^2}}{32\cdot 10^{-6}\,\frac{m^2}{s}}D^2 = n\left(3\cdot 10^5\,\frac{1}{sm}\right)D^2$$

(Kinematic viscosity of water at 20°C $\eta = 10^{-6}$ m^2/s)

	sand	silt	clay	
d_{grain} (μm)	300	30	3	
d_{pore} (μm)	30	3	0.3	*D*
$n \cdot k$ *(m/s)*	$3\cdot10^{-4}$	$3\cdot10^{-6}$	$3\cdot10^{-9}$	

Flow through an unsaturated capillary tube



S_0 = specific surface
S_r = degree of saturation
e = void ratio

As for the saturated tube:

$$A_w = S_r \frac{e}{1+e} A$$

$$P_w = A_s S_0 = \frac{1}{1+e} A S_0$$

$$v = \frac{v_{act} \cdot A_w}{A} = \left[\frac{g}{2\eta} \left(\frac{A_w}{P_w} \right)^2 \right] \cdot \frac{A_w}{A} \cdot i$$

$$\Downarrow$$

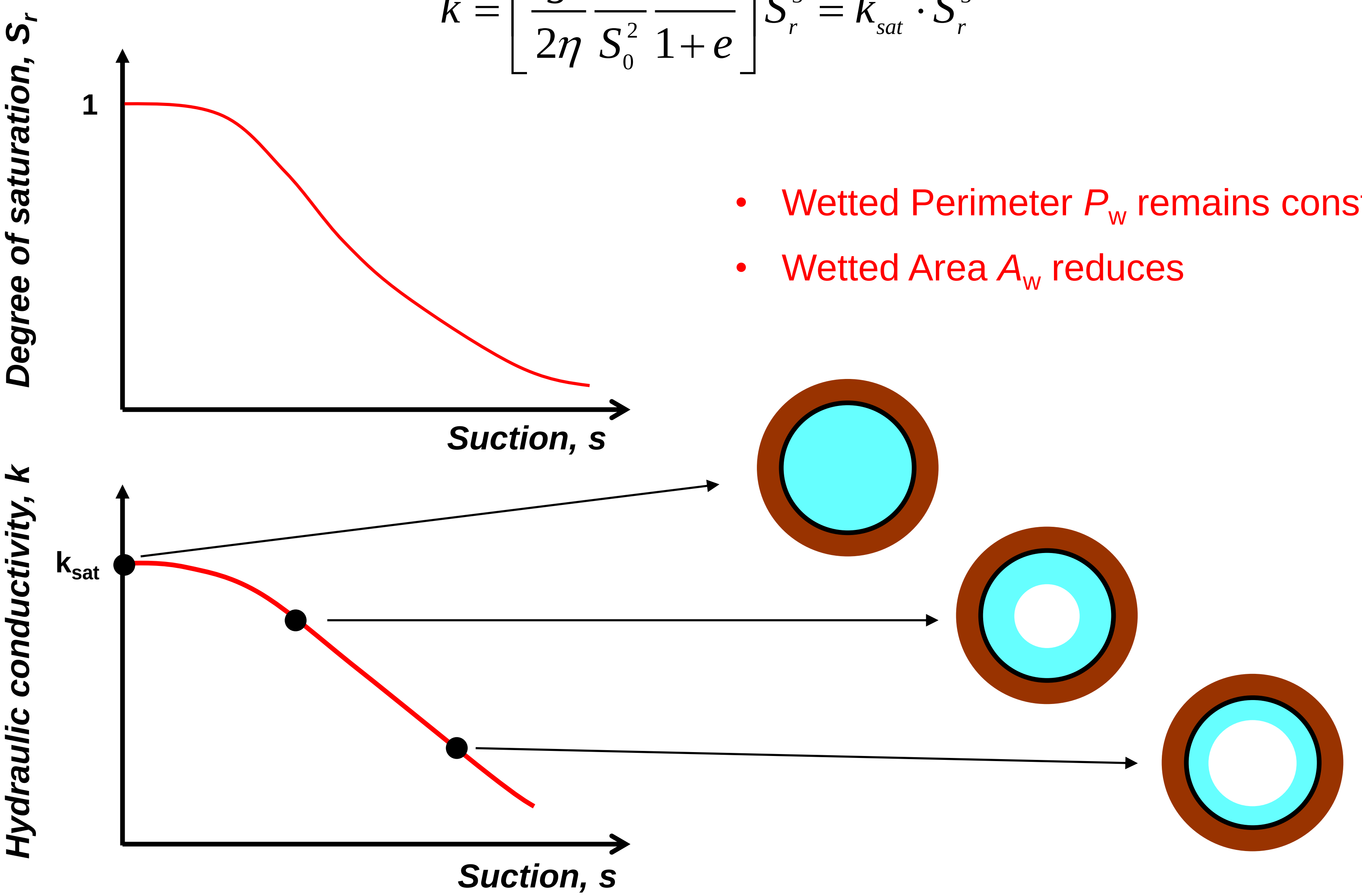
$$v = \overbrace{\left[\frac{g}{2\eta} \frac{1}{S_0^2} \frac{e^3}{1+e} S_r^3 \right]}^{k} \cdot i$$

Kozeny-Carman equation

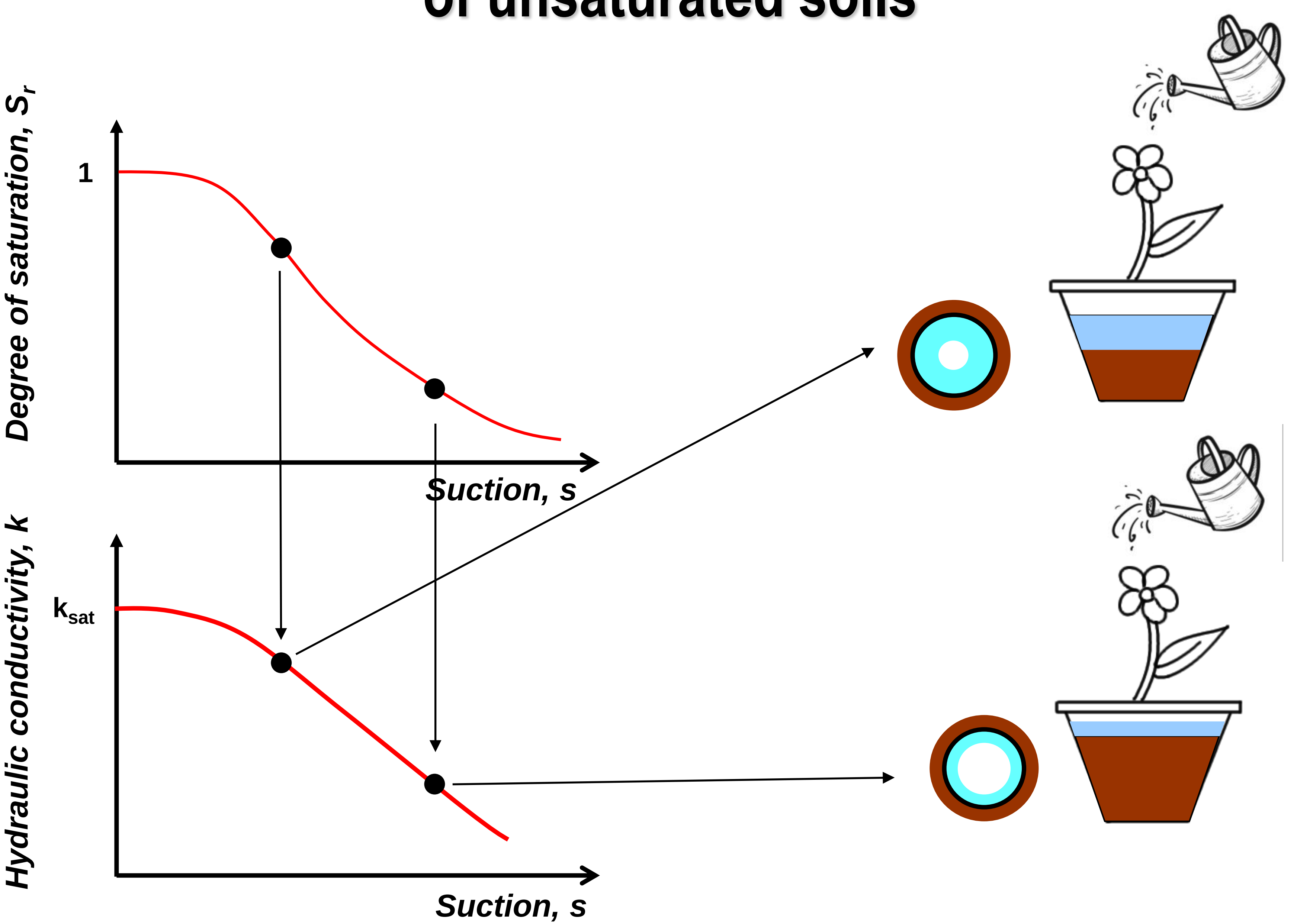
Hydraulic conductivity of unsaturated soils

$$k = \left[\frac{g}{2\eta} \frac{1}{S_0^2} \frac{e^3}{1+e} \right] S_r^3 = k_{sat} \cdot S_r^3$$

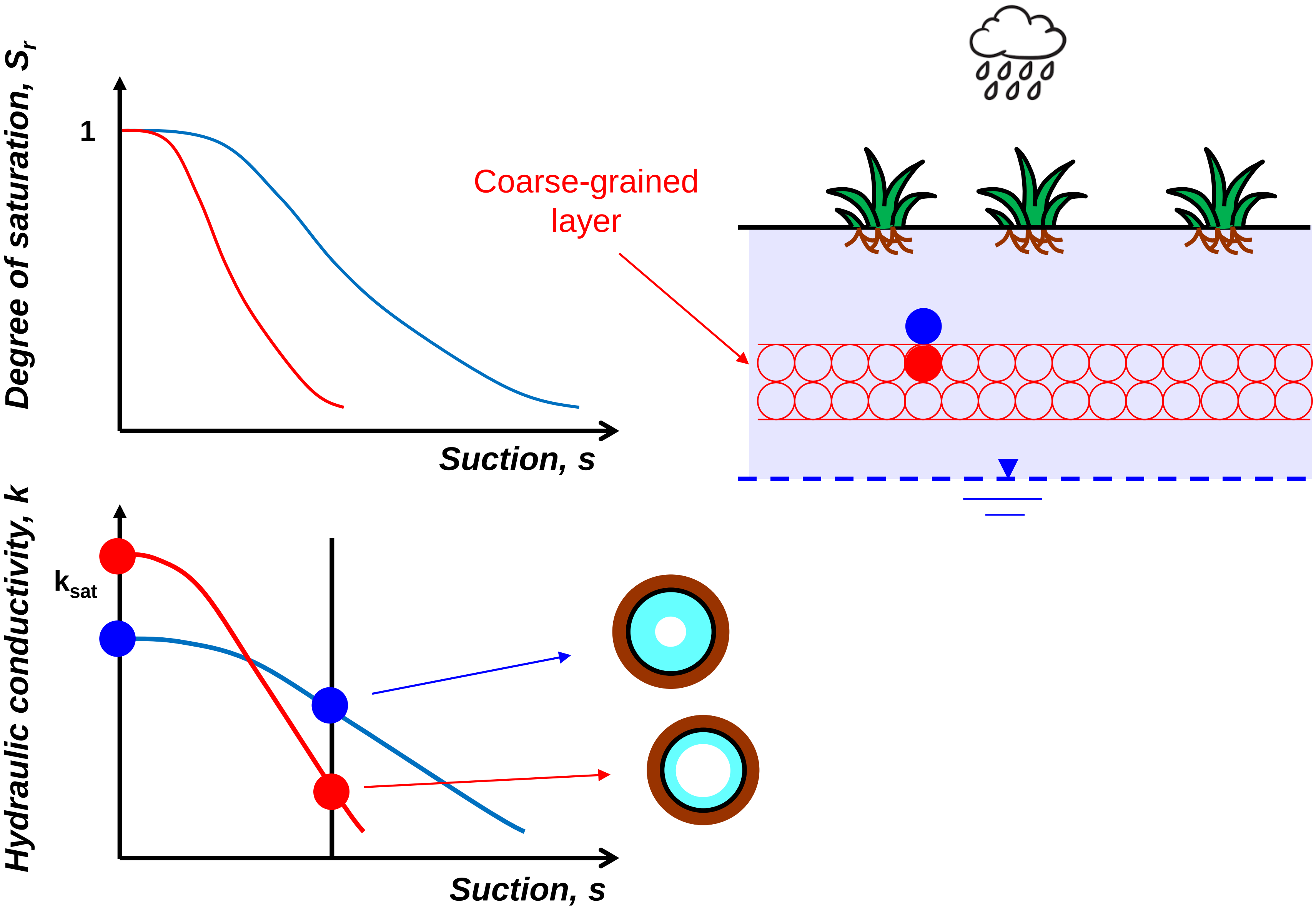
- Wetted Perimeter P_w remains constant
- Wetted Area A_w reduces



Real life example of hydraulic conductivity behaviour of unsaturated soils



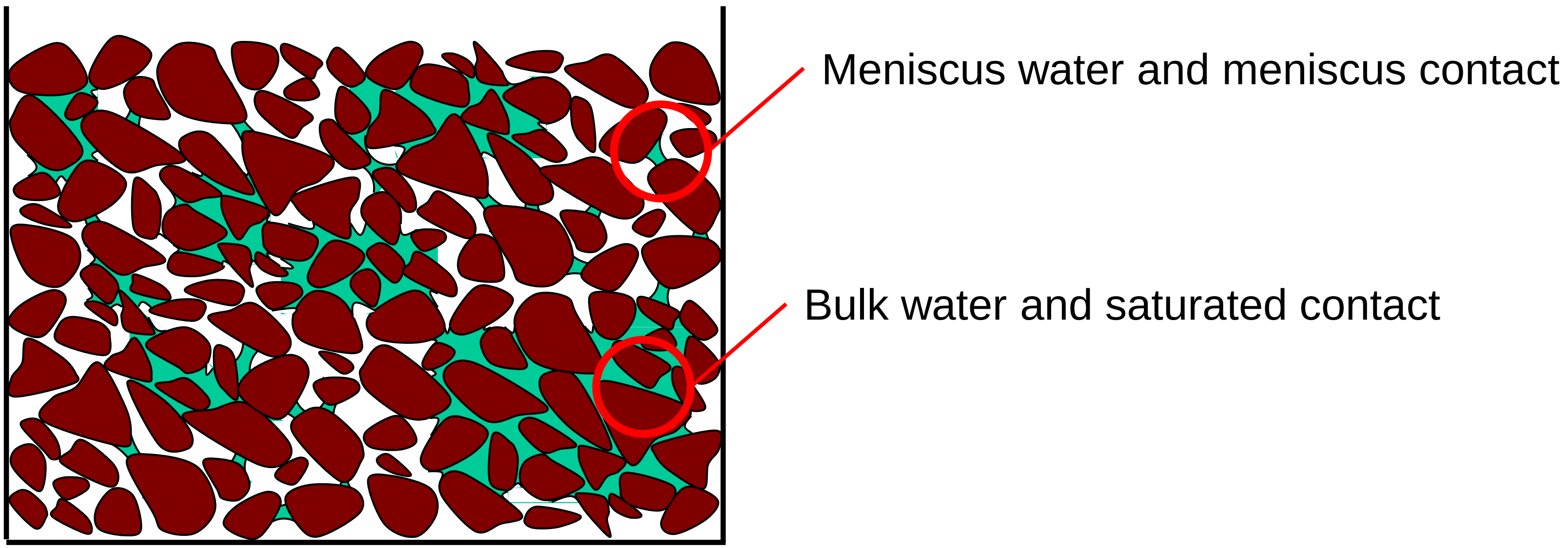
Real life example of hydraulic conductivity behaviour of unsaturated soils: capillary barrier



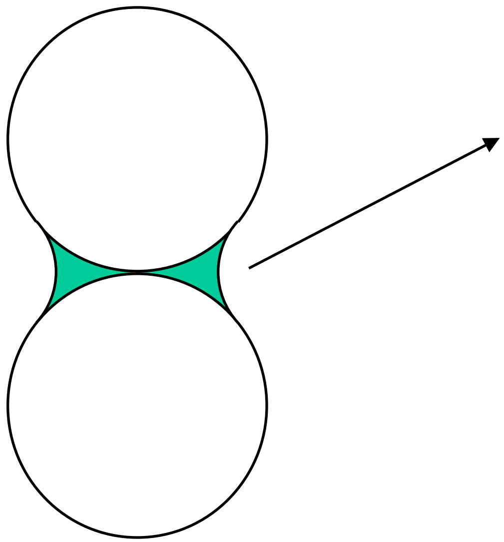
~~Micro-mechanical insight into shear strength of unsaturated geomaterials~~

Tarantino A, Di Donna A (2019). Mechanics of unsaturated soils: simple approaches for routine engineering practice. Rivista Italiana di Geotecnica N. 4/2019

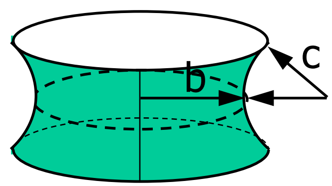
Bulk water and meniscus water



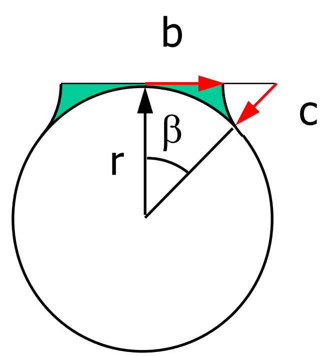
Contact between spherical particles in presence of meniscus



Plateau Nodoide



$$u_w - u_a = -T\left(\frac{1}{c} - \frac{1}{b}\right)$$

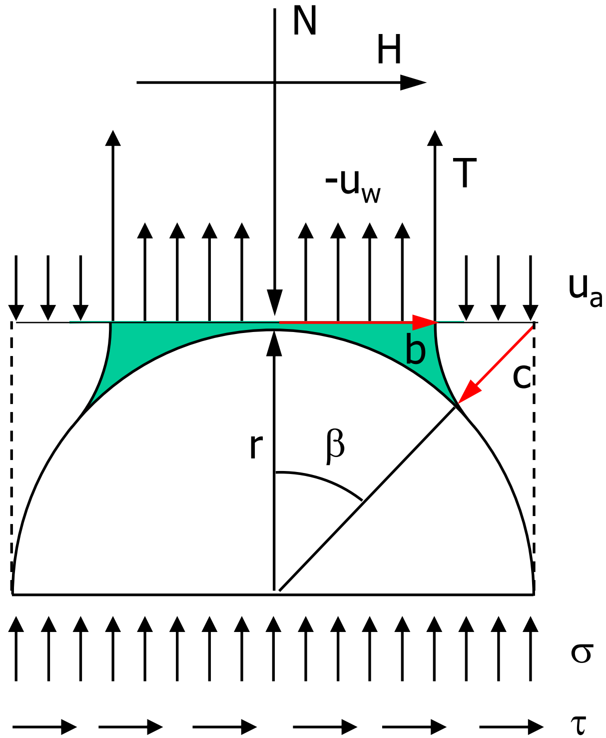


$$c = r\left(\frac{1}{\cos\beta} - 1\right)$$

$$b = r\left(1 + \tan\beta - \frac{1}{\cos\beta}\right)$$

For b=53°, $c \equiv b$ ⇒ $u_w - u_a = 0$

Intergranular stress in presence of menisci



$$\sigma_i = \frac{N}{A} = (\sigma - u_a) + (u_a - u_w)\frac{A_w}{A} - T\frac{P_w}{A_w}$$

Total stress

Capillary water

$$\sigma_i = \frac{N}{A} = \boxed{(\sigma - u_a)} + \boxed{\frac{1}{A}\left[A_w + \frac{cb}{b-c}P_w\right](u_a - u_w)}$$

suction

$$\sigma_i = (\sigma - u_a) + \underbrace{\frac{1}{\pi r^2}\left[\pi b^2 + \frac{cb}{b-c}2\pi b\right](u_a - u_w)}_{f(\beta) \Rightarrow f(S_r)}$$

$$\sigma_i = (\sigma - u_a) + \frac{1}{\pi r^2}\left[\pi b^2 + \frac{cb}{b-c}2\pi b\right](u_a - u_w)$$

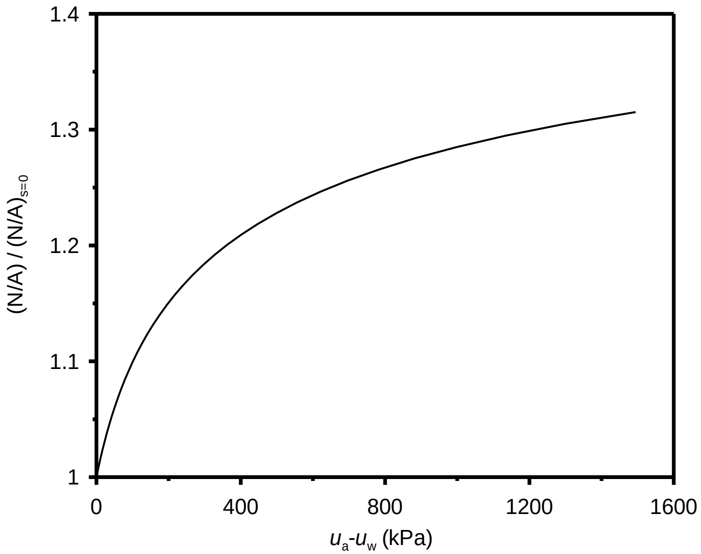
N = normal intergranular force
H = shear intergranular force
u_w = water pressure
u_a = air pressure
T = surface tension

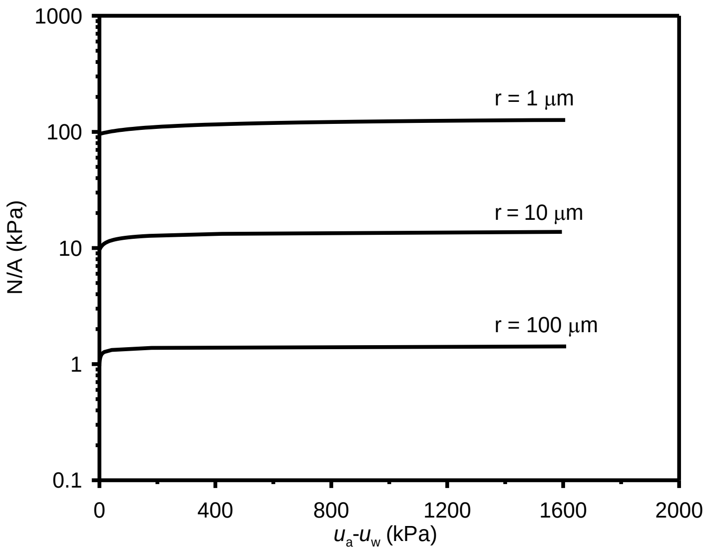
P_w = wet perimeter
A = totale area
A_w = wet area
σ = total normal stress
τ = shear stress

See Tutorial T2c - Mechanical interactions at particle scale

Effect of meniscus suction on intergranular stress

$$(\sigma_i)_m = \left.\frac{N}{A}\right|_{u_a-u_w} = \frac{1}{A}\left[A_w + \frac{cb}{b-c}P_w\right](u_a-u_w) = \frac{2T}{r}\left[\frac{1}{1+\tan\left(\frac{\beta}{2}\right)}\right]$$

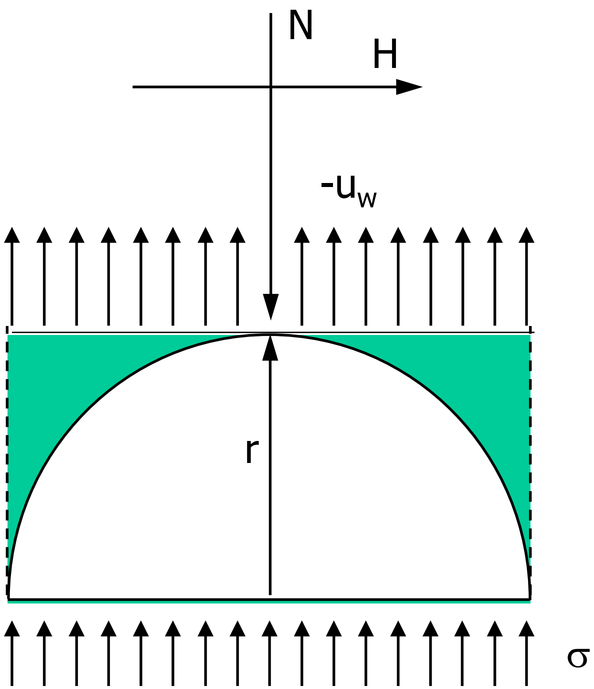




The integranular stress associated with meniscus suction undergoes little variation as suction increases.

As a first approximation, the integranular stress generated by meniscus suction can be assumed to be constant

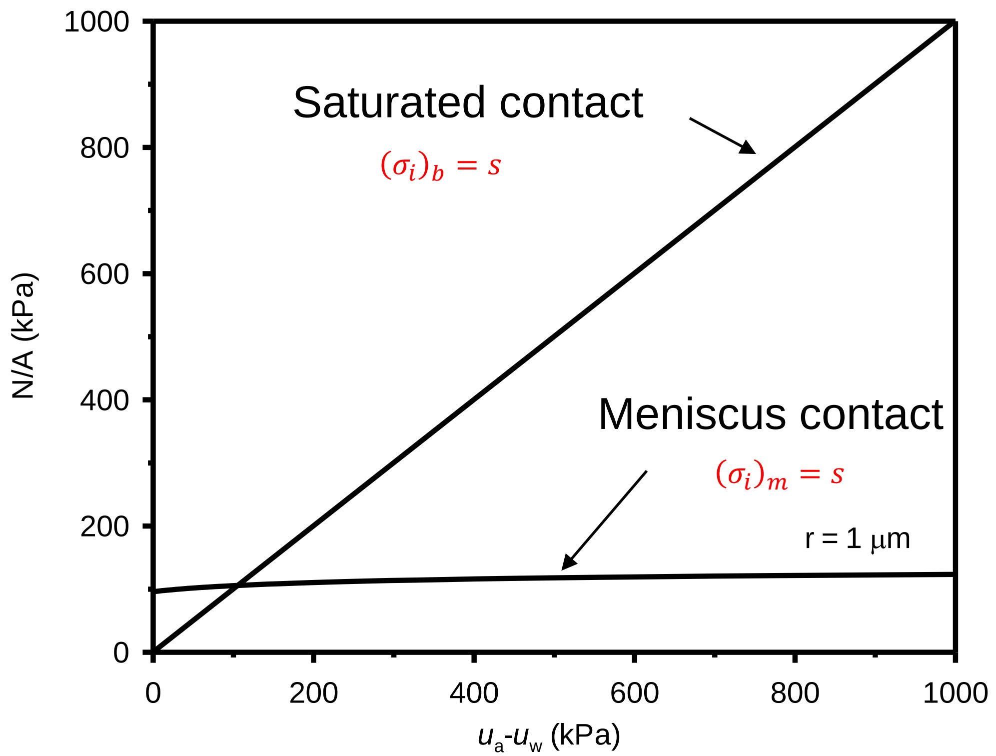
Effect of bulk suction on intergranular stress



$$\sigma_i = \frac{N}{A} = \sigma - u_w = \sigma + s$$

Effect of suction on intergranular stress for saturated contact

$$\left.\frac{N}{A}\right|_{u_a - u_w} = -u_w$$



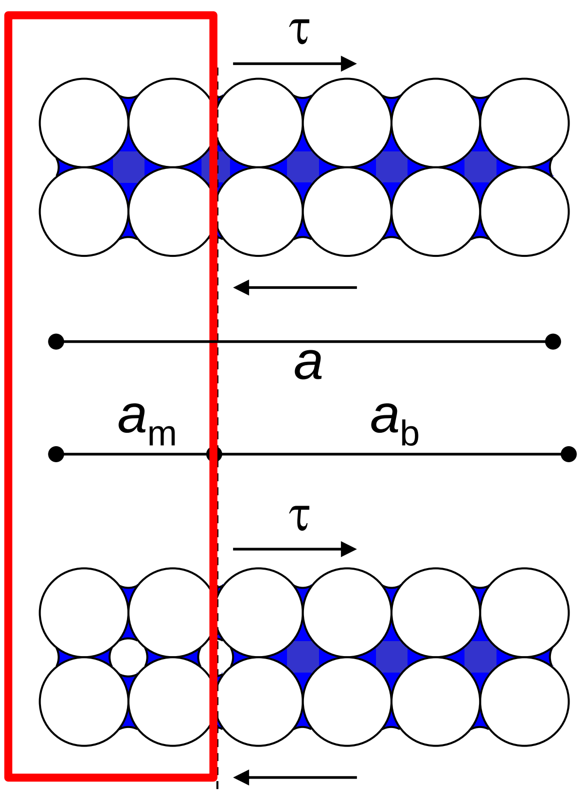
For saturated contact, the intergranular stress changes linearly with suction

Effect of suction on shear strength

ASSUMPTION

$$\tau = \sigma_i \cdot \tan \phi'$$

This may be acceptable only from a qualitative point of view !!



$$(\sigma_i)_s = (\sigma_i)_b = s$$

$$\Downarrow$$

$$(\sigma_i)_s = s\frac{a_m}{a} + s\frac{a_b}{a}$$

Saturated

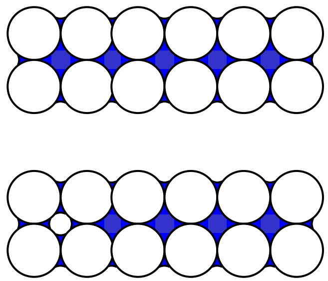
$$(\sigma_i)_s = (\sigma_i)_m\frac{a_m}{a} + (\sigma_i)_b\frac{a_b}{a}$$

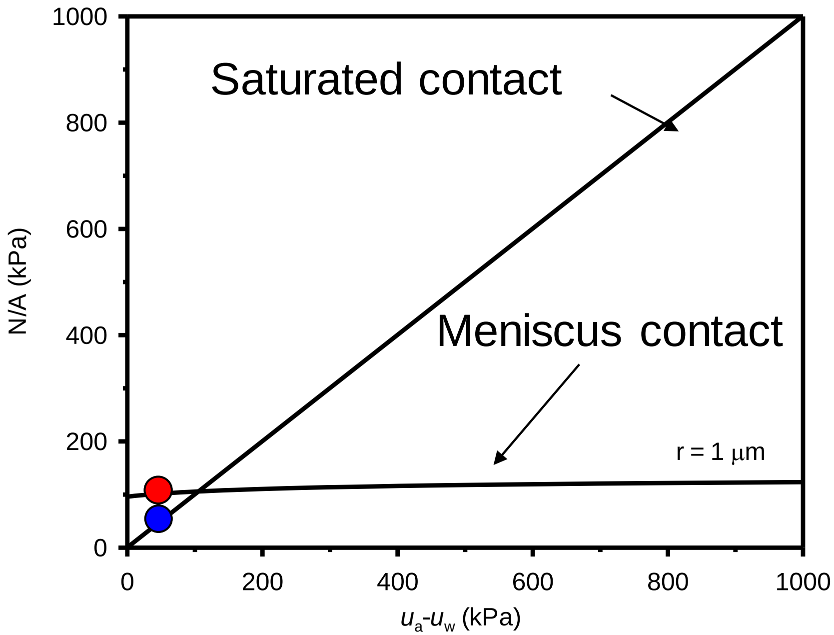
$$\Downarrow$$

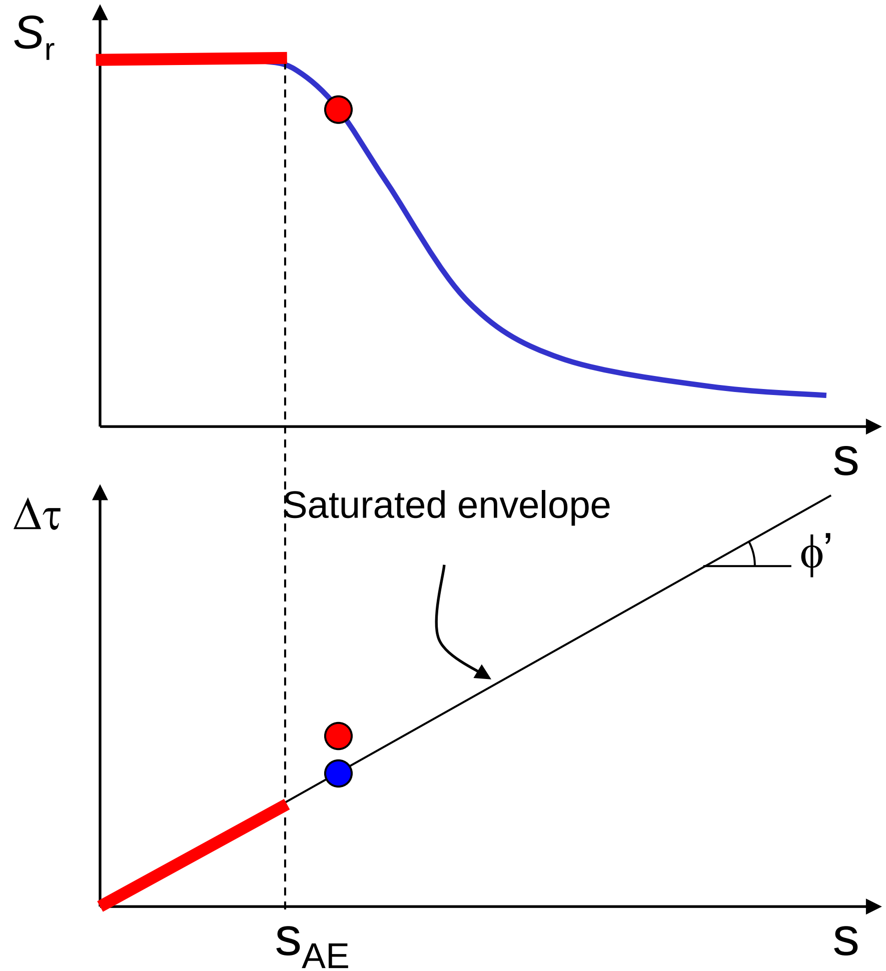
$$(\sigma_i)_s = (\sigma_i)_m\frac{a_m}{a} + s\frac{a_b}{a}$$

Partially saturated

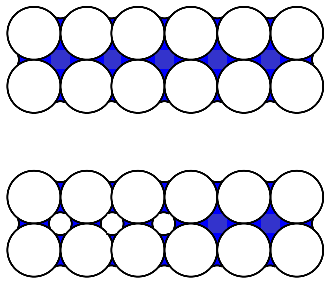
Shear strength of unsaturated soils:
Quasi-saturated state

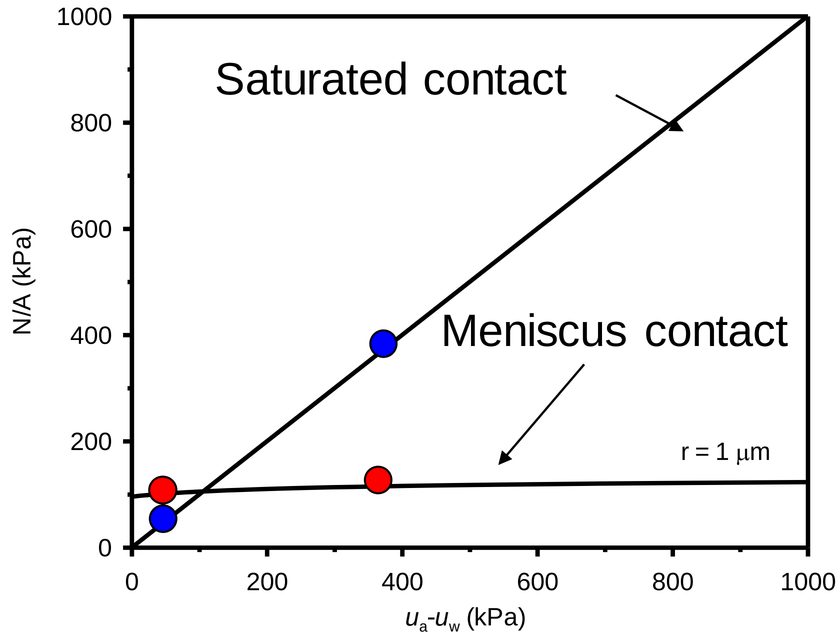


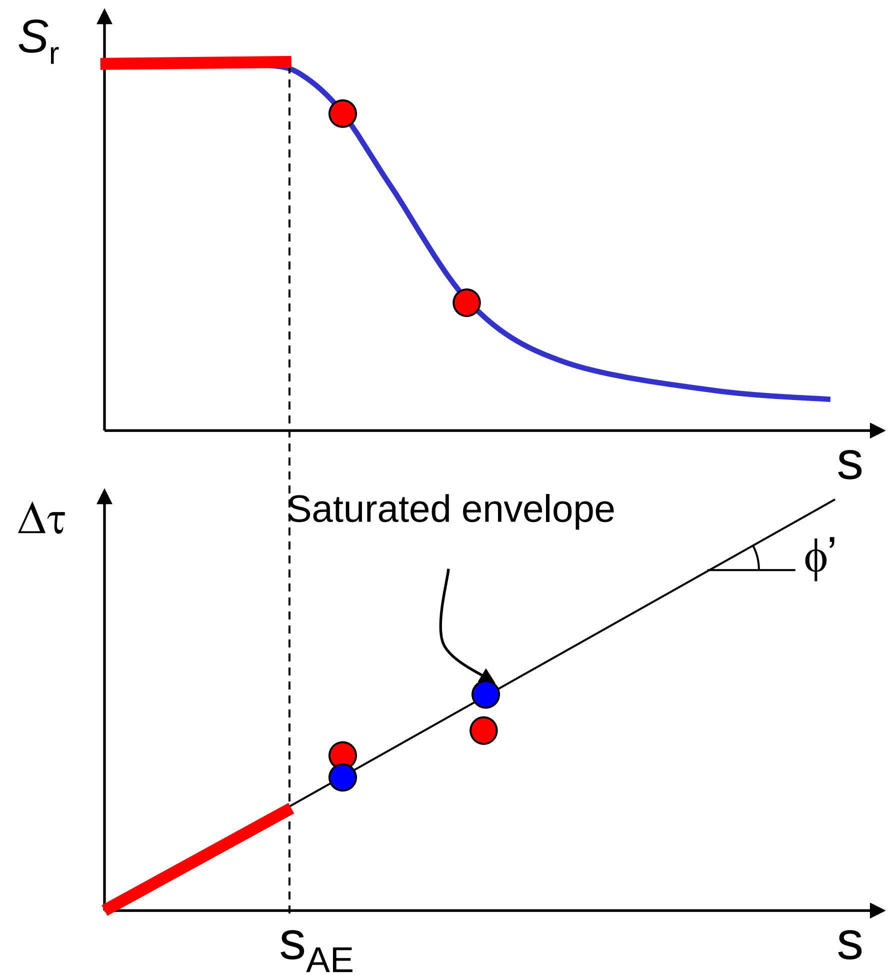




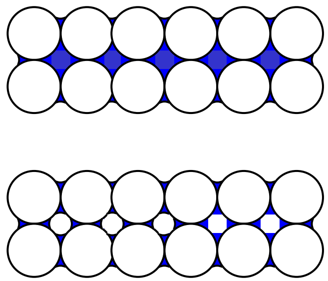
Shear strength of unsaturated soils: Partially saturated state

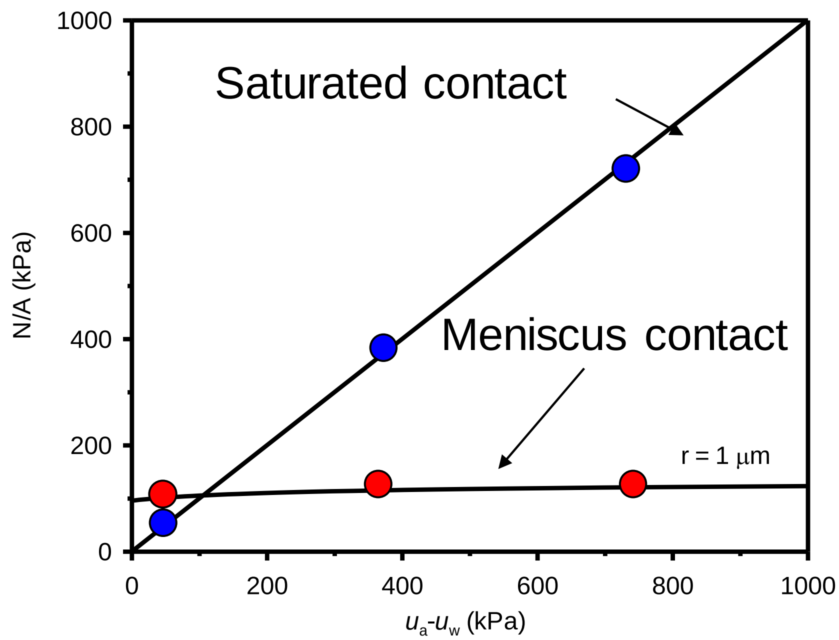


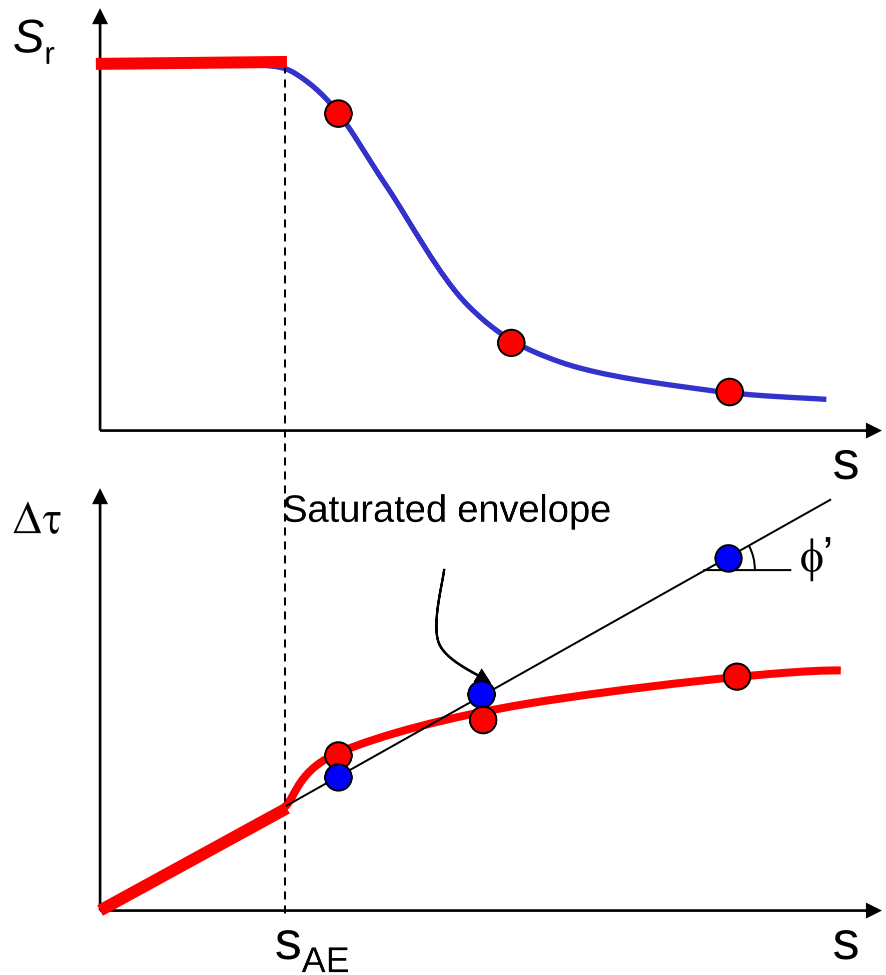




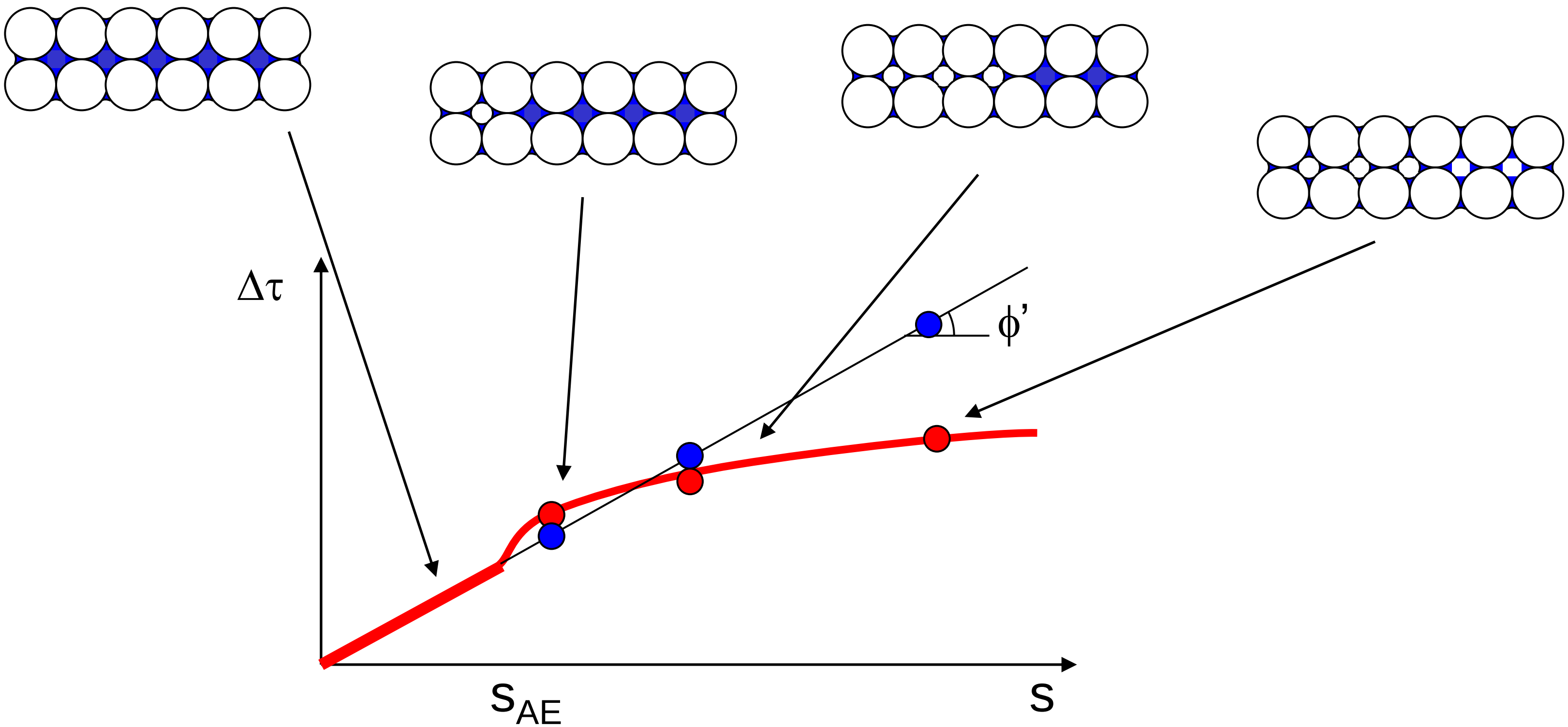
Shear strength of unsaturated soils: Residual state







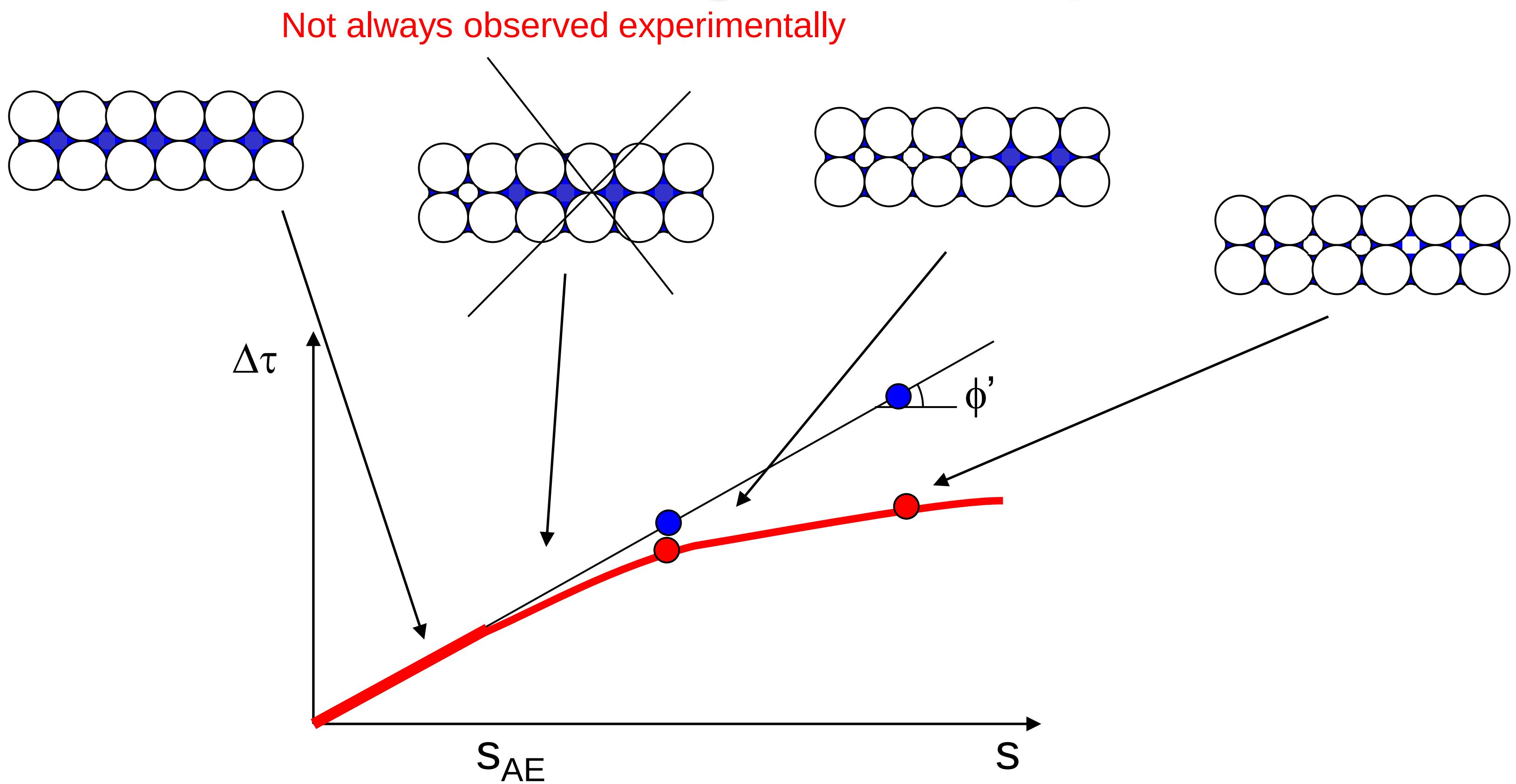
Shear strength envelope



Shear strength depends on suction (controlling the integranular stress in the bulk water) and on the number of menisci, in turn controlled by the degree of saturation

$$\Delta\tau = \Delta\tau\,(s,\,S_r)$$

Shear strength envelope



Shear strength depends on suction (controlling the integranular stress in the bulk water) and on the number of menisci, in turn controlled by the degree of saturation

$$\Delta\tau = \Delta\tau\ (s,\ S_r)$$

Shear strength behaviour

Shear strength of saturated soils

Saturated state

$$\tau = (\sigma - u_w) \tan \phi'$$

$$\Downarrow$$

$$\tau = (\sigma + s) \tan \phi'$$

$$\Downarrow$$

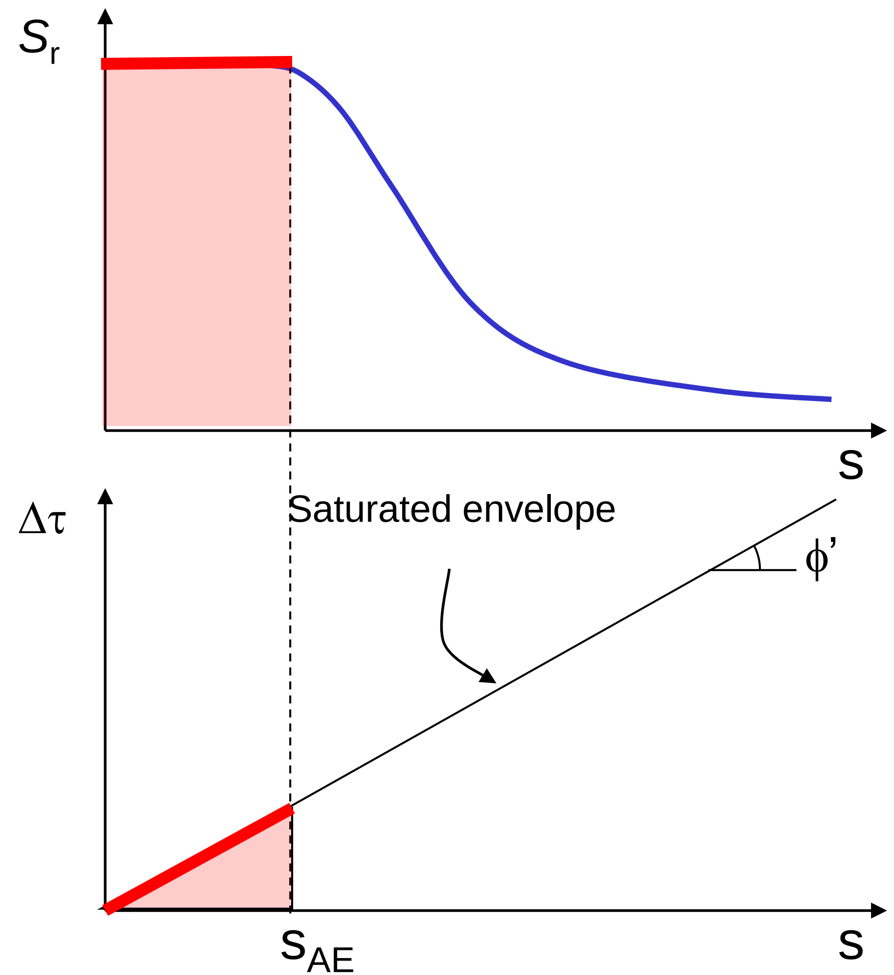
$$\tau = \sigma \tan \phi' + s \tan \phi'$$

$$\Downarrow$$

$$\tau = \sigma \tan \phi' + \Delta\tau(s)$$

$$\downarrow$$

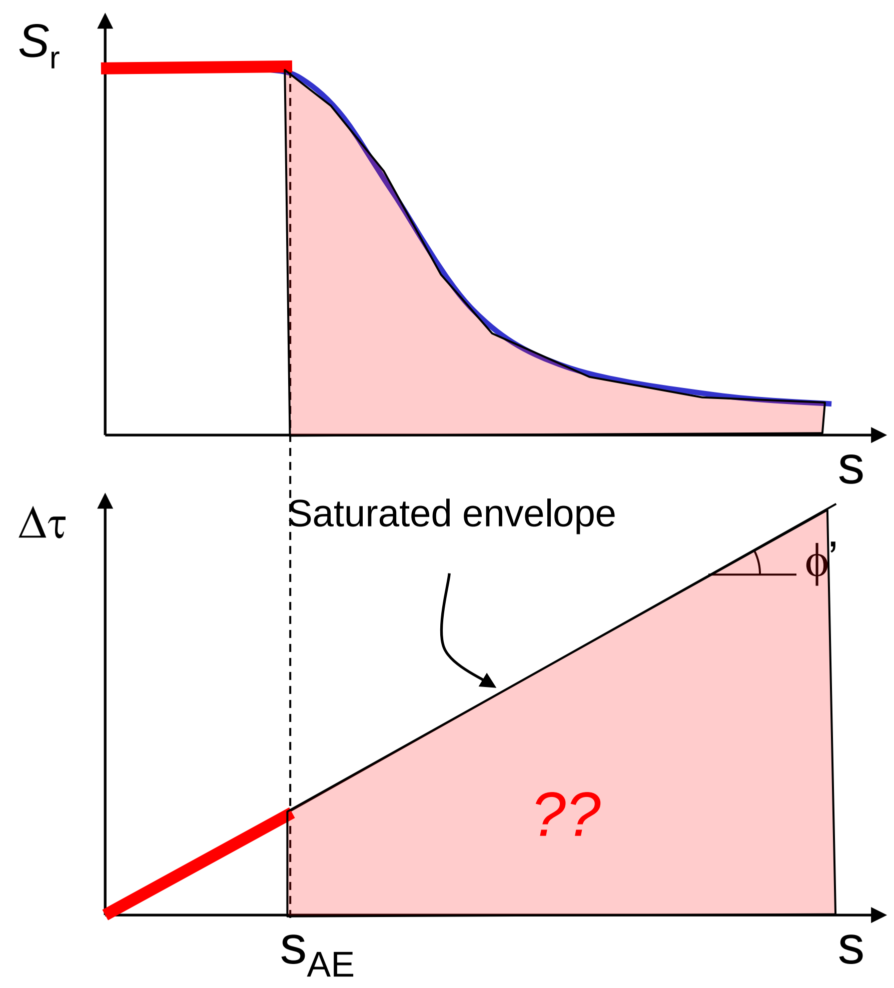
$$s \tan \phi'$$



Shear strength of unsaturated soils

$$\tau = \sigma \tan \phi' + \color{red}{\boldsymbol{\Delta\tau(s)}}$$

??



Shear strength criteria for sandy/silty unsaturated soils

Sandy/Silty soils

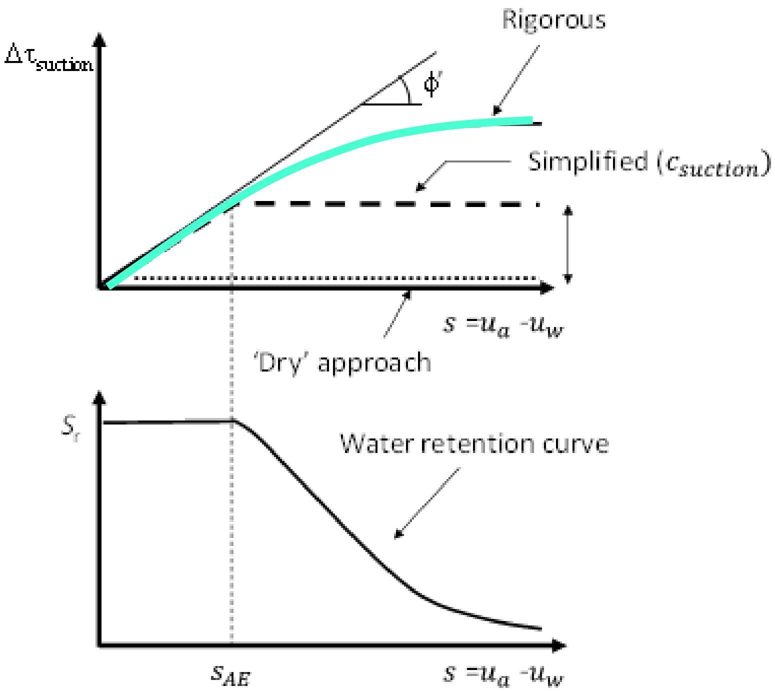
$$\Delta\tau_{suction} = s \cdot \tan\phi' \qquad s \leq s_{AE}$$

$$\Delta\tau_{suction} = (s \cdot S_r) \cdot tan\phi' \qquad s > s_{AE}$$

$$\tau = \sigma \cdot \tan\phi' + \overbrace{(s \cdot S_r) \cdot tan\phi'}^{\Delta\tau_{suction}=c_{suction}}$$

$$\tau = \underbrace{(\sigma + s \cdot S_r)}_{Unsaturated\ effective\ sress} \cdot \tan\phi'$$

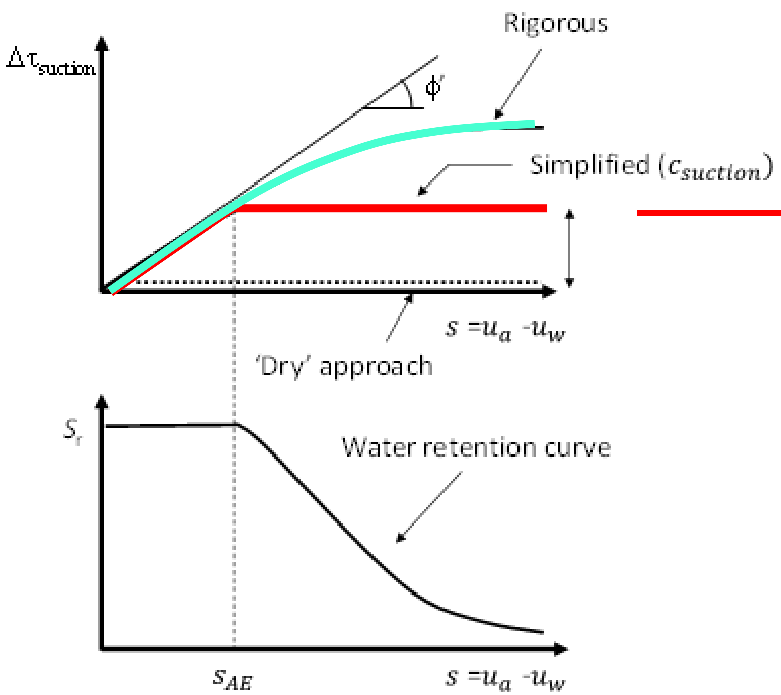
$$\tau = \underbrace{(\sigma - u_w \cdot S_r)}_{Unsaturated\ effective\ sress} \cdot \tan\phi'$$



- Need for the relationship between suction s and degree of saturation S_r, i.e. water retention curve
- Need to predict evolution of suction s and degree of saturation S_r in response to rainfall, i.e. water retention curve and hydraulic conductivity

Simplified shear strength criterion for geotechnical applications

$$\Delta\tau_{suction} = s \cdot \tan\phi' \qquad s \leq s_{AE}$$
$$\Delta\tau_{suction} = s_{AE} \cdot \tan\phi' \qquad s > s_{AE}$$



$$\Delta\tau_{suction} = s_{AE} \cdot \tan\phi'$$

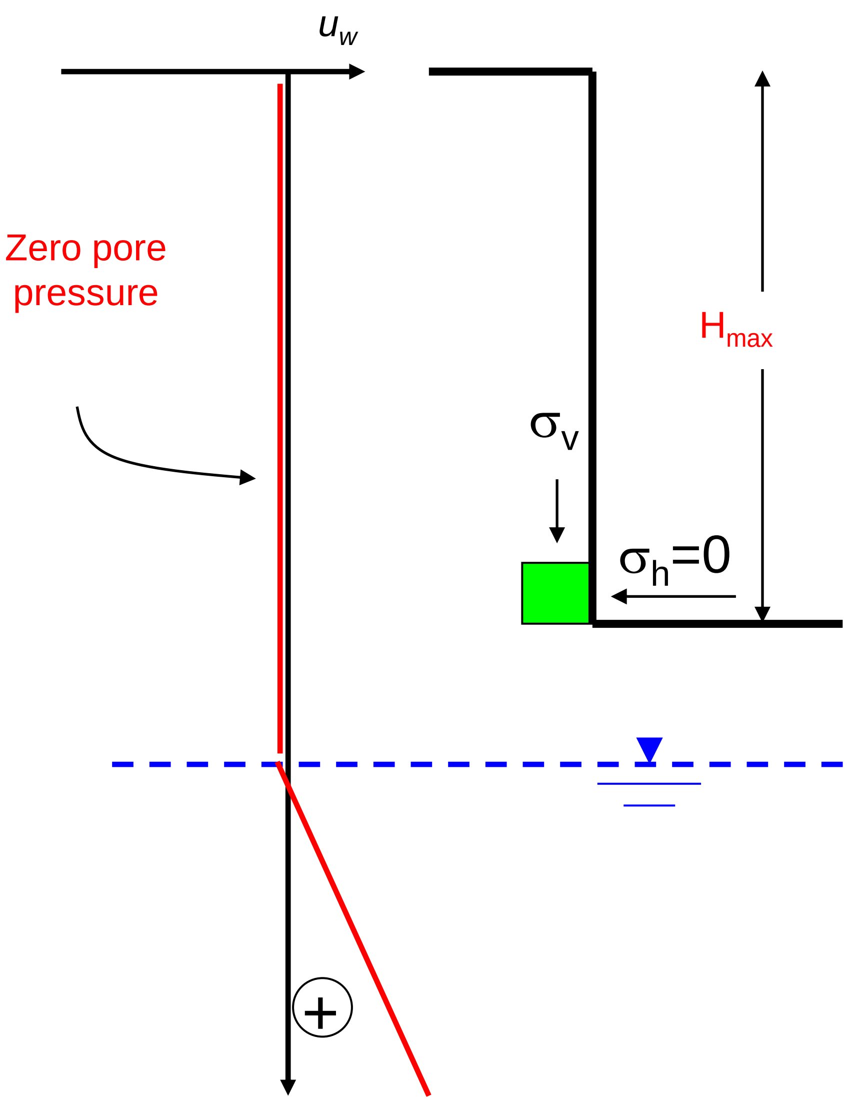
Silt

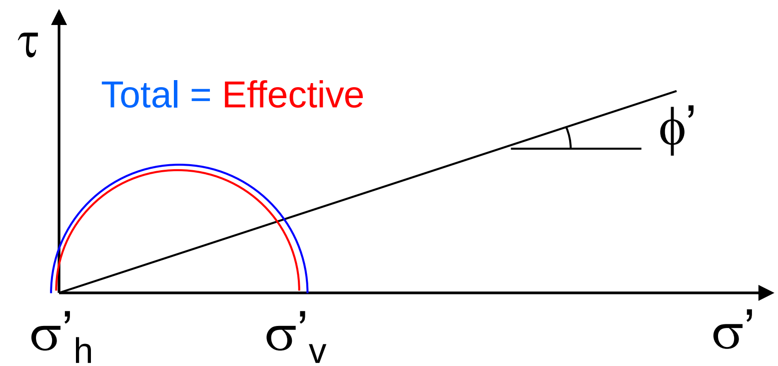
$$\Delta\tau_{suction} = 100\ kPa \cdot \tan 28° = 50\ kPa$$

Sand

$$\Delta\tau_{suction} = 10\ kPa \cdot \tan 35° = 7\ kPa$$

Stability of vertical cut in silt: ‘dry’ approach

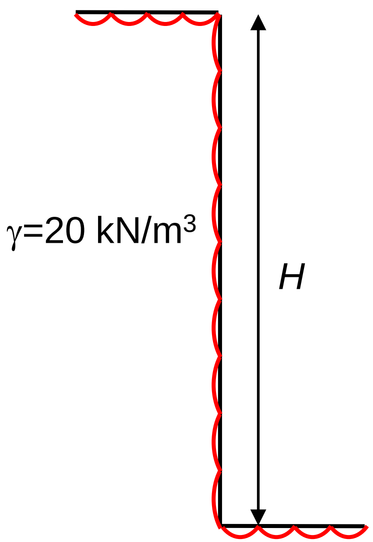




H_{max}=0

Vertical cuts cannot be stable

Stability of vertical cut: unsaturated ‘simplified’ approach



In the classical dry soil mechanics, H=0 if c’=0

Very little evaporation is sufficient to curve menisci and lower water pressure to the air entry value, say u_w=-100 kPa

As the soil is saturated, the shear strength ctiterion can be written as follows:

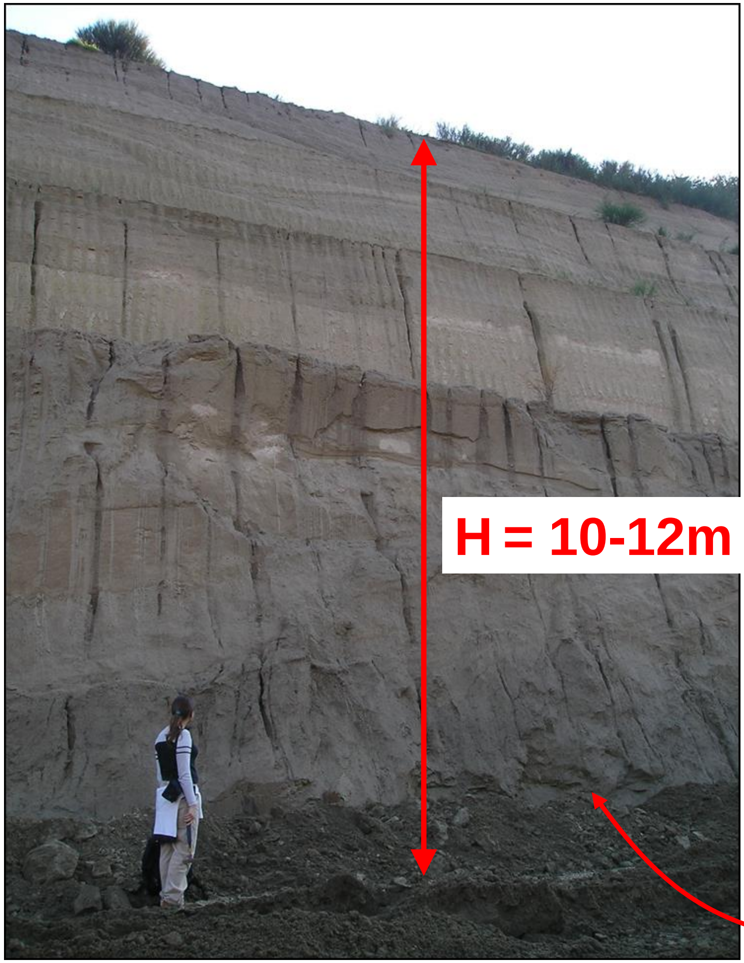
$\tau = (\sigma - u_w) \tan \phi' = \sigma \tan \phi' + (-u_w) \tan \phi' = \sigma \tan \phi' + c_{apparent}$

Assuming ϕ'=28 °, risulta c_{apparent} = 50 kPa

Assuming that $H=2c / \gamma(k_a)^{1/2}$ we obtain H= 7.8 m!

Stable vertical cuts in ‘cohesionless’ soils

(De Vita et al. 2008, IJEGE)



Giugliano near Naples, Italy
(courtesy of Prof. De Vita, University of Naples Federico II)

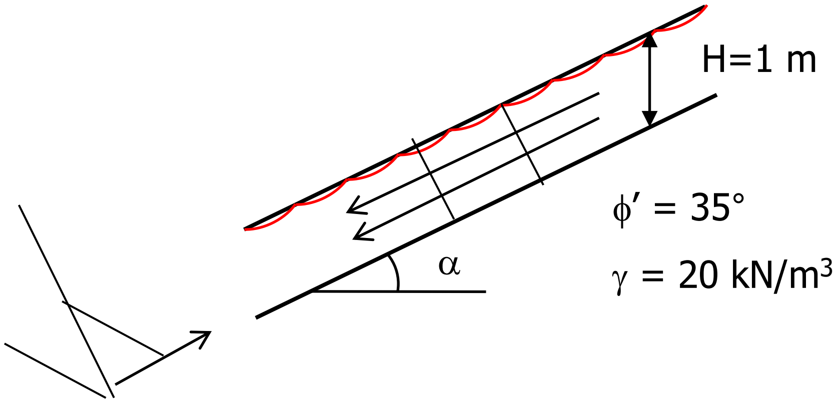
Dry approach (c’=0)

⇩

H_{max} = 0 !!!

Pyroclastic ‘cohesionless’ silty sand

Infinite slope in sand



Water table at the ground surface.

$$\eta = \left(1 - \frac{\gamma_w}{\gamma}\right)\frac{\tan\phi'}{\tan\alpha} = 1 \quad \Rightarrow \quad \alpha_{max} = 19^\circ$$

Very little evaporation is sufficient to curve menisci and lower water pressure to the air entry value, say u_w=-10 kPa

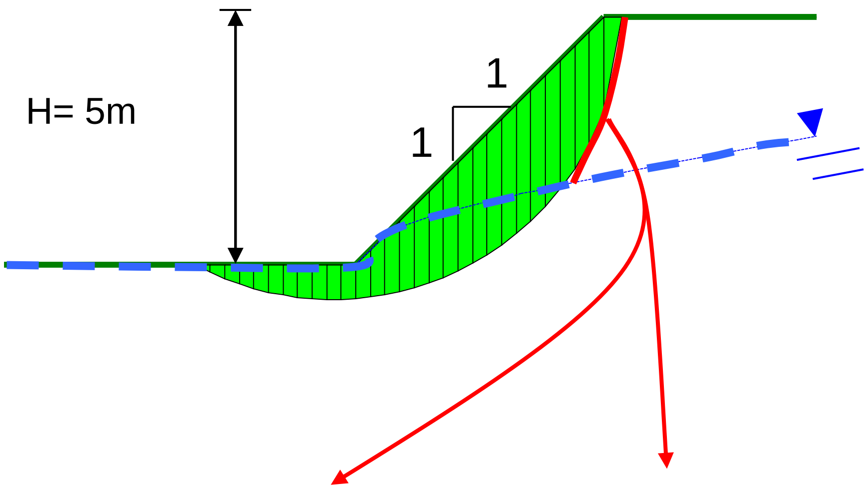
As the soil is saturated, the facor of safetu can be written as follows:

$$\eta = \left(1 - \frac{\gamma_w}{\gamma}\right)\frac{\tan\phi'}{\tan\alpha} + \frac{(-u_w)\tan\phi'}{H\,\gamma\sin\alpha\cos\alpha}$$

Assuming $\eta=1$, we obtain α_{max}= 50° !

Stable cut slope in ‘cohesionless’ soils

Pyroclastic silty sand



Unsaturated

FoS = 1.04

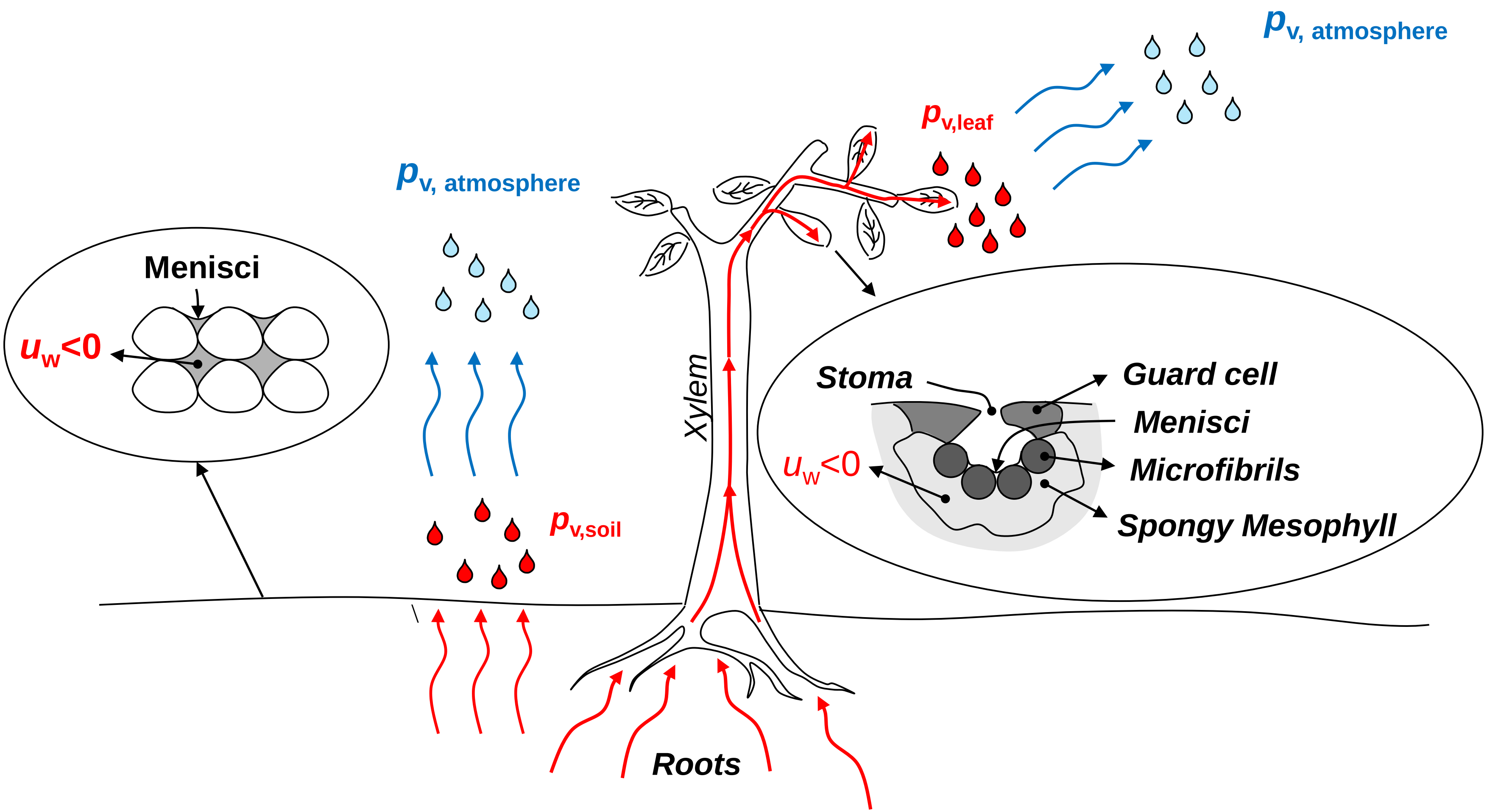
Dry (c’=0)

FoS = 0.87

need to ‘INVENT‘ a cohesion to make the cut slope stable

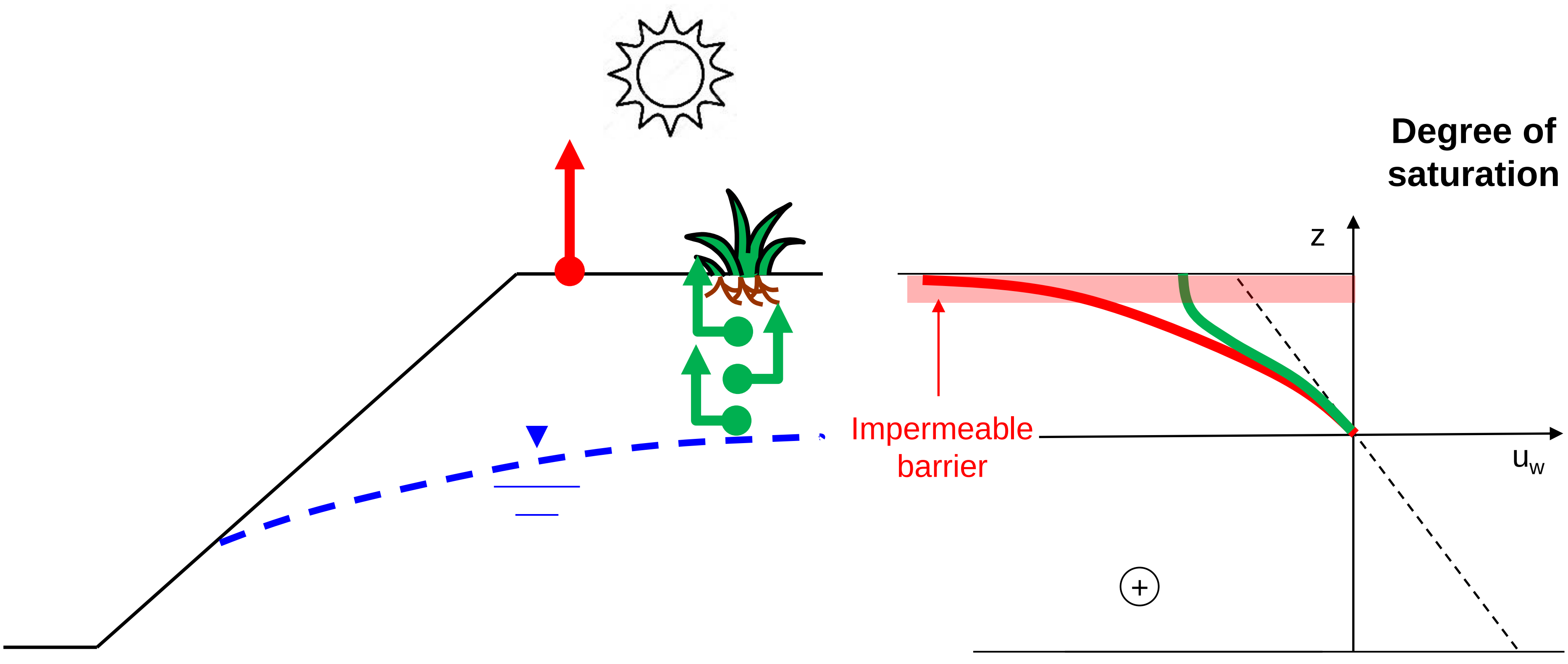
Remedial measures: thinking out loud

Driving mechanism of evaporation and transpiration



- Water is extracted by the atmosphere THROUGH the plant (and not by the plant)
- The driving mechanism of water extraction is the same for bare and vegetated soil

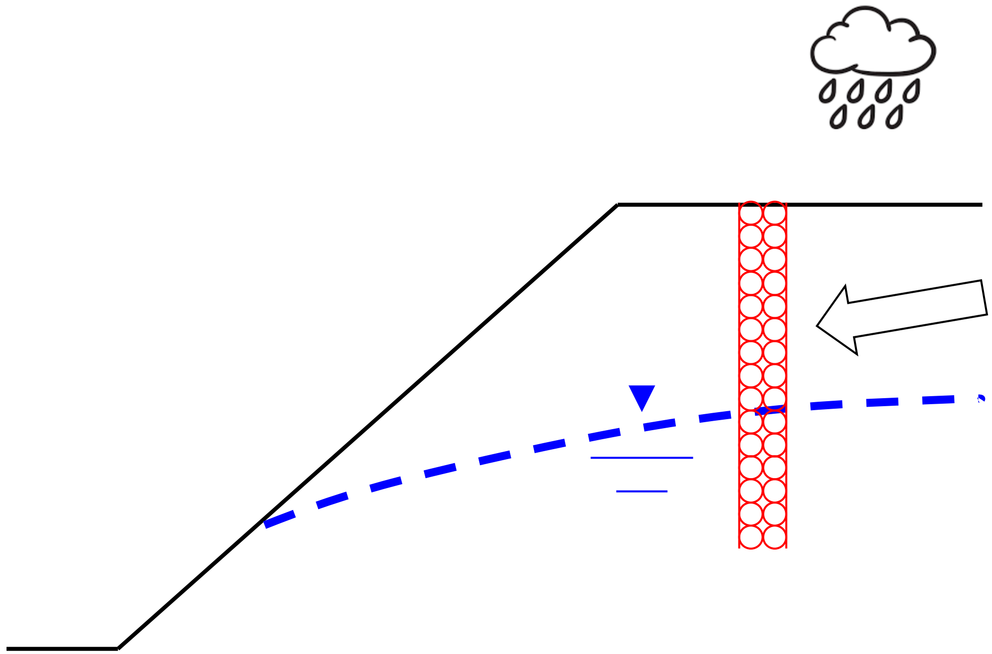
Remove soil water by transpiration (but not evaporation)



Transpiration

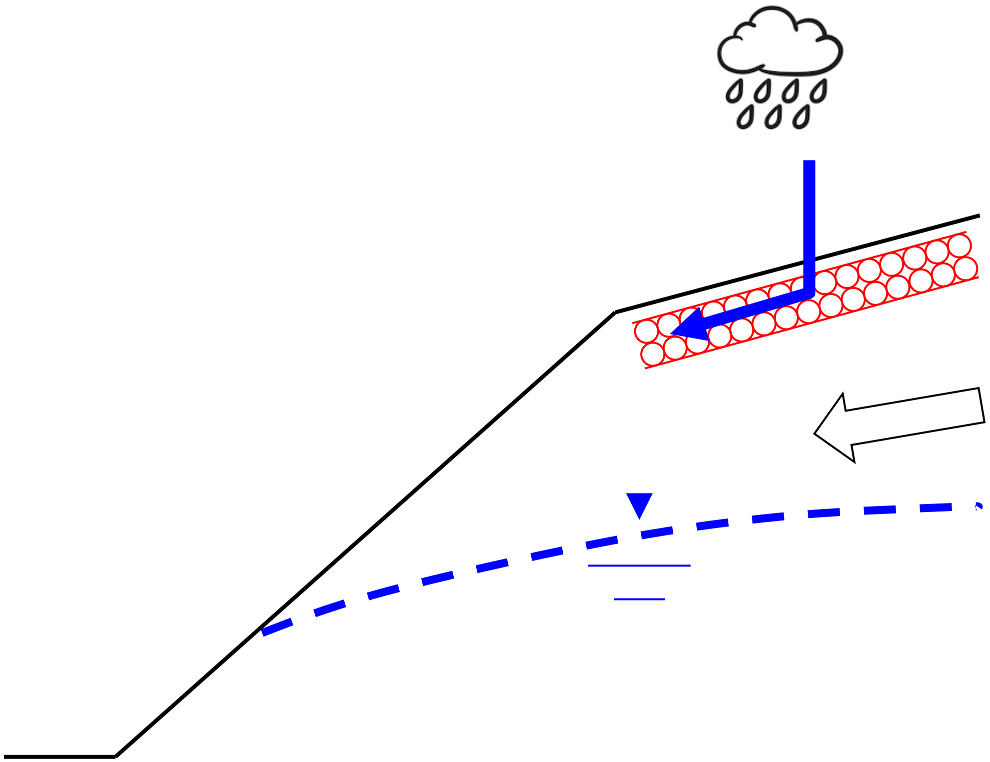
Gentler suction generate lower shear strains minimising susceptibility to cracking and maintaining unsaturated soil more conductive

No coarse-grained drains above phreatic surface



Coarse-grained layers act as capillary barrier above phreatic surface and favour water accumulation

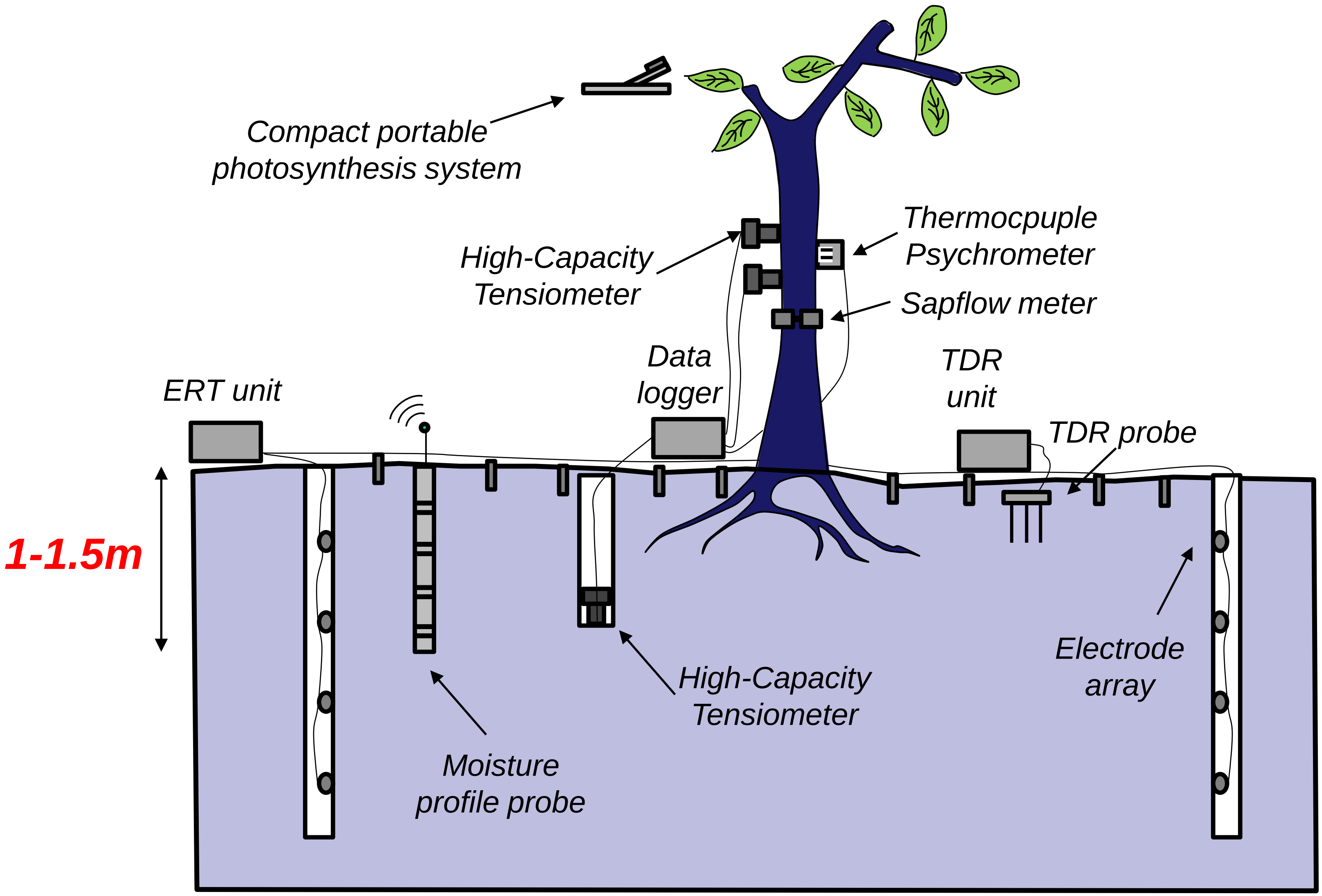
Divert rainwater



Coarse-grained surface layers can act as natural drainage

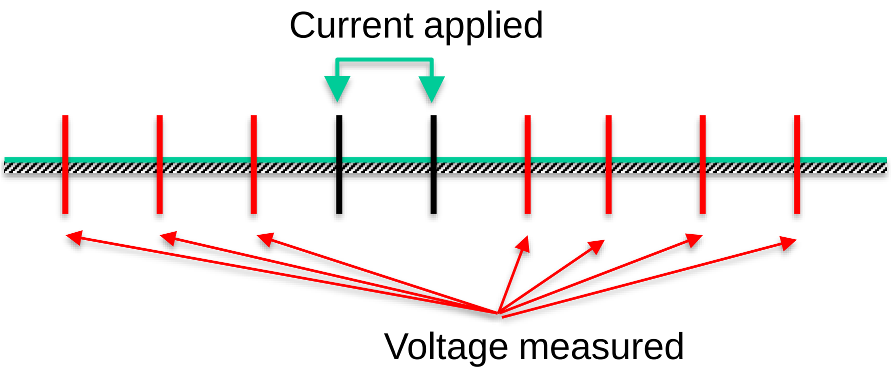
Monitoring the vadose zone

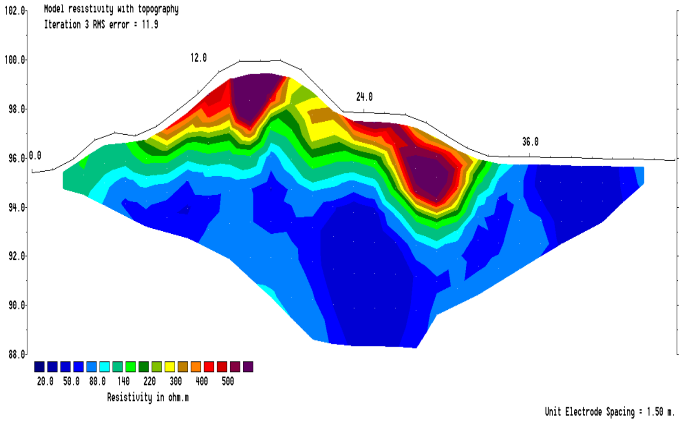
Monitoring borrowed from agricultural systems



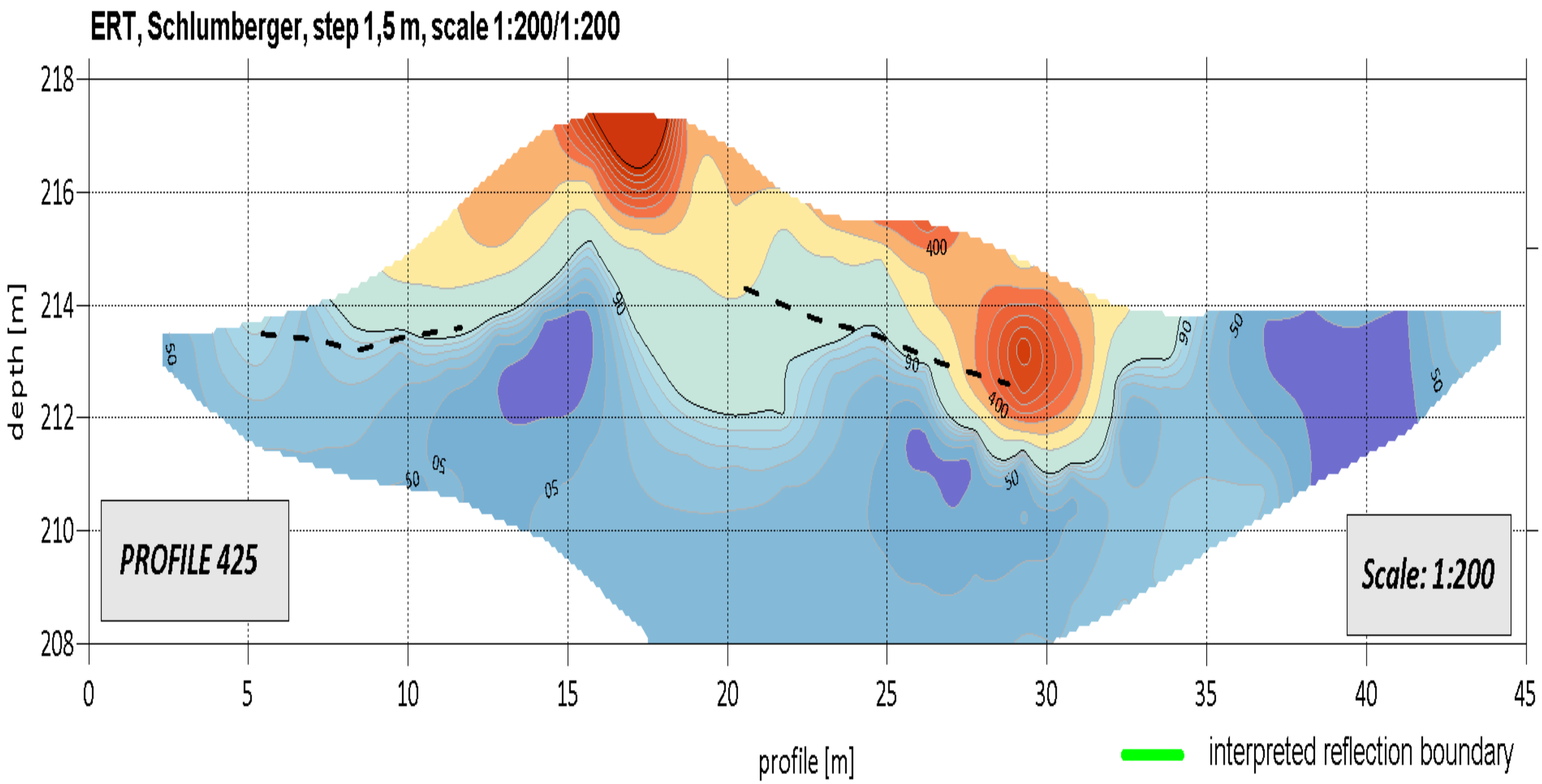
ERT - Electrical Resistivity Tomography

- DC electrical current is injected through a pair of electrodes and the voltage is measured by the remaining ones.
- A line (array) of electrodes is used and a multiplexer sends current to different pairs of electrodes through a set sequence
- The distribution of electrical resistivity in the ground is obtained by tomographic reconstruction (inverse problem)



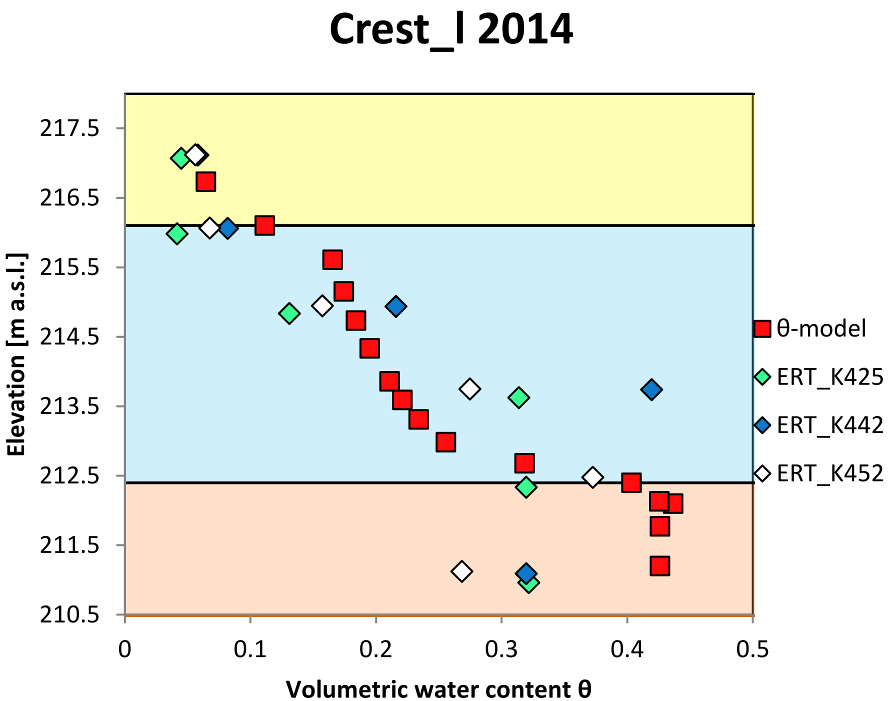


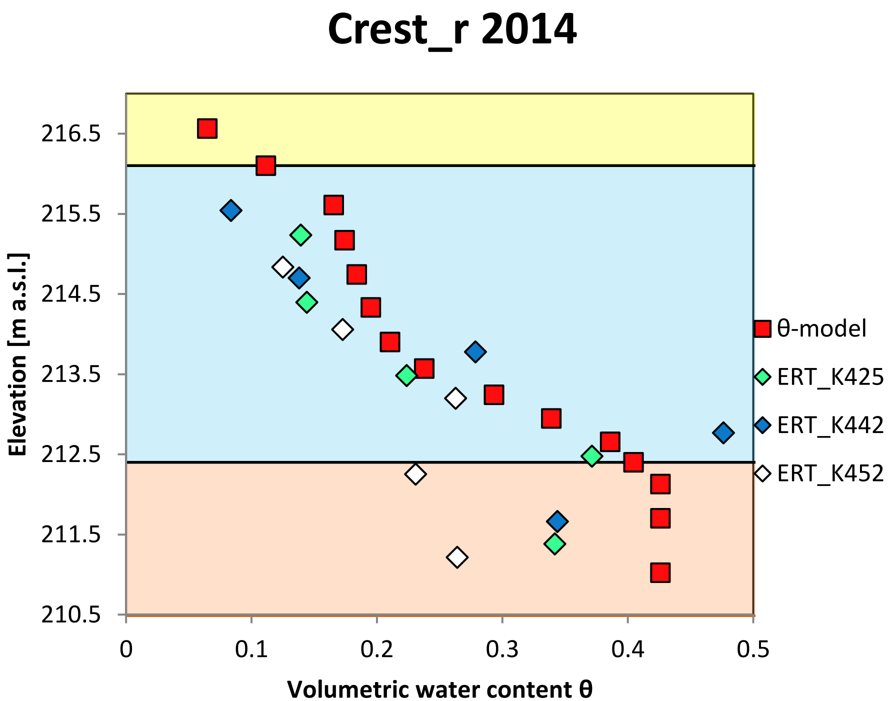
Electrical resistivity mapping



Water content – simulation vs. ERT

Water content profiles – November 2014





- Excellent match in the unsaturated embankment
- In deep foundation $\theta=\theta_{sat}$