6 INTERNATIONAL CONFERENCE

CHARTING THE PATH
TOWARD THE FUTURE
Geotechnical Engineering **Education**

Undergraduate teaching of Unsaturated Soil Mechanics: Building on fundamental physical mechanisms to pave the way for geotechnical analyses

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SIMSG ISSMGE

UNIVERSITÉ DE LORRAINE

ECOLE NATIONALE SUPÉRIEURE GÉOLOGIE NANCY

cfms COMITÉ FRANÇAIS DE MÉCANIQUE DES SOLS ET DE GÉOTECHNIQUE

Contents

1. Motivation and Scope
2. Historical barriers (to undergraduate teaching of unsaturated soil mechanics)
3. WHY (teaching unsaturated soil mechanics at undergraduate level)
4. WHAT (is convenient to start with)
5. HOW do we teach (sharing our experience)

In Scope

We are turning towards undergraduate teaching

- Unsaturated soil introduced at same time as saturated soil (water flow, compressibility, shear strength)
- Non-specialist teachers (not involved in unsaturated soil research)

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Challenges:
i) Use same language as ‘saturated’ soils
ii) Simple but not simplistic

Out of Scope

- Advanced unsaturated soil mechanics
- Specialist teachers (involved in unsaturated soil research)
    - **Teaching unsaturated seepage and wetting-collapse coupled modelling**
      N.M. Pinyol & E.E. Alonso
    - **Integrating soil suction in geotechnical education: a case study on partially saturated slope stability analysis in Sweden**
      A. Abed & M. Karstunen
    - **Teaching unsaturated soil mechanics through rammed earth**
      C. Vulpe & C.T.S. Beckett

Motivation

Proceedings of the XVIII ECSMGE 2024
GEOTECHNICAL ENGINEERING CHALLENGES
TO MEET CURRENT AND EMERGING NEEDS OF SOCIETY

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DOI 10.1201/9781003431749-120

ECSMGE 24
XVIII EUROPEAN CONFERENCE ON SOIL MECHANICS AND GEOTECHNICAL ENGINEERING

Alert soil mechanics instructors of the main unsaturated soil issues: What and how to teach when experts disagree

Alerter les formateurs en mécanique des sols sur les principales questions relatives aux sols non saturés: Quoi et comment enseigner lorsque les experts ne sont pas d'accord

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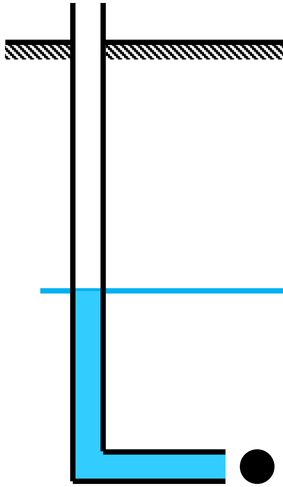
Historical barriers to undergraduate teaching of unsaturated soil mechanics

Teaching of unsaturated soil mechanics: building on fundamental physical mechanisms to pave the way for geotechnical analyses
Alessia Amabile & Alessandro Tarantino

Suction versus pore-water pressure (1)

Saturated soil – Pore-water pressure



Pore-water pressure:
- drives water seepage (via the hydraulic head)
- controls mechanical behaviour (via the 'saturated' effective stress)

Operational definition
Measured using a piezometer in contact with the soil through a porous filter

Teaching of unsaturated soil mechanics: building on fundamental physical mechanisms to pave the way for geotechnical analyses
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Suction versus pore-water pressure (2)

Unsaturated soil – Suction

[Fredlund, D., Rahardjo, H. 1993. Soil Mechanics for Unsaturated Soils. John Wiley & Sons]

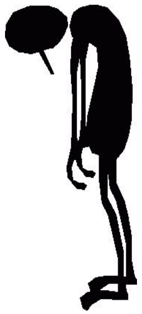
Suction:

- drives water seepage (via the hydraulic head)
- controls mechanical behaviour (via effective stresses)

Definition:

Suction is defined as the free energy state of soil water. It can be measured in terms of the partial vapor pressure of the soil water via

$$\psi = \frac{RT}{v_w} ln \frac{p_v}{p_{v0}}$$



where T is the absolute temperature, R is the universal gas constant, v_w is the molar volume of water, p_{v0} is the saturated vapour pressure at the temperature T, and p_{v0} the pressure of the vapour in equilibrium with the soil water.

Odd, as soon as the soil desaturates, we enter the exoteric world of thermodynamics !

Suction versus pore-water pressure (3)

Unsaturated soil – Suction

[Fredlund, D., Rahardjo, H. 1993. Soil Mechanics for Unsaturated Soils. John Wiley & Sons]

Puzzle even more intricate when suction is separated into a matric and an osmotic component

- *Matric or capillary component of free energy*. In suction terms, it is the equivalent suction derived from the measurement of the partial pressure of the water vapor in equilibrium with the soil water residing in the soil, relative to the partial pressure of the water vapor in equilibrium with a solution identical in composition with the soil water.
- *Osmotic (or solute) component of free energy*. In suction terms, it is the equivalent suction derived from the measurement of the partial pressure of the water vapor in equilibrium with a solution identical in composition with the soil water, relative to the partial pressure of water vapor in equilibrium with free pure water.

Non-specialist teachers get away !!

Suction versus pore-water pressure (4)

Unsaturated soil – Suction

[Fredlund, D., Rahardjo, H. 1993. Soil Mechanics for Unsaturated Soils. John Wiley & Sons]

Final (and perhaps fatal) blow:

Matric suction can be expressed in 'practical terms' as the difference between air-pressure and pore-water pressure, $u_a - u_w$

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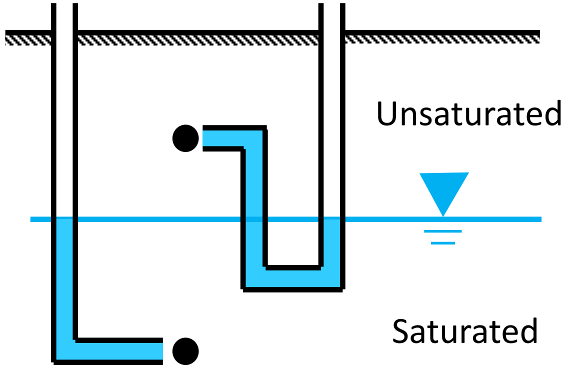
The 'grand' thermodynamical definitions given above flying away !!

So what?

Suction versus pore-water pressure (5)

Saturated soil/Unsaturated soil – Pore-water pressure



- Pore-water pressure – same definition for saturated and unsaturated soils
- Pore-water pressure in unsaturated soils is negative and problematic to measure
- Indirect measurement techniques require thermodynamics to be interpreted

- If instruments to measure negative pore-water pressure directly were available since early days (high-capacity tensiometer)

→ No one would have ever defined suction thermodynamically and talked about matric and osmotic suction.
→ No one would have ever defined suction as u_a-u_w, because we always operate with gauge pressures

Moral of the story:

- Forget about thermodynamics, matric and osmotic suction if you are not concerned with measurements
- To deal with a positive variable, we introduce a variable named suction, the opposite of pore water pressure, s=-u_w

Effective stress(es) for unsaturated soils – Where are we?

• Bishop stress $\sigma' = \sigma - \chi(S_r)\, u_w$	Bishop (1959)
• Net stress $\sigma - u_a$ • Matric suction $(u_a - u_w)$	Coleman (1962) Bishop & Blight (1963) Matyas & Radhakrishna (1968) Fredlund and Morgenstern (1977) Tarantino et al. (2000)
• Average skeleton stress $\sigma - S_r u_w$ • Modified suction $n(-u_w)$	Houlsby (1997) Wheeler et al. (2003)
• Average skeleton stress $\sigma - S_r u_w$ • Bonding stress suction $f(u_w)(1 - S_r)$	Gallipoli et al. (2003)
• Microstructurally based effective stress (elastic and shear strength behaviour) $\sigma' = \sigma - \frac{e_w - e_{wm}}{e - e_{wm}}\, u_w$	Tarantino and Tombolato (2005) Alonso et al. (2010)

Are we violating the Principle of Effective Stress?

Effective stress for saturated soils: demystify the sacred !

- The effective stress for saturated soils, $\sigma - u_w$, is an experimental finding and not a sacred principle:

All the measurable effects of a change of the stress, such as compression, distortion and a change of the shearing resistance are exclusively due to changes in the effective stresses (Terzaghi, 1936):

- If we focus on particular 'measurable' effects, why not choosing a 'bespoke' effective stress?
  - Shear strength and stability → $\sigma - S_r u_w$ (this presentation)
  - Wetting-induced collapse → $\sigma - u_a$ and $u_a - u_w$ (Pinyol et al., this conference)

WHY teaching unsaturated soil mechanics at undergraduate level

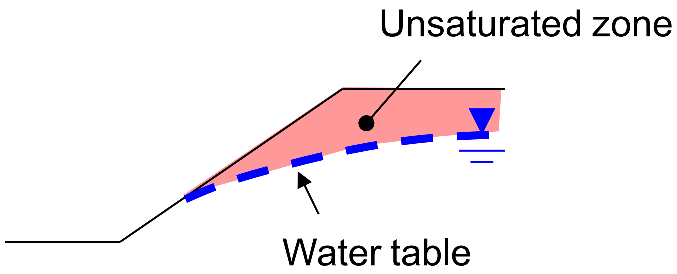
⇩

This conference

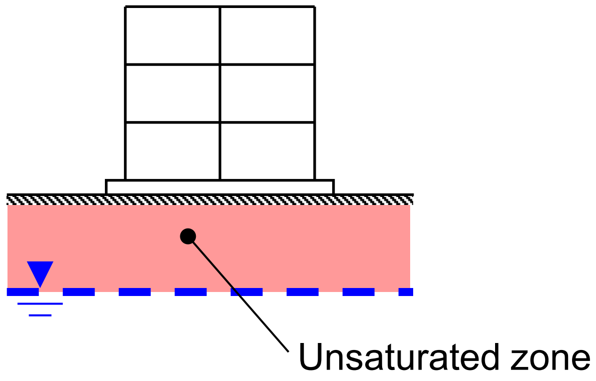
- T.S. da Silva Burke & C.J. MacRobert
- A. Ledesma, E. Romero, P.C. Prat, A. Ramon & N.M. Pinyol
- K.V. Bicalho

Phreatic surface / groundwater table is rarely at the ground surface

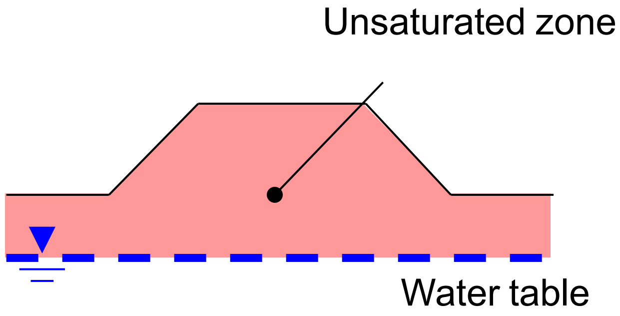
Slope



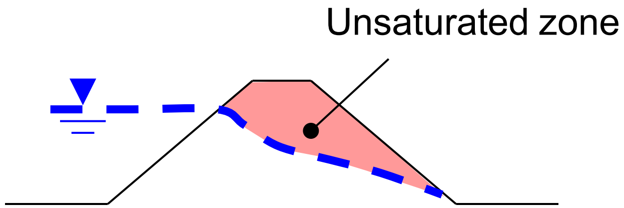
Foundation



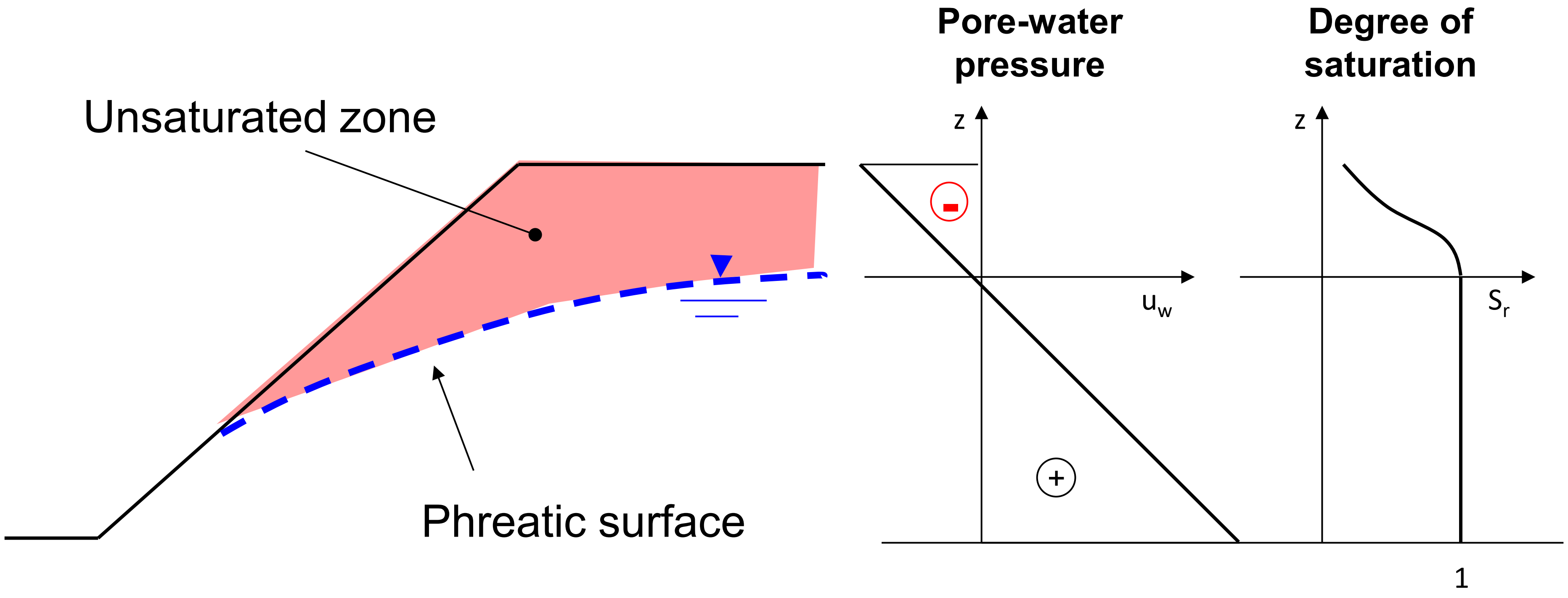
Embankment



Dam

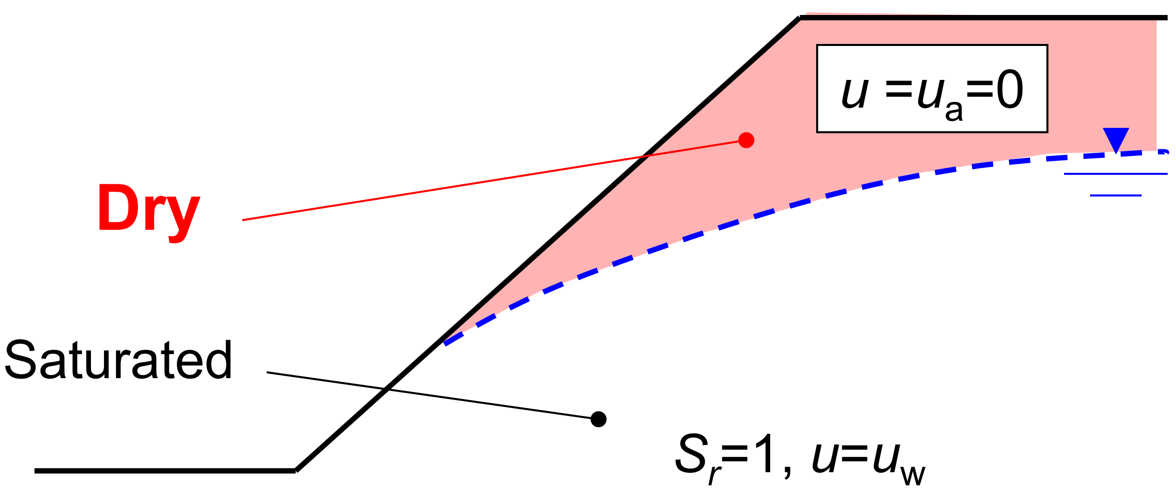


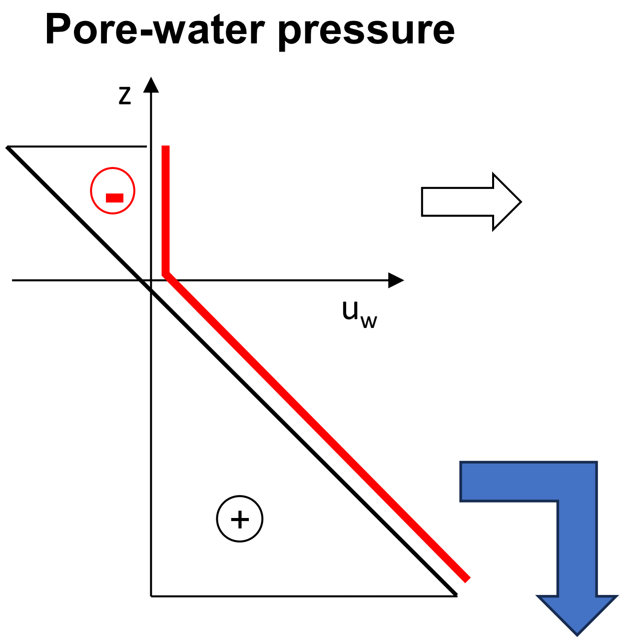
Soils above the water table are unsaturated and have negative pore-water pressure (suction)



The 'dry' assumption

Soil above the water table is assumed dry in engineering practice





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

Conservative

This assumption has limitations as:

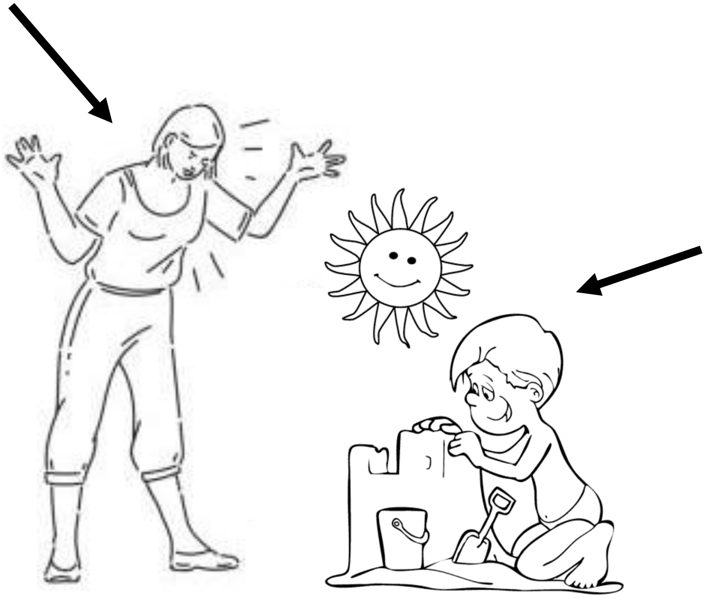
- Lead to excessively conservative design (carbon-expensive)
- No climate interaction (no climate-resilient geostructure)
- Lead to faulty design (incorrect assumptions from back-analysis)
- You can't understand compaction (after Marina's Lecture)

Limitation of the ‘dry’ assumption:

Excessively conservative design

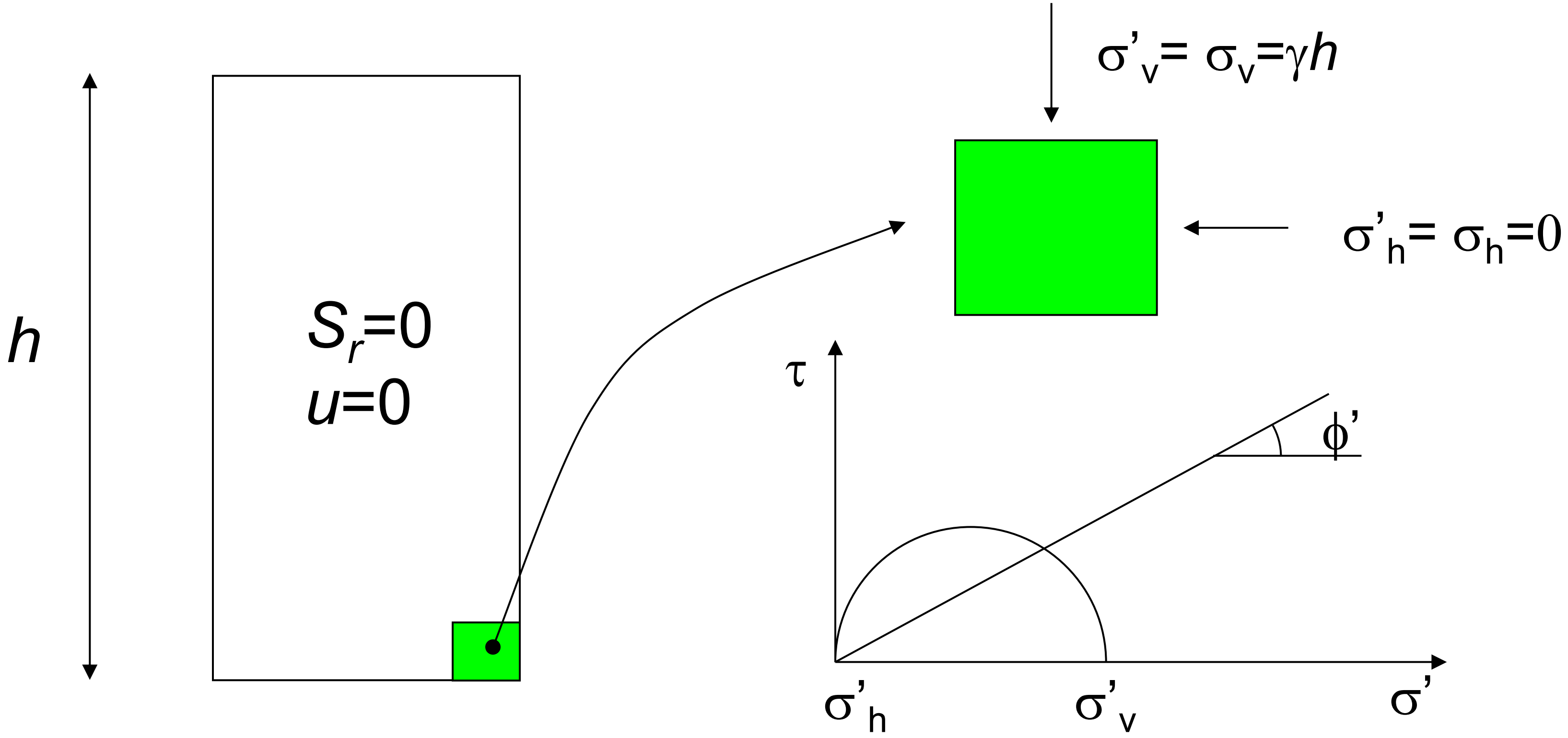
Geotechnical parent

‘No way, sandcastle is mission: impossible!’



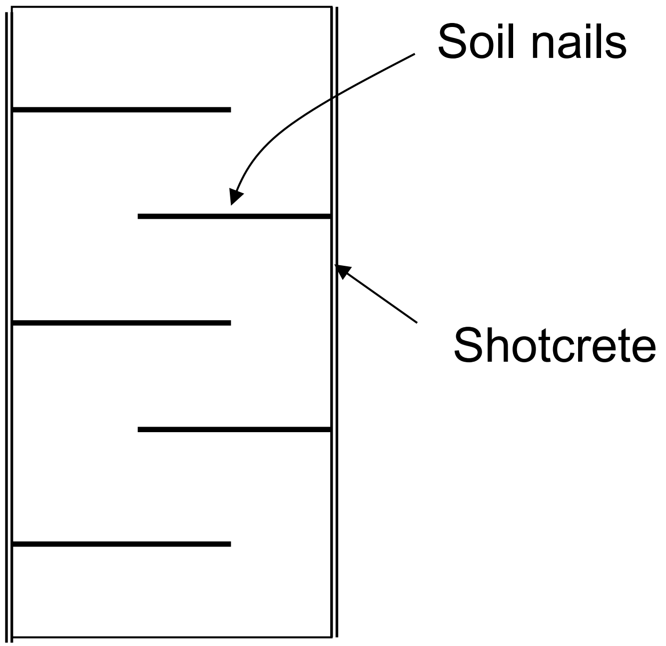
Poor geotechnical kid

Stability of sandcastle above the water table



According to our calculations, sand castles should not stand up .... !!

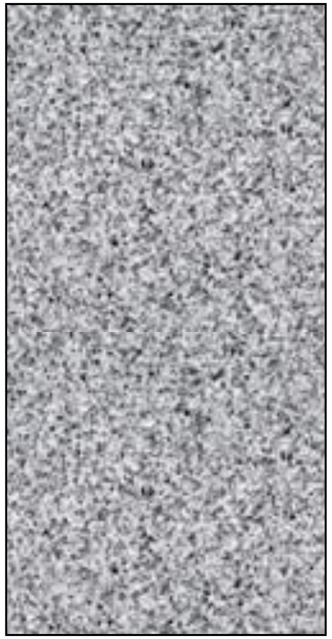
Nailed sandcastles (high-carbon footprint)



- Bottom-up technique
- Pre-drill holes
- Install steel bars
- Inject grout
- Spray face with concrete

.... fun for kids, labourios for (geotechnical) parents

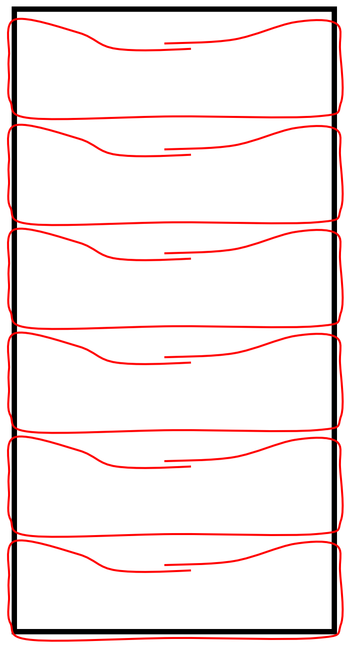
Lime-stabilised sandcastles (high-carbon footprint)



- Mix the soil with cement
- Compact the mixture in layers
- Wait for curing

.... fun for kids, labourios for (geotechnical) parents

Geotextile-reinforced sandcastles
(good for Jorge, but still high-carbon footprint)



- Spread the geotextile
- Place a soil layer
- Wrap and overlap the geotextile

.... fun for kids, laborious for (geotechnical) parents

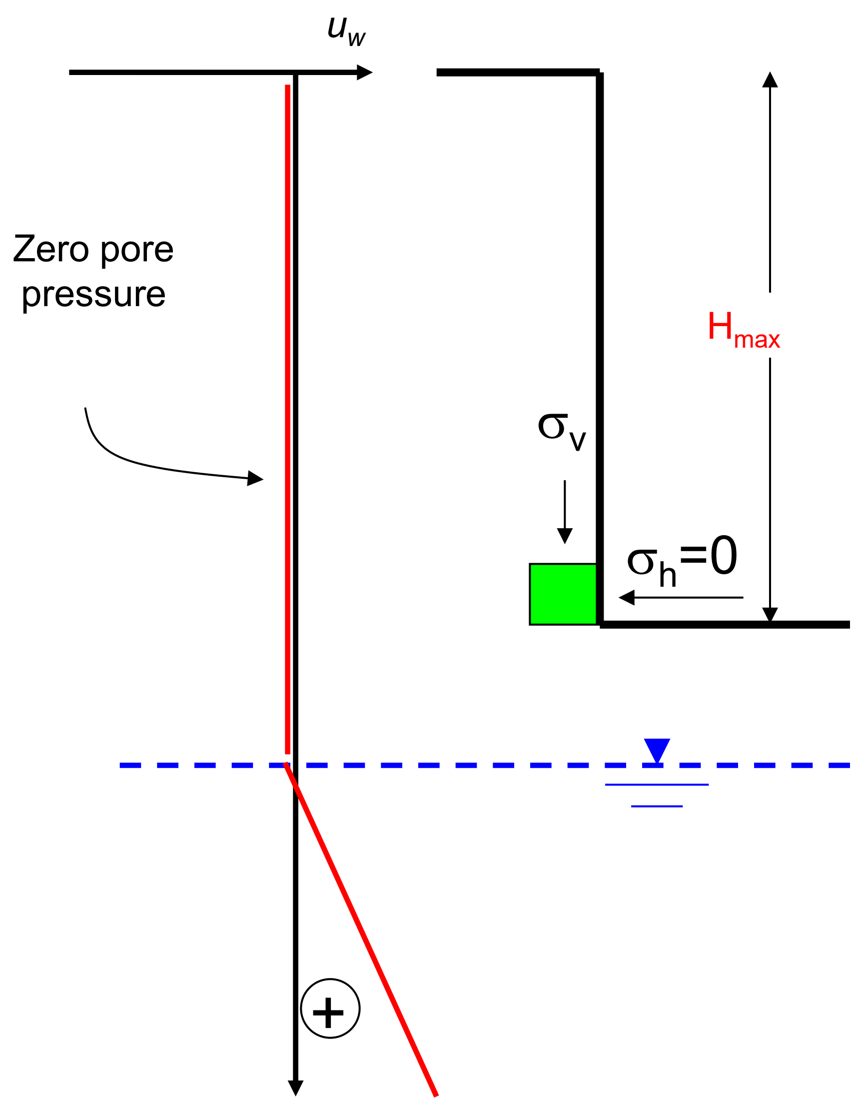
Sustainable design of sandcastles

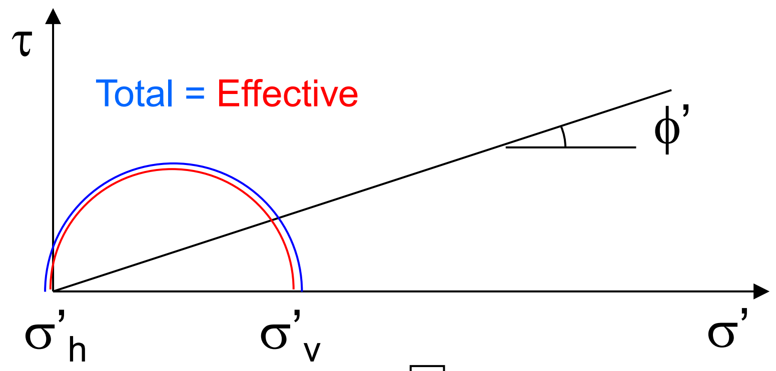
- Add the right amount of water to obtain an soil
- The sand castle can stand up
- Capillary water is a low-cost sustainable solution

.... fun for kids, SUSTAINABLE for (geotechnical) parents

Excessively conservative → Carbon expensive

Limitation of the 'dry' approach:





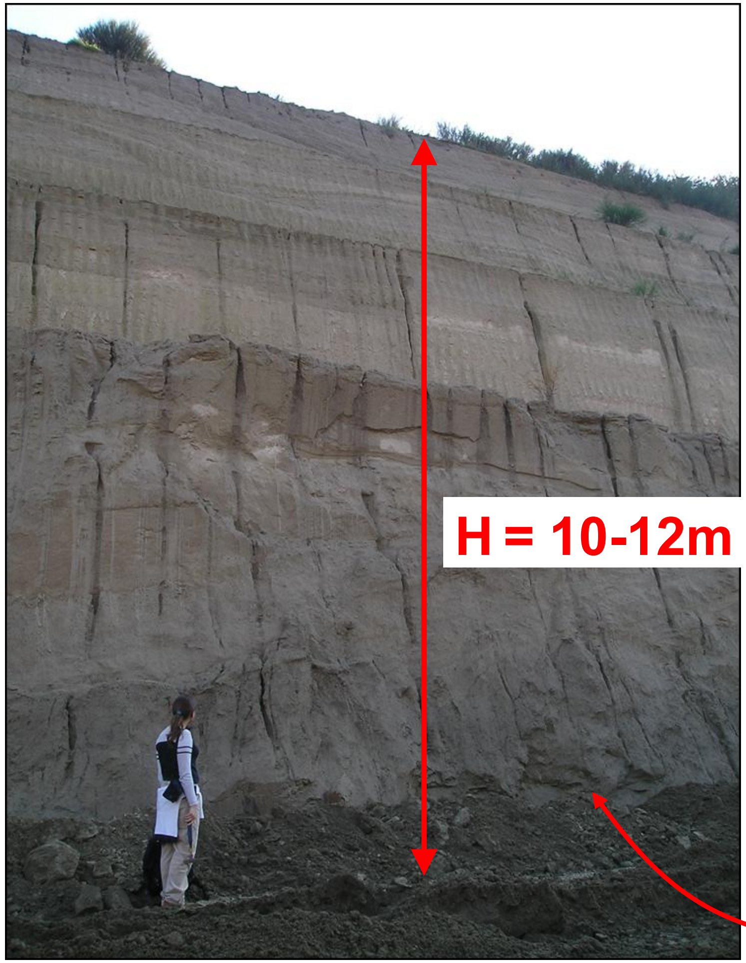
$H_{max}=0$

Vertical cuts cannot be stable

Build retaining structure !!

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)

Contractor

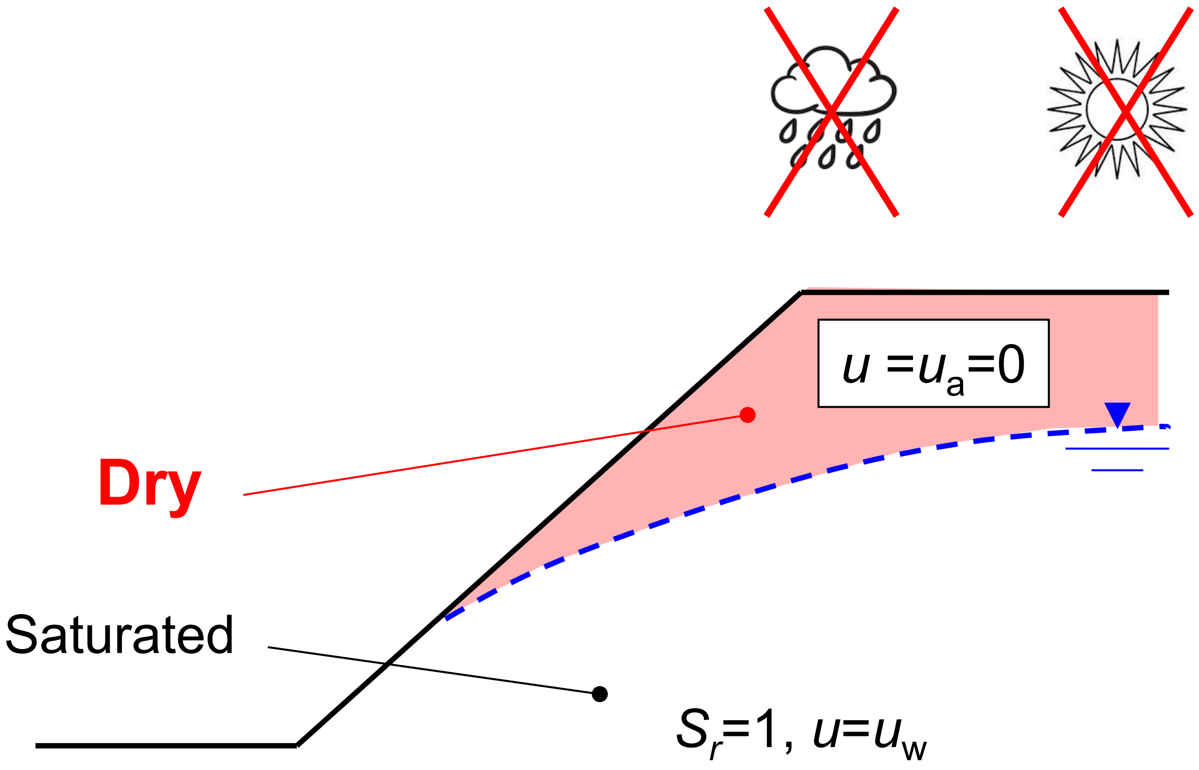
Pyroclastic ‘cohesionless’ silty sand

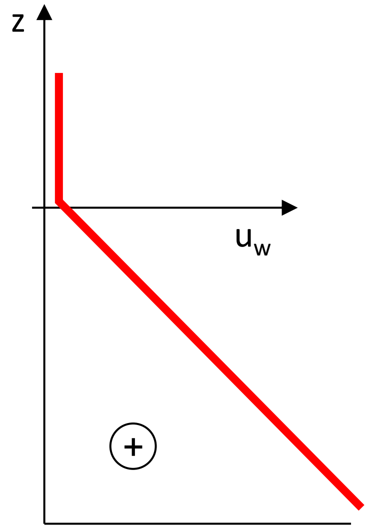
Limitation of the ‘dry’ assumption:

<u>Climate interaction</u>

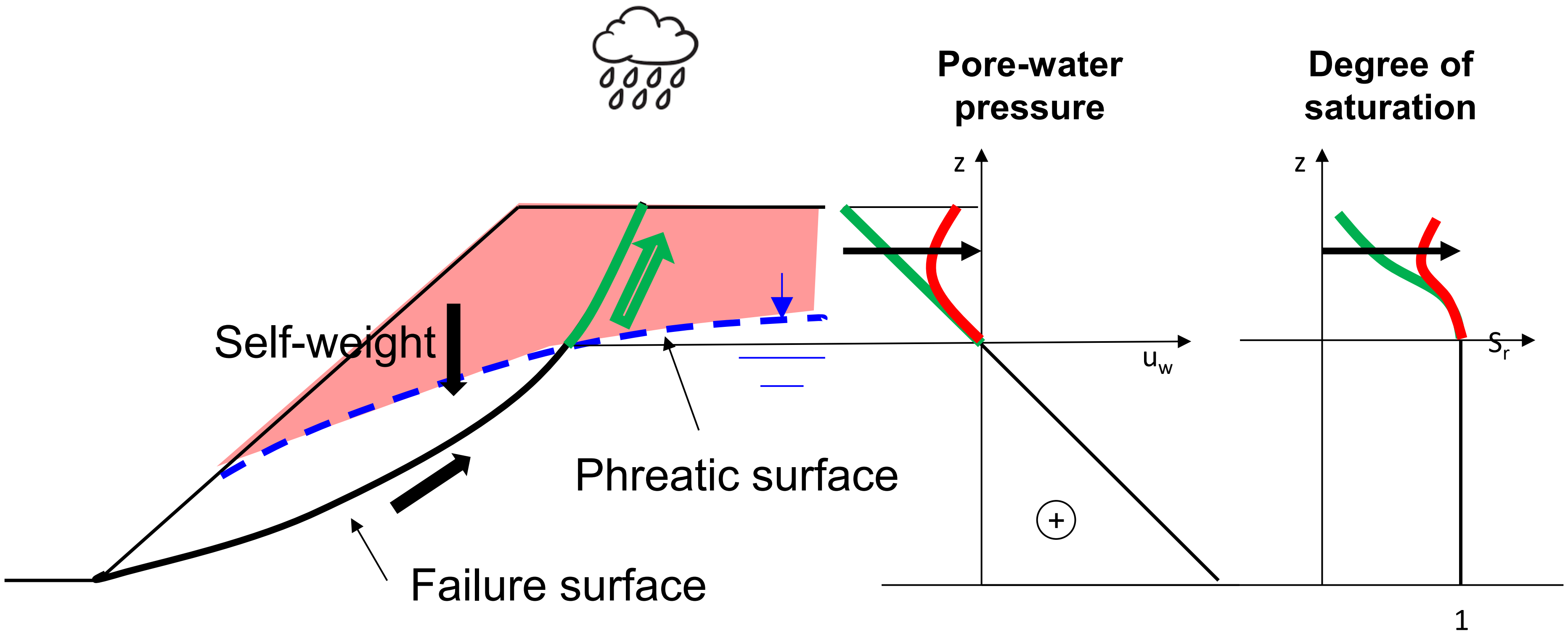
The ‘dry’ assumption

Soil above the water table is assumed dry in engineering practice





Effect of rainwater infiltration on stability of slopes



Landslides impacting transportation corridors

Rest and Be Thankful A83 trunk road, Scotland
(Balzano, Tarantino, Ridley 2019)

Landslides impacting transportation corridors

Hatfield Collery, UK (RAIB 2014)

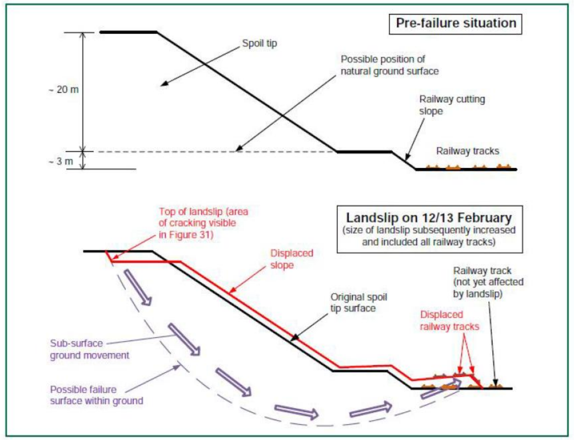


Figure 3 a) Failure of rail line near Hatfield Colliery, UK, b) Aerial view of failure, c) Failure mechanism (from RAIB 2014)

Drought-induced building damage

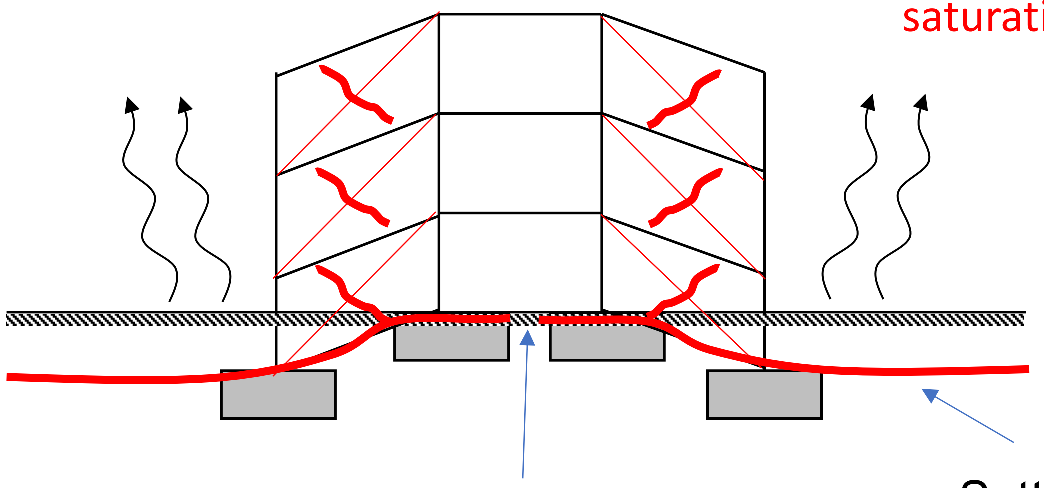
University of Strathclyde Engineering

UK Association of Specialist Underpinning Contractors
Surge year when more than 50,000 subsidence claims
Since 1976 repair bills have exceeded £400M a surge year, totalling £14bn

SwissRe (top world reinsurance company)
In France alone, subsidence-related losses have increased by more than 50% within two decades, costing affected regions an average of €340M/year

Mechanisms of drought-induced building damage

Drying inducing partial saturation



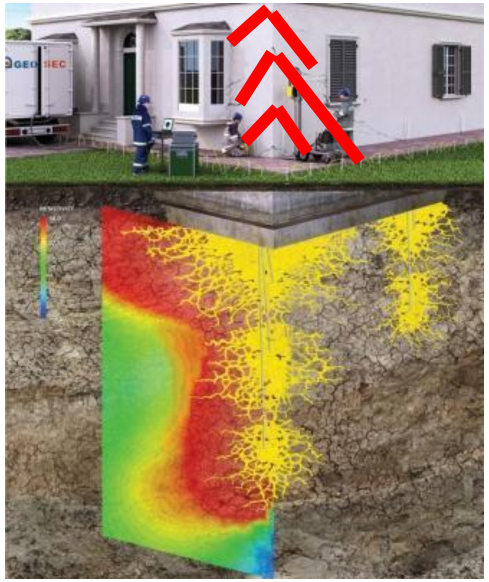
No settlement due to umbrella effect

Settlement due to shrinkage induced by evaporation

Mechanics of unsaturated soils required to model drought-induced foundation settlements and design remedial measures

Examples of drought-induced building damage

ITALY



https://www.lavorincasa.it/cedimento-delle-fondazioni-di-casa/

https://www.lavorincasa.it/cedimento-delle-fondazioni-di-casa/

V-shaped fissures !

Examples of drought-induced building damage

FRANCE

https://www.leprogres.fr/environnement/2020/07/29/maison-fissuree-suite-a-la-secheresse-10-jours-pour-faire-votre-declaration-a-l-assurance

https://www.radiorva.com/news/locales/7703/des-centaines-de-maisons-fissurees-par-la-secheresse-en-auvergne

V-shaped fissures !

Examples of drought-induced building damage

FRANCE

https://www.estrepublicain.fr/edition-belfort-hericourt-montbeliard/2019/08/01/maisons-fissurees-il-faut-s-armer-de-patience

https://www.lemoniteur.fr/article/secheresse-attention-danger.788114

V-shaped fissures !

Examples of drought-induced building damage

UK

https://www.ageas.co.uk/solved/your-home/subsidence-how-to-spot-it-and-heatwave-risks/

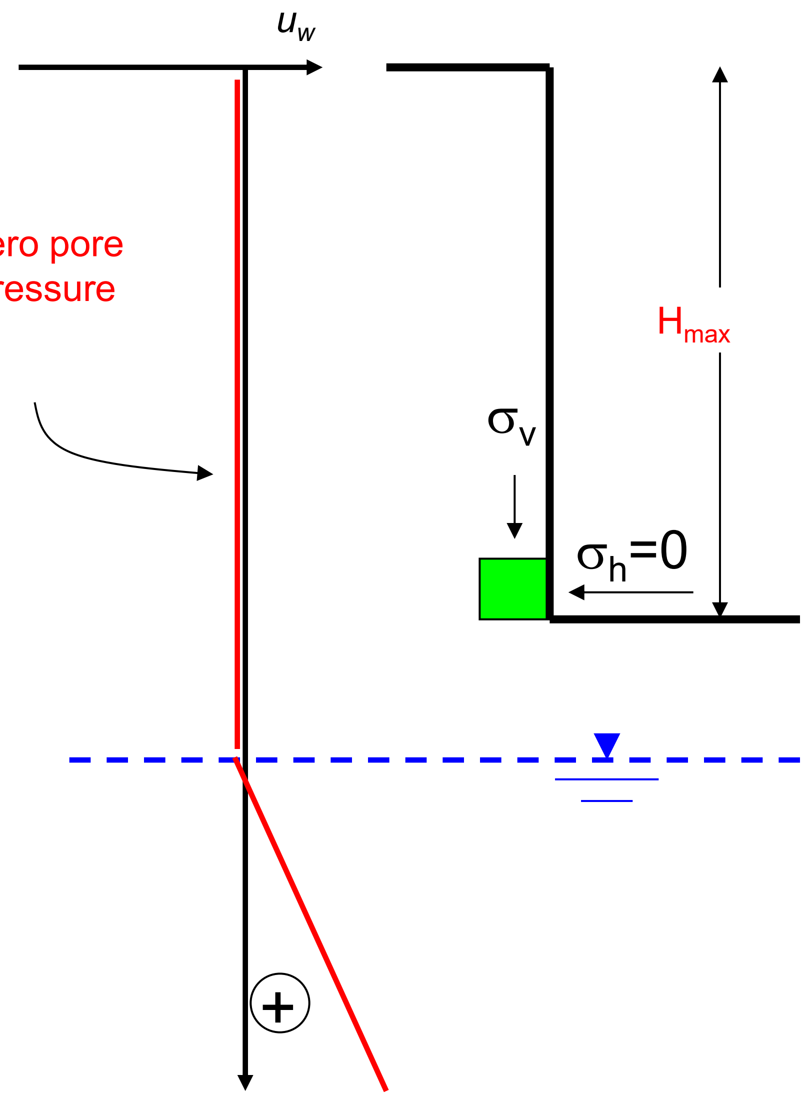
https://link.springer.com/content/pdf/10.1057%2Fpalgrave.jba.2940020.pdf

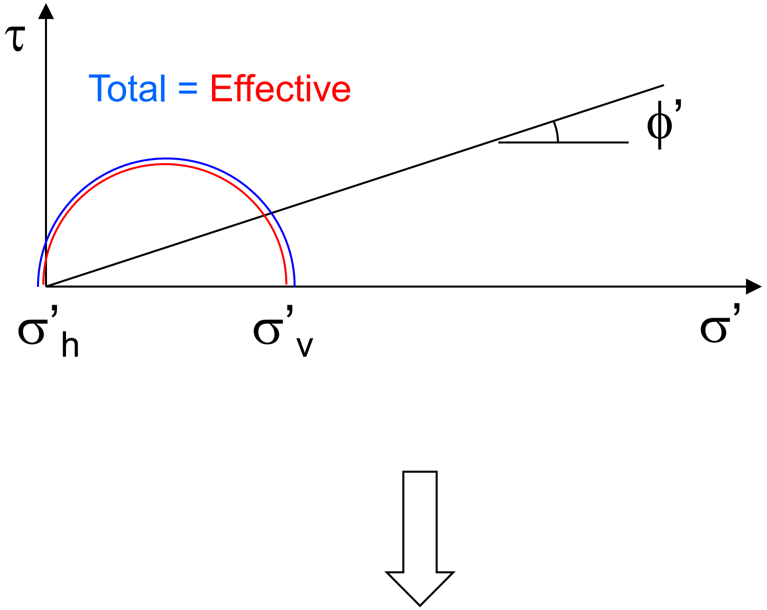
V-shaped fissures !

Limitation of the ‘dry’ assumption:

<u>Faulty design</u>

Limitation of the ‘dry’ approach: Misinterpreting Cohesion



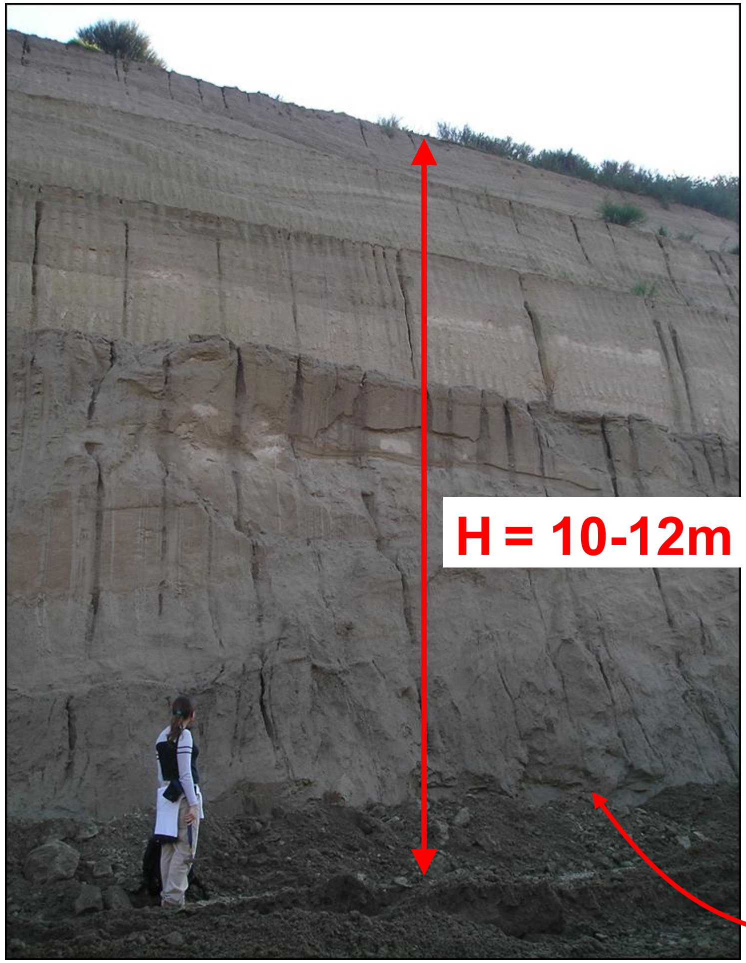


H_{max}=0

Vertical cuts cannot be stable

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)

Reconcile

Calculation $H_{max} = 0$

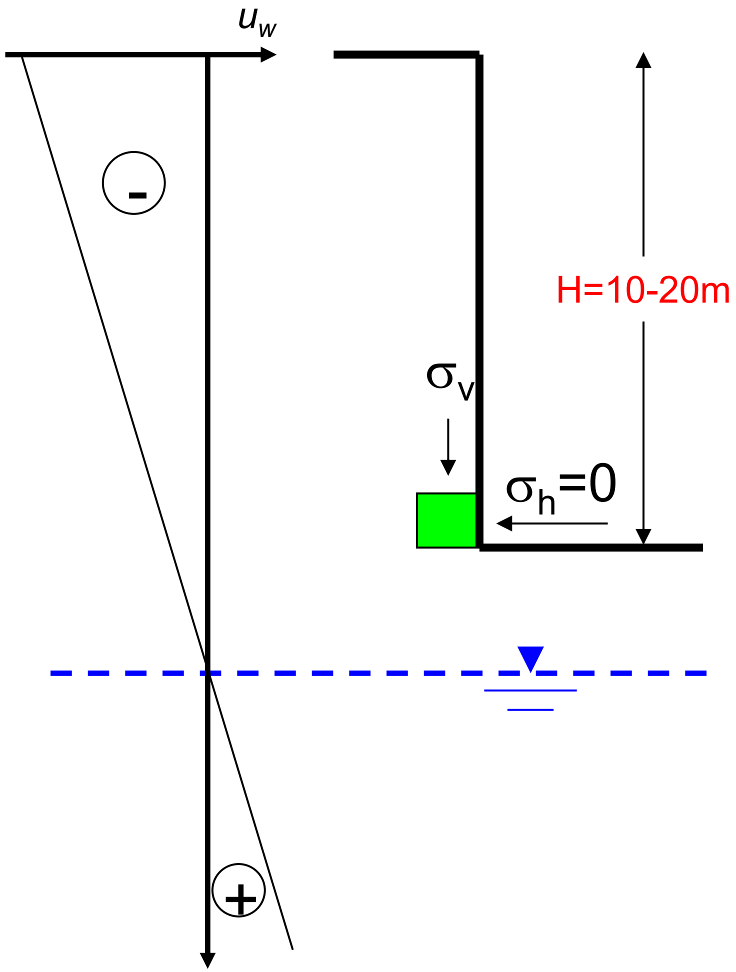
with

Observation $H_{max} > 0$

Pyroclastic ‘cohesionless’ silty sand

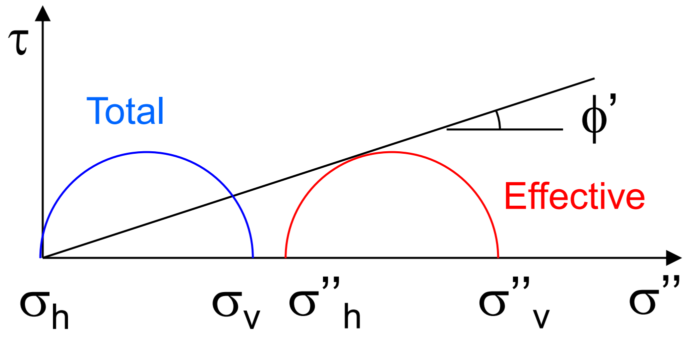
Stable vertical cuts in 'cohesionless' soils (Stanier and Tarantino 2013)

Pyroclastic 'cohesionless' silty sand



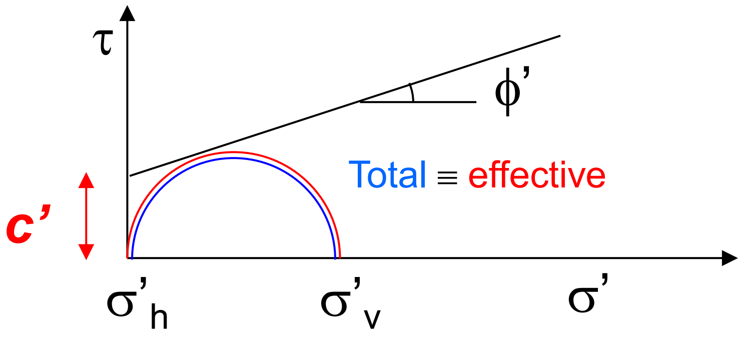
The real situation

Stable because of suction



Dry approach

Need to 'INVENT' a cohesion



Faulty design

(Apparent) cohesion invented to match the calculation with the observed behaviour

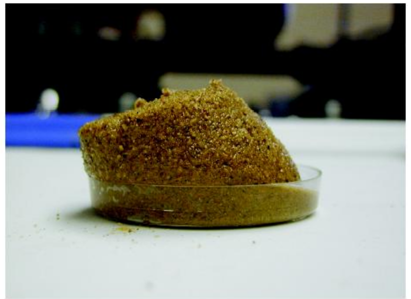
⬇

(Apparent) cohesion intepreted as soil parameter and used in design of countermeasures

⬇

Unfortunately, the apparent cohesion may vanish if suction is lost (e.g. rainfall)

Medium water content (partially saturated)



High water content (quasi-saturated)

Consequences of faulty design

MARCH 31, 2022 | SUSAN NAPIER-SEWELL

Contractor Faces Prison Time for Trench Collapse Fatality

Alki Construction owner Phillip Numrich was sentenced on March 4, 2022, to 45 days in jail for his role in the 2016 trench collapse death of 36-year-old Harold Felton.

After several days of heavy rainfall, Numrich work allowed to go on in a 2.5-3m deep trench.

In construction industry, it is common knowledge that soil becomes less stable following heavy rains.

https://www.taproot.com/contractor-faces-prison-time-for-trench-collapse-fatality/

WHAT is convenient to start with

Design Limit States

Ultimate Limit State
(ULS)

Structure must not collapse

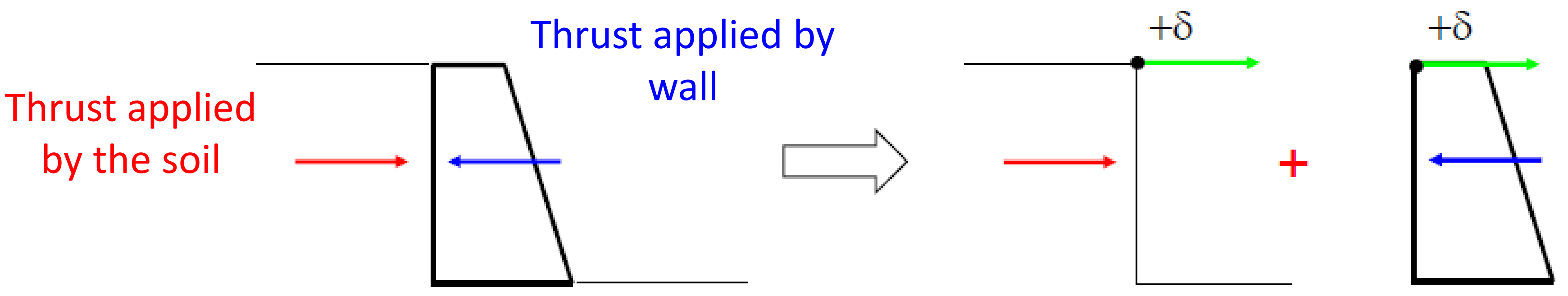
We are mainly concerned about resistance

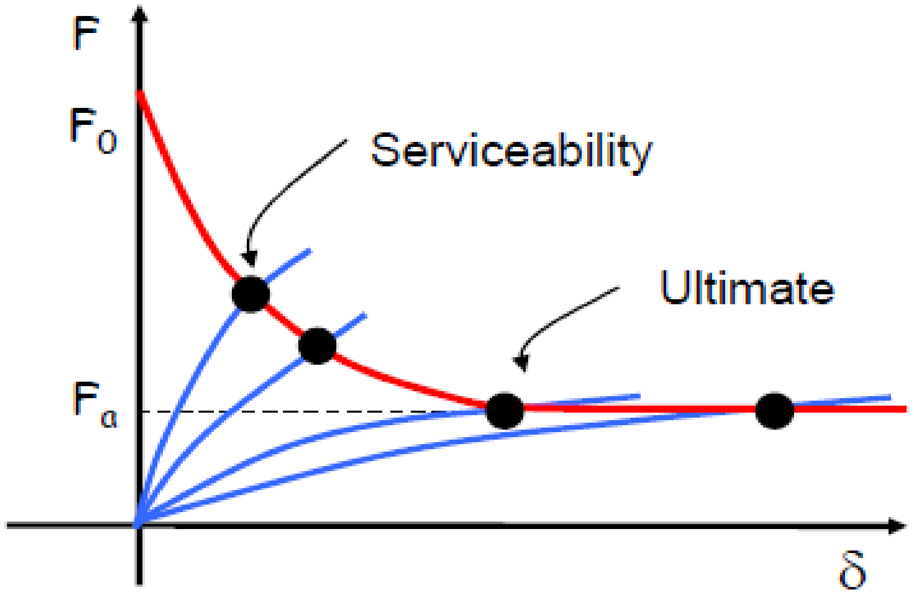
Serviceability Limit State
(SLS)

Structure must remain functional for its intended use

We are mainly concerned about deformations

Example of retaining wall

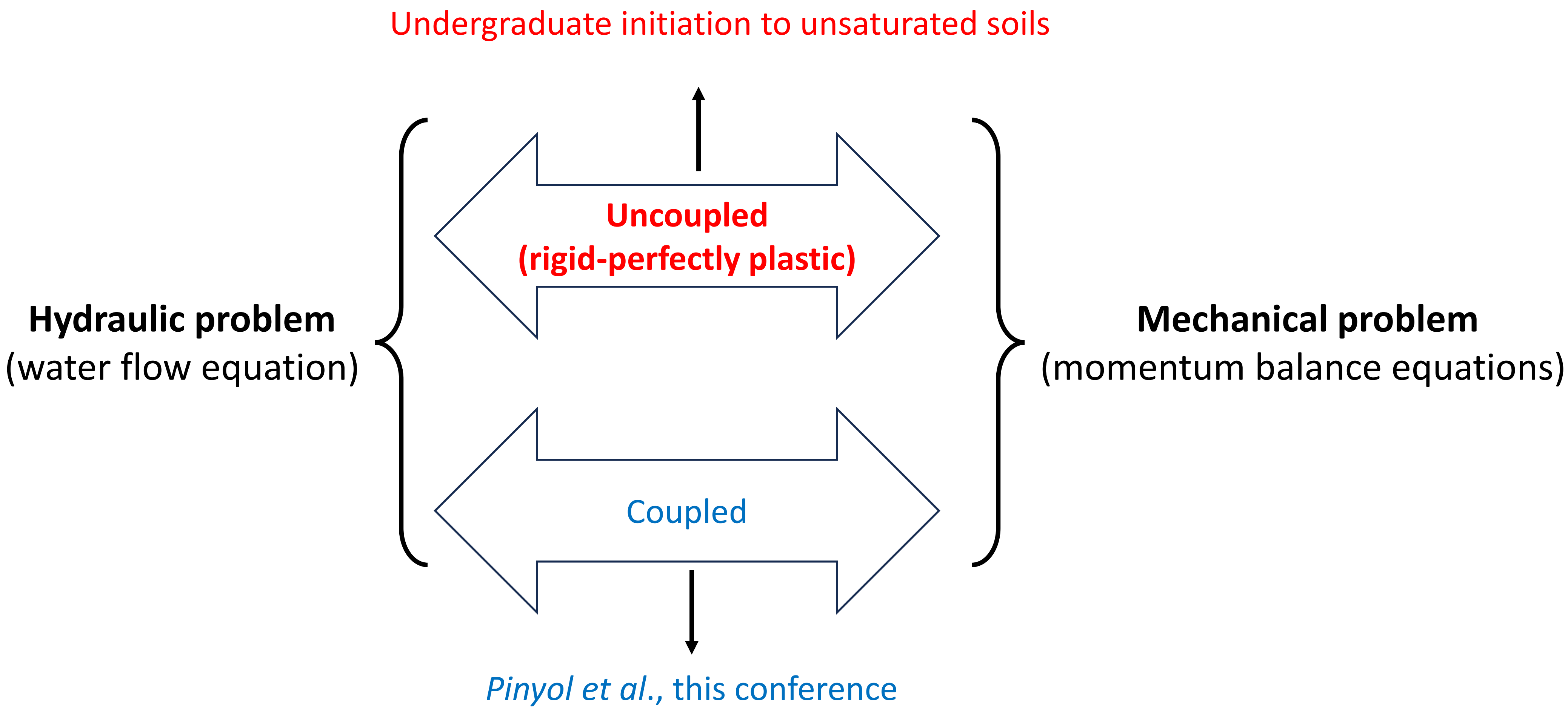




Serviceability. Thrust depends on soil-structure interaction (i.e. it is controlled by both soil and wall stiffness,

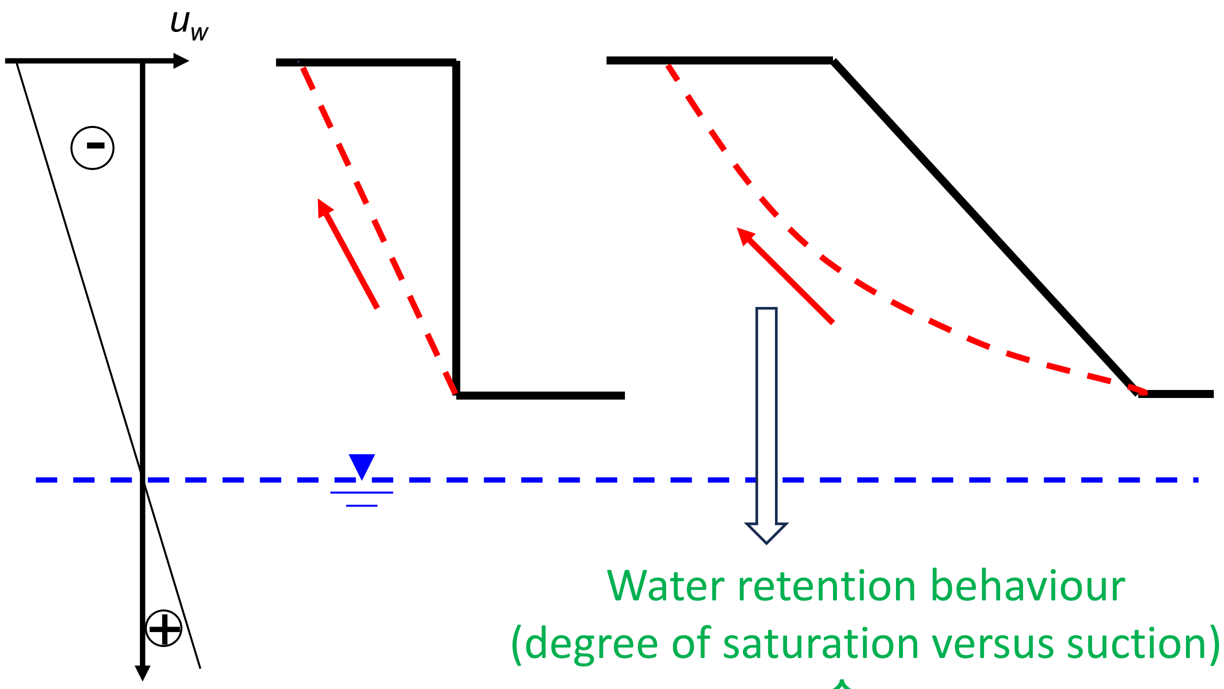
Ultimate state. Thrust does ***NOT*** depend on the soil-structure interaction. Ultimate state of the soil (i.e. the shear strength) is often sufficient.

Ultimate limit state - Slope stability



Ultimate limit state - Slope stability

The exercise in this lecture considers the simplest water flow problem, i.e., hydrostatic condition.
(we also consider transient water flow in the class)



Water retention behaviour
(degree of saturation versus suction)

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

Shear strength criterion for unsaturated soil

HOW do we teach

(water retention behaviour & shear strength)

Three main ‘design’ instructional criteria

- **Non-axiomatic fashion**

  Instead of mathematical models fitted on experimental data, we develop mathematical models derived from elementary physical mechanisms

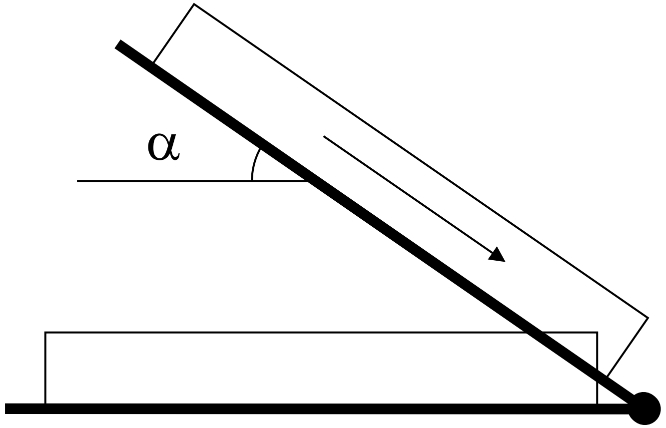
- **Building upon elementary physical mechanisms**

  To help students develop a bottom-up understanding of the fundamentals of unsaturated soil mechanics

- **Real-time, small-scale experiment**
  - To provide a visual demonstration of key micro-mechanisms of unsaturated soil mechanics
  - To add an experimental component, as specialised unsaturated equipment is typically unavailable in most university research laboratories, and even more so in teaching laboratories

An example of the effect of partial saturation

Dry sand



$$\eta = \frac{\tan\phi'}{\tan\alpha} = 1 \quad \Longrightarrow \quad \alpha_{max} = \phi' = 33°$$

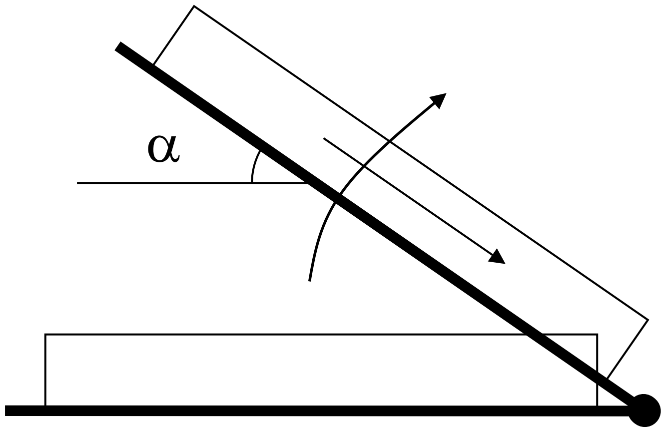
An example of the effect of partial saturation

Unsaturated sand - Dry approach

No negative pressure
No surface tension

⇩

No meniscus bonding

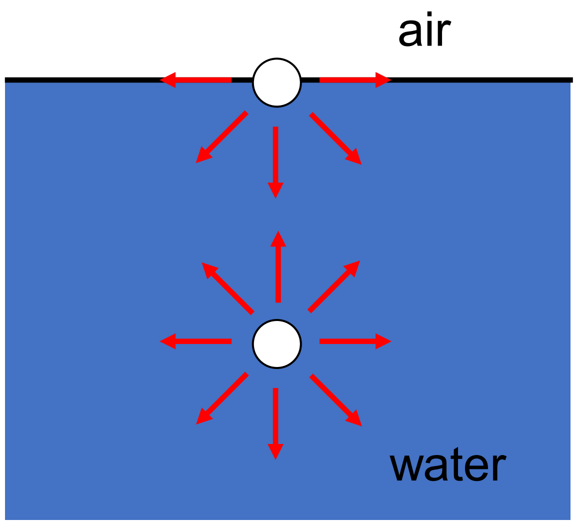


$$\eta = \frac{\tan \phi'}{\tan \alpha} = 1 \quad \Longrightarrow \quad \alpha_{max} = \phi' = 33°$$

Water retention behaviour

Concept 1 - Surface tension

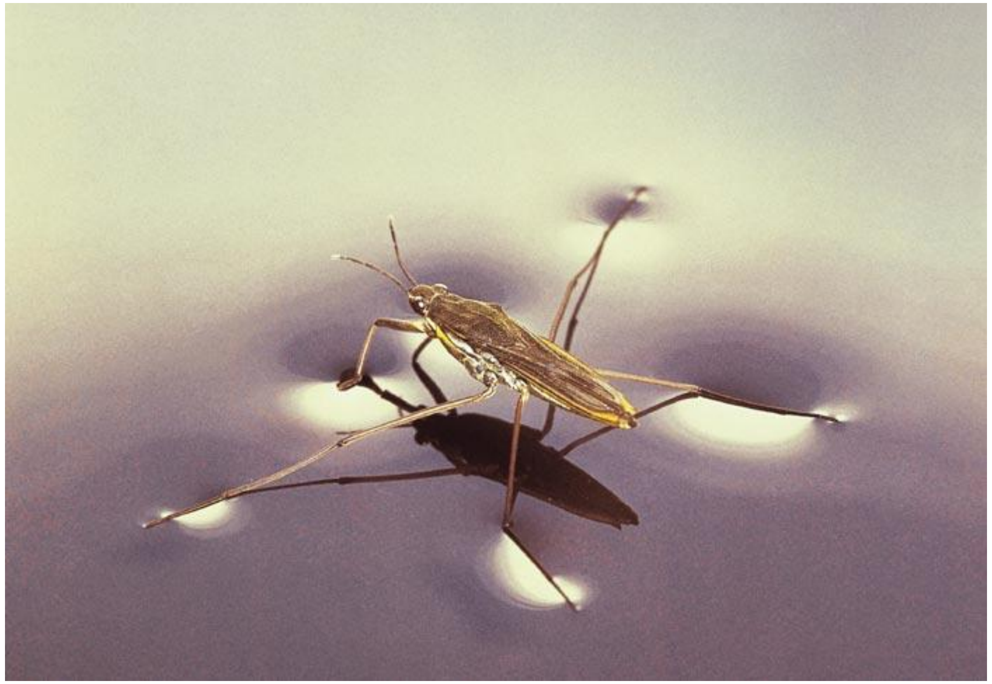
Cohesion = Attraction force between molecules of the same type



The air-water interface behaves like a membrane subject to a uniform tensile stress

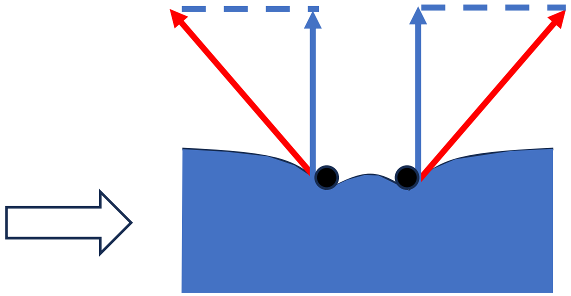
This stress is termed surface tension

Real life example of surface tension: insect walking on water



Real-time experiment in the class

Paper clip 'floating' on membrane-like air-water interface

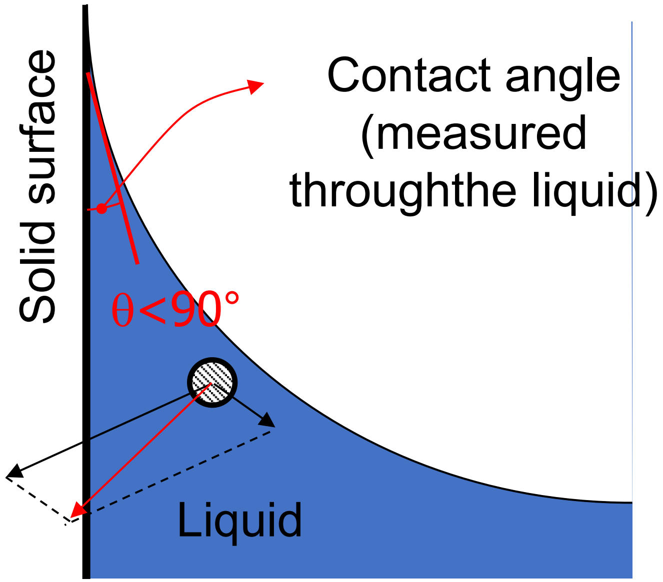


Paper clip sunk at the bottom of the container

Concept 2 – Contact angle

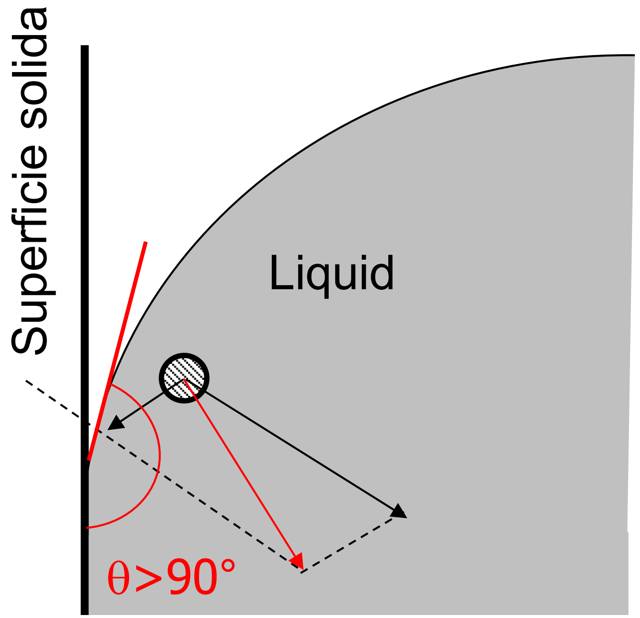
Adhesion = Attraction force between molecules of different type

Adhesion > Cohesion



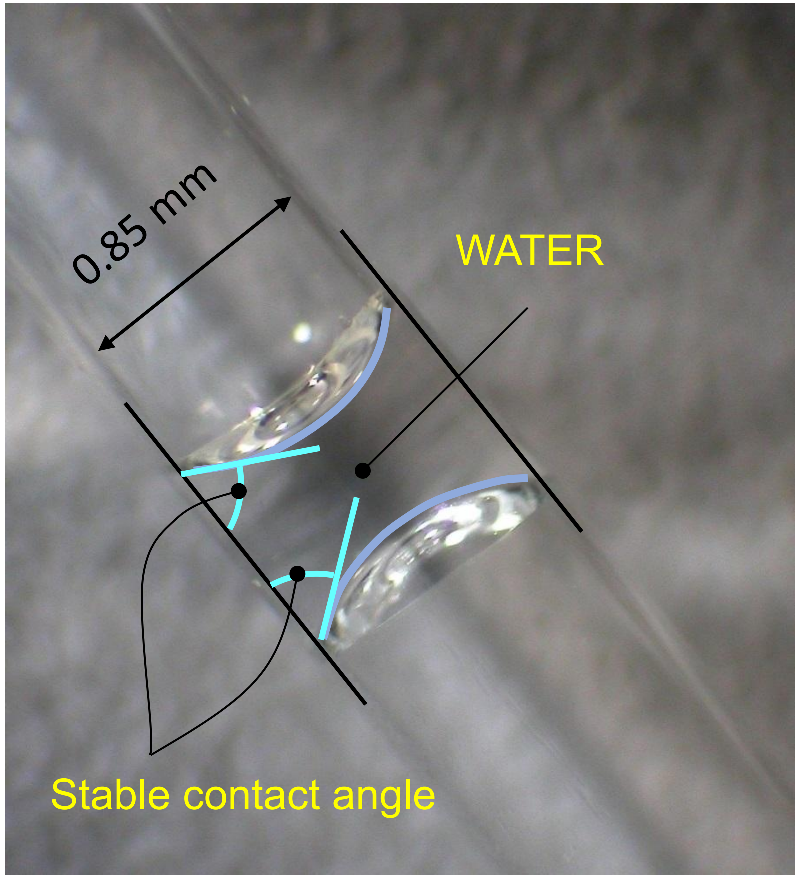
The liquid 'wets' the surface

Adhesion < Cohesion

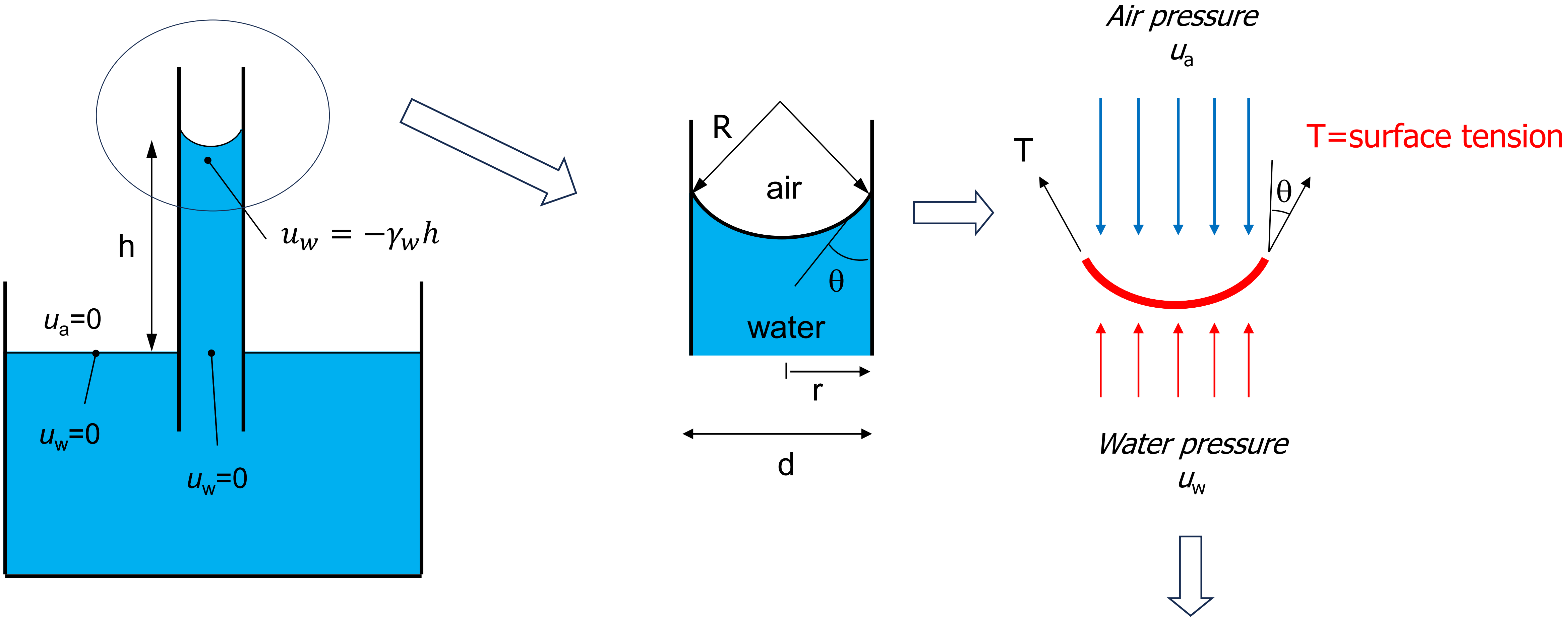


The liquid does not wet

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

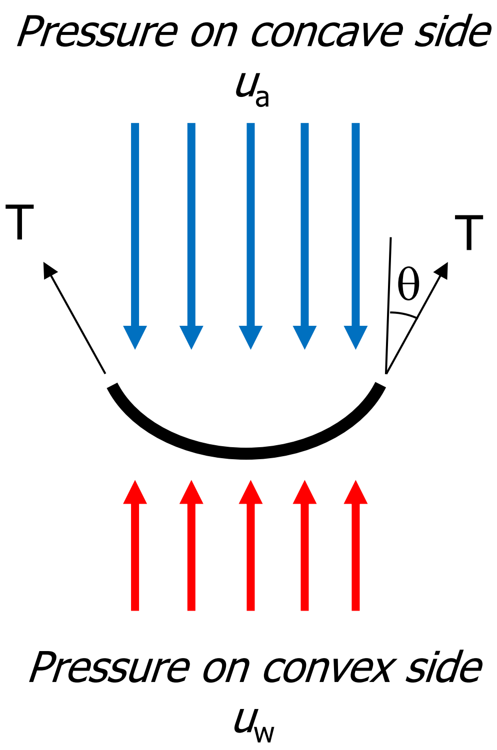


Concept 3 - Capillary pressure



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

Real-time experiment in the class: effect of membrane curvature



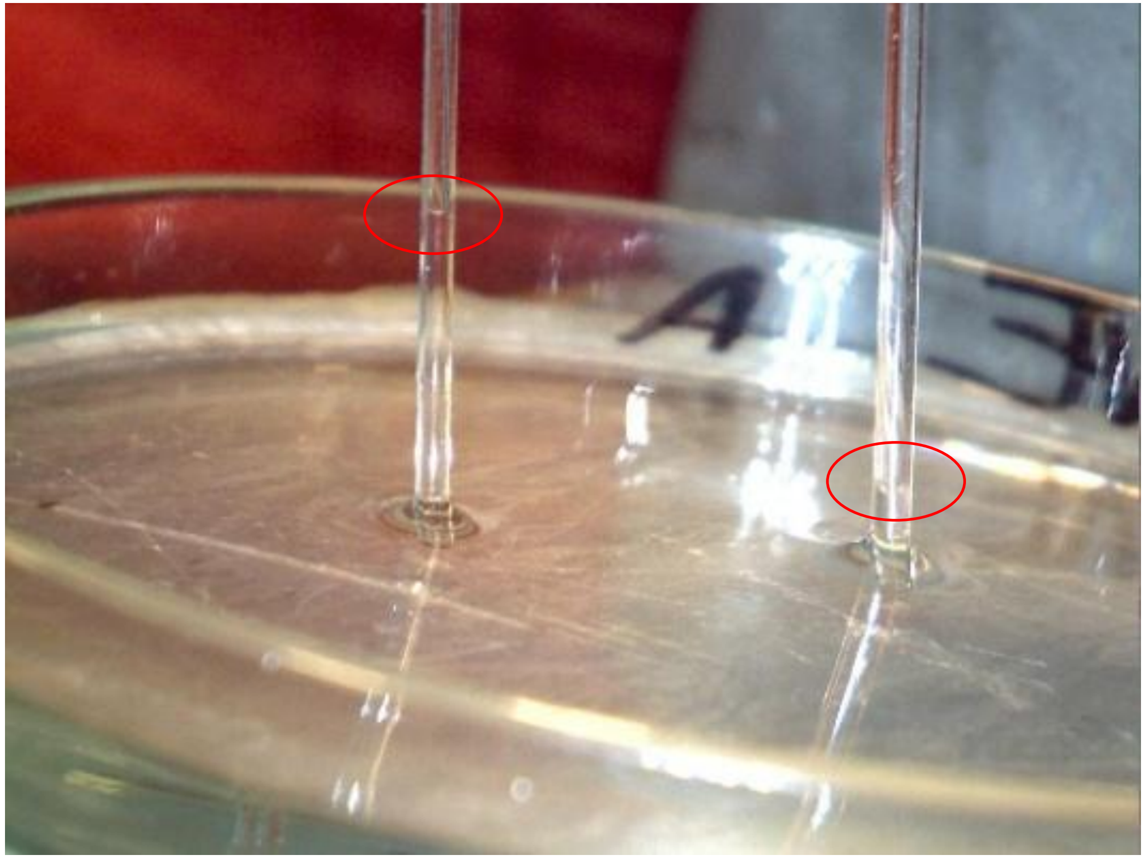
Pressure on convex side < *Pressure on concave side*

Real-time experiment in the class: effect of tube diameter

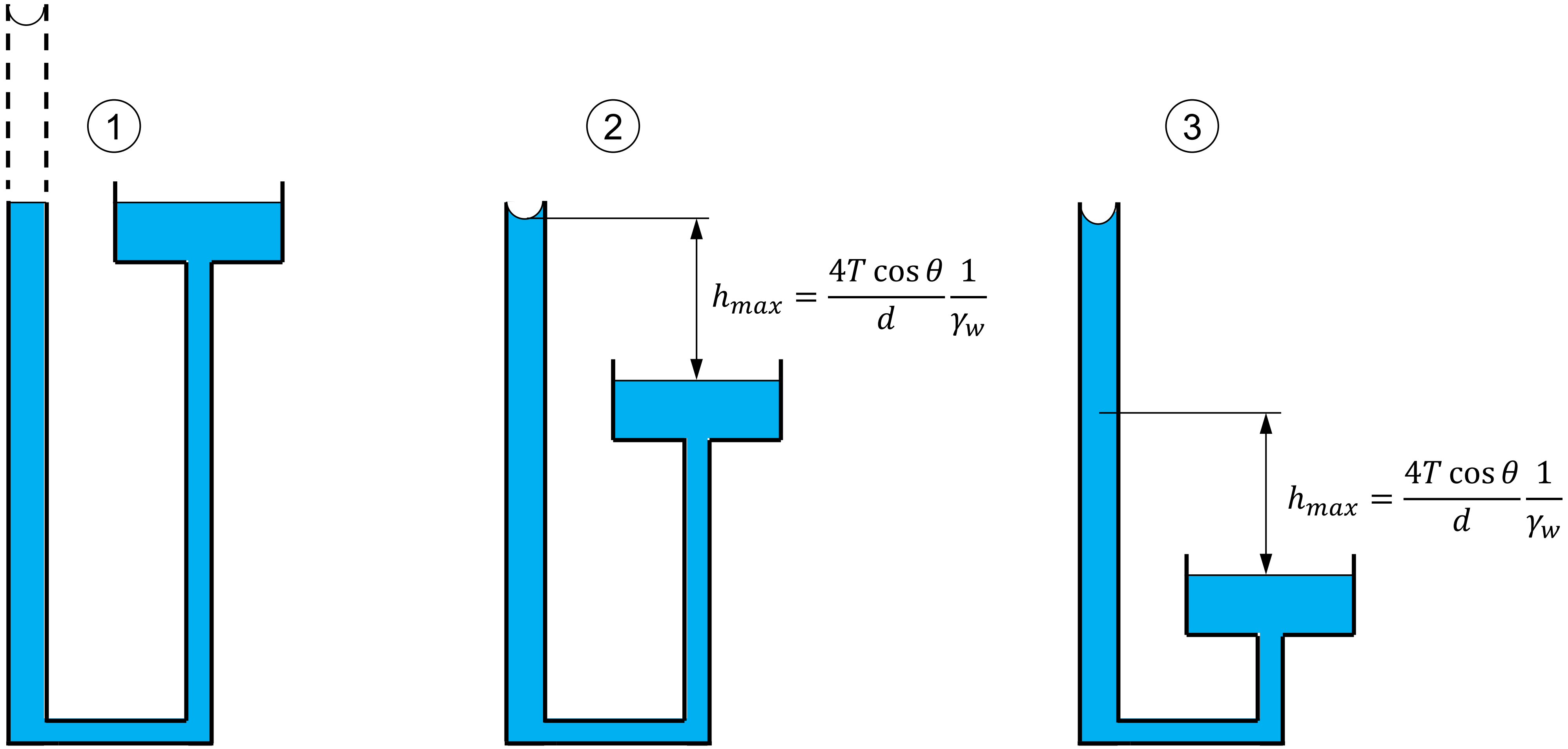
$$u_w - u_a = -\gamma_w h = -\frac{4T\cos\theta}{d}$$

$$\Downarrow$$

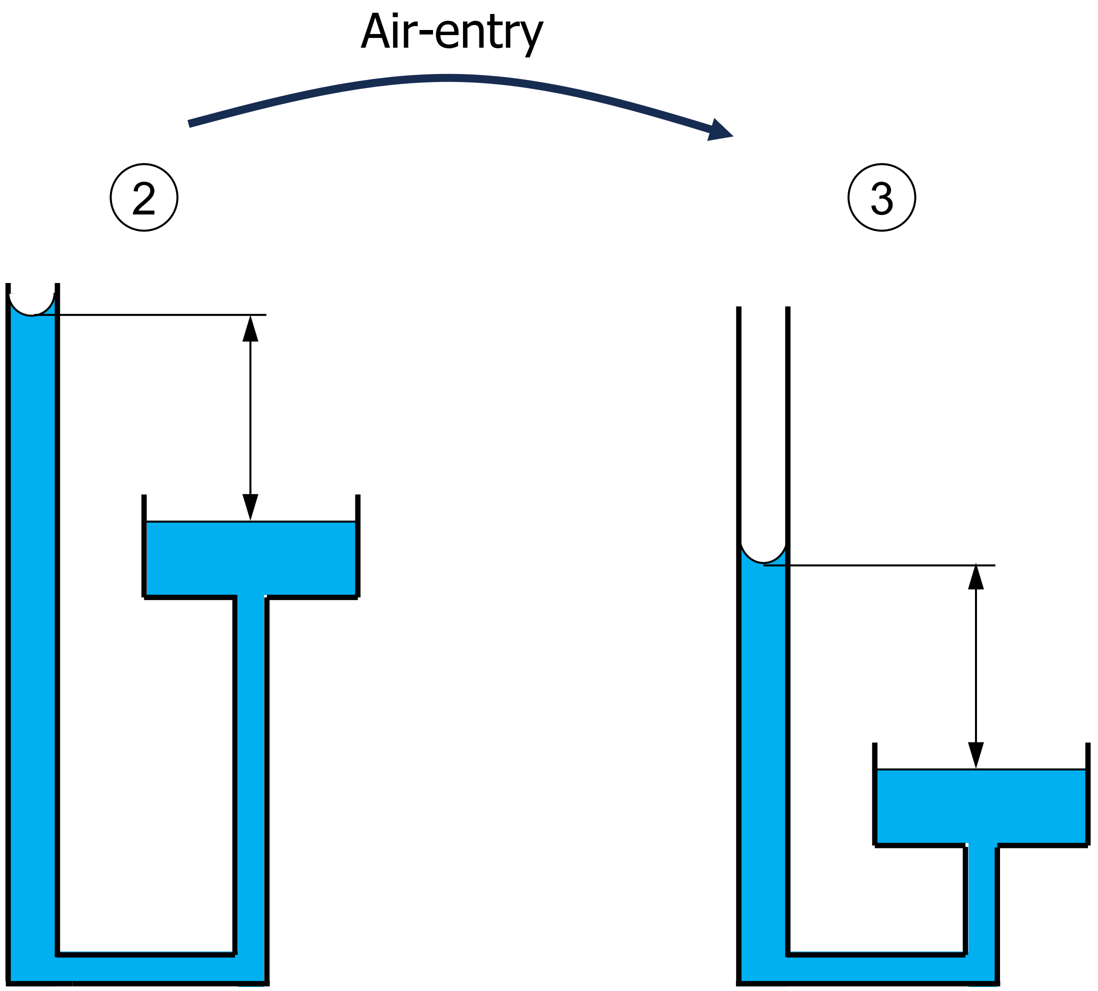
$$h \propto \frac{1}{d}$$



Concept 4 – Water retention → Single capillary tube



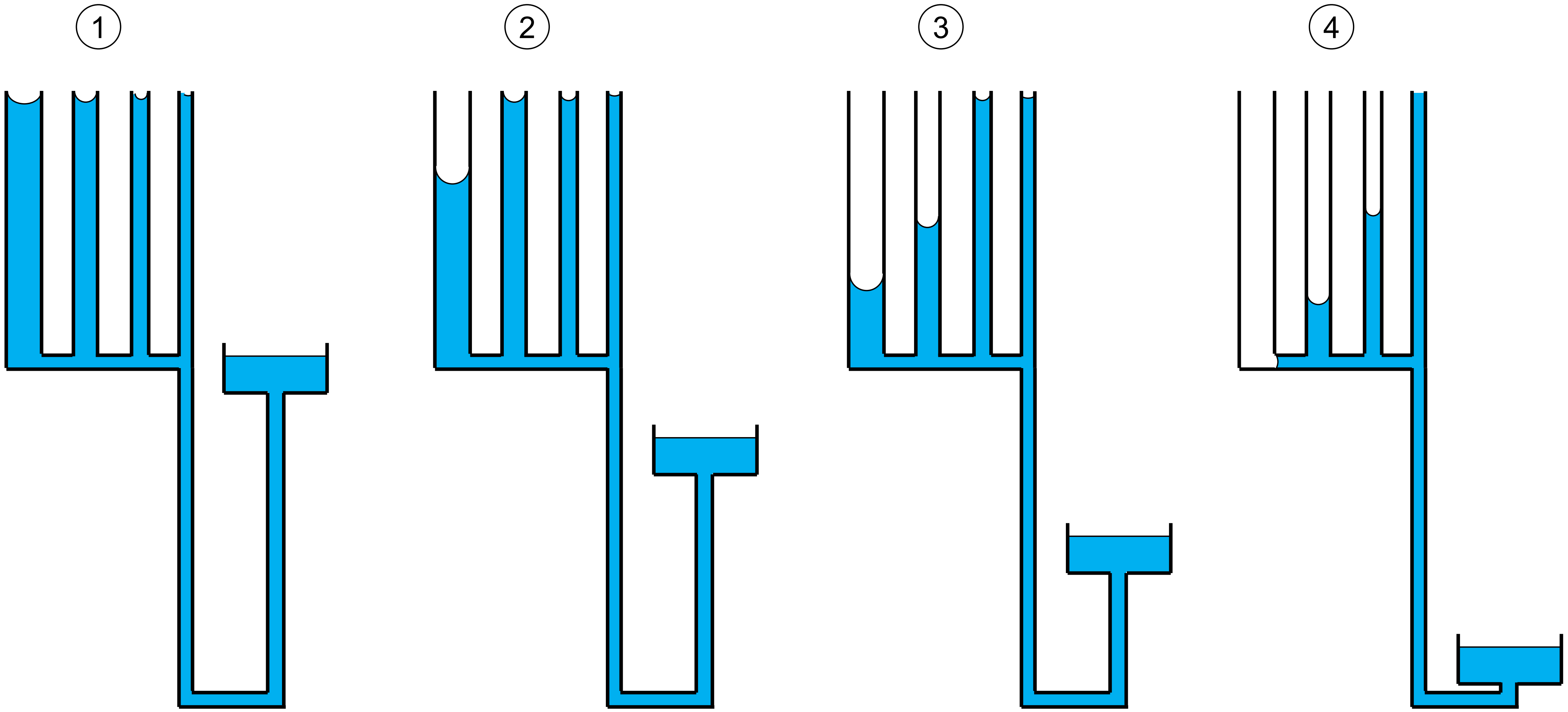
Concept 4 – Water retention → Air-entry



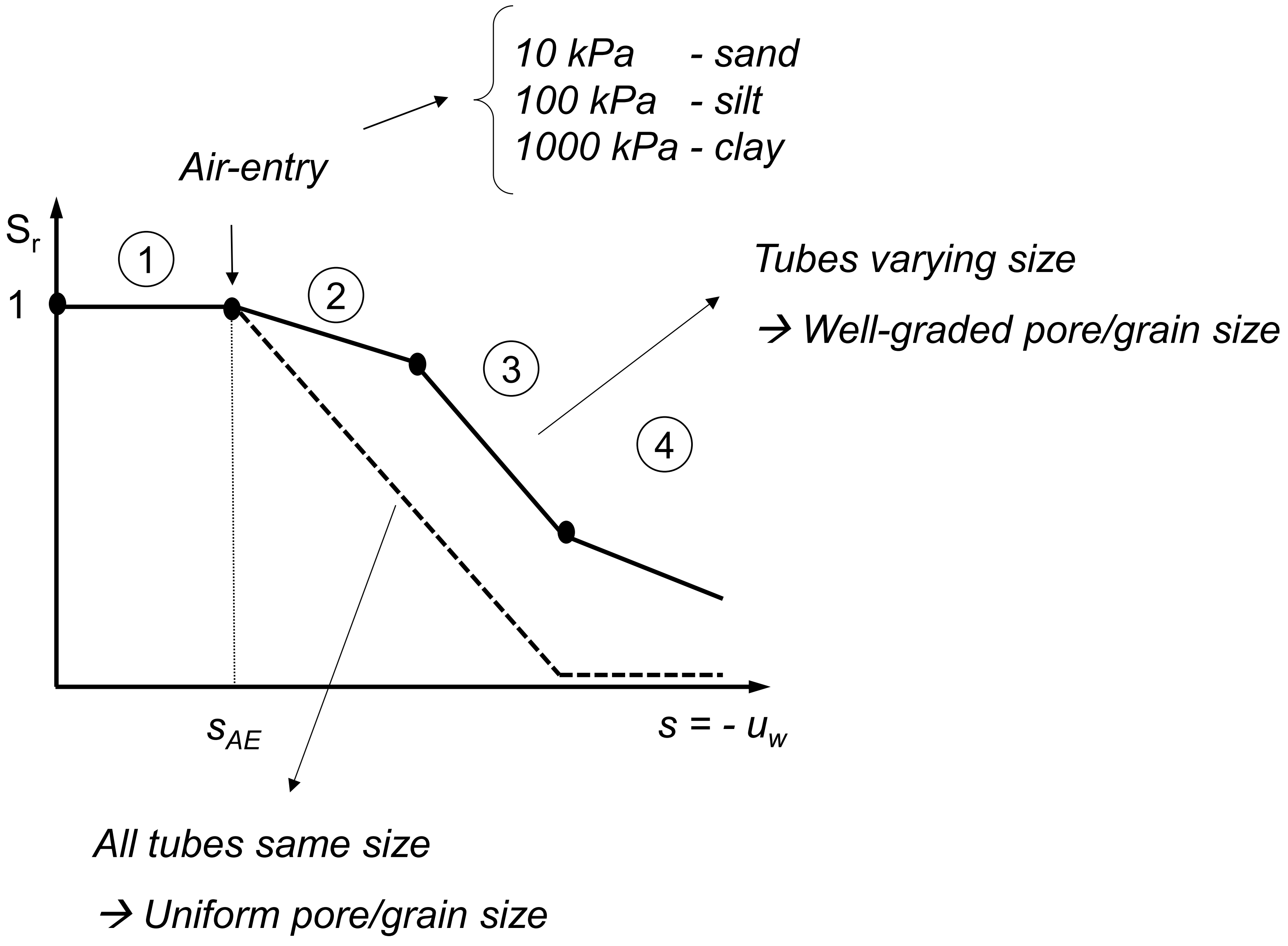
$$s = u_a - u_w = \frac{4T\cos\theta}{d}$$

	Sand	Silt	Clay
d_{grain} (mm)	200	20	2
d_{pore} = 1/6 d_{grain} (mm)	30	3	0.3
u_w (kPa)	-10	-100	-1000
s (kPa)	10	100	1000

Concept 4 – Water retention → system of capillary tubes

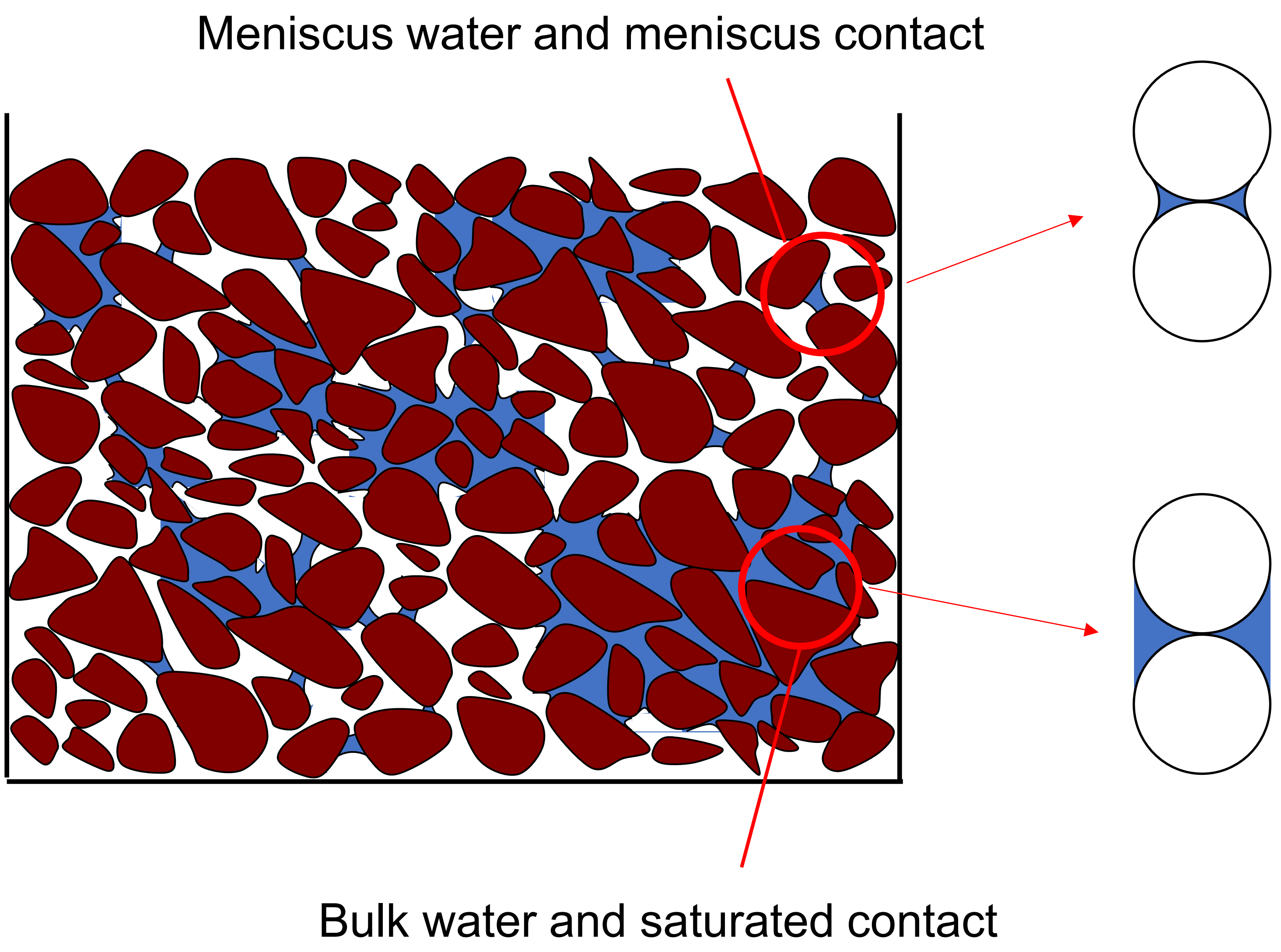


Concept 4 – Water retention of soils

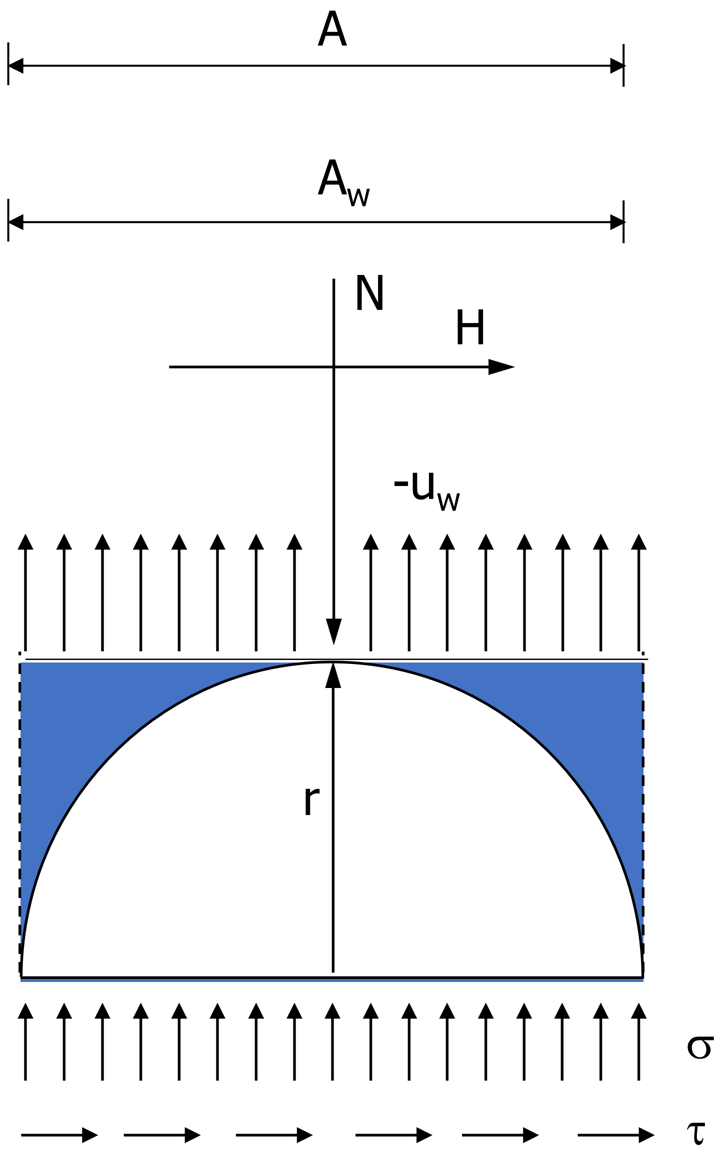


Shear Strength

Concept 5 – Bulk water and meniscus water



Concept 5 – Integranular stress at saturated contact



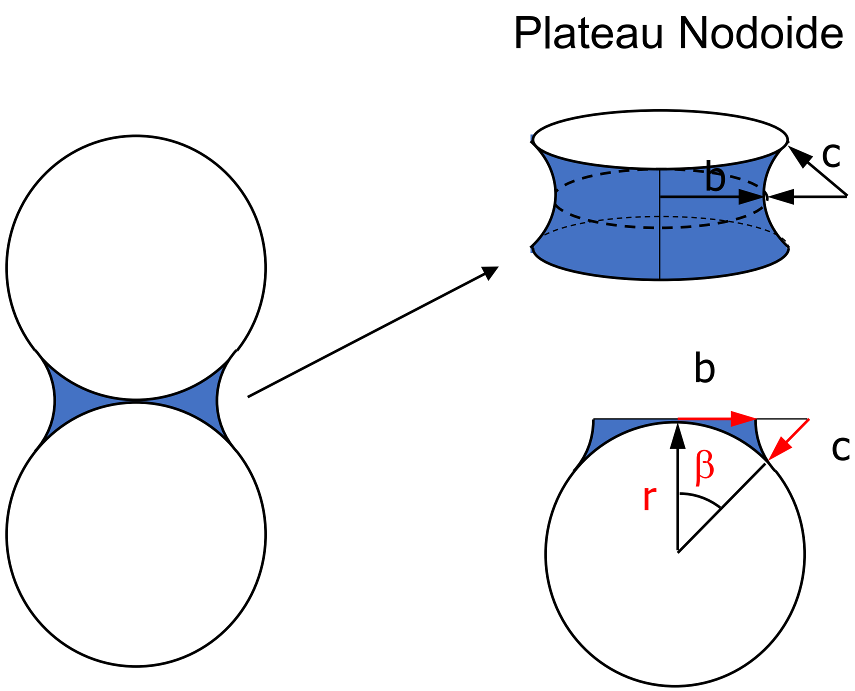
$$\sigma_i = \frac{N}{A} = \sigma - u_w = \sigma + s$$

Let us continue the discussion assuming the intergranular stress ≡ effective stress

$$\sigma_i \equiv \sigma'$$

(Bishop and Skempton, I beg your pardon!!)

Concept 5 – Integranular stress at meniscus contact



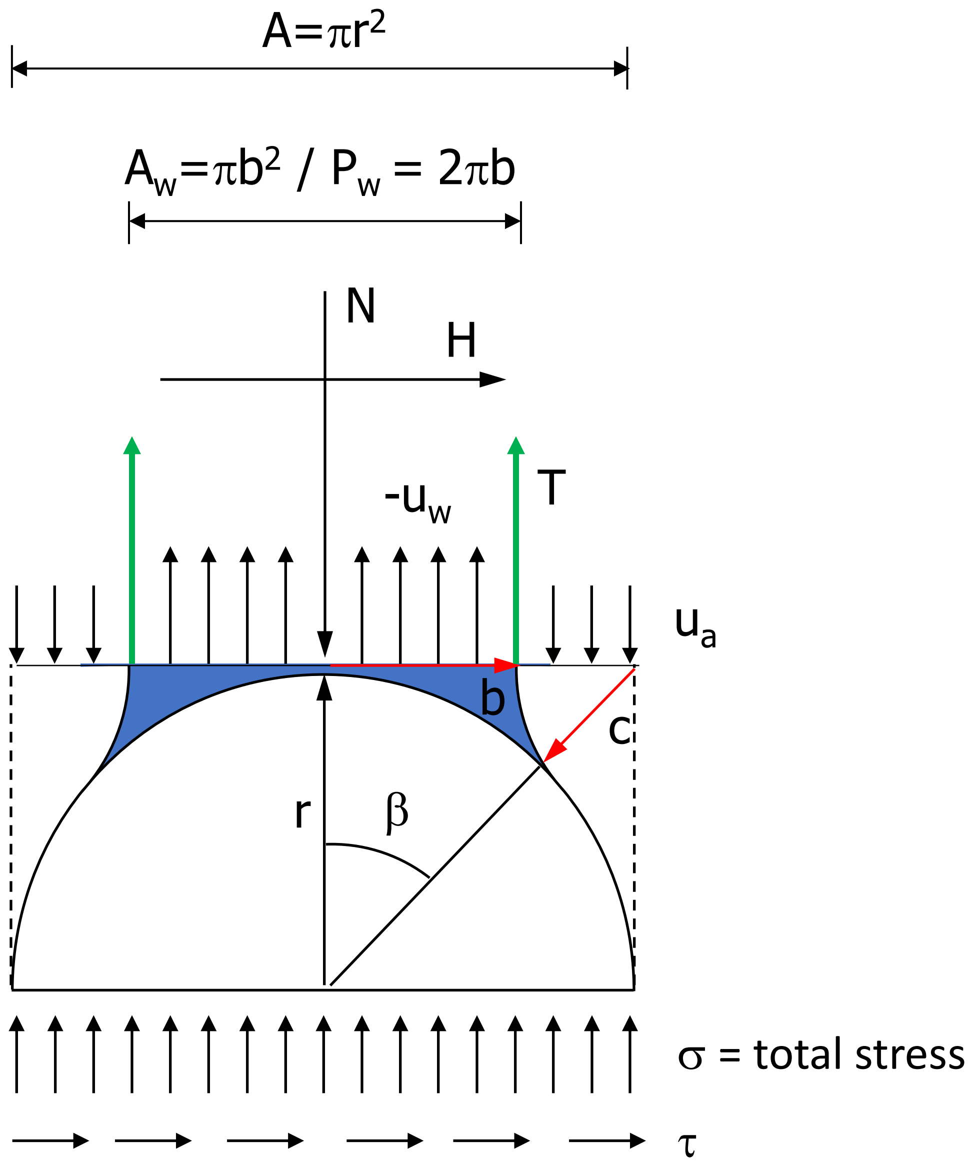
$$s = u_a - u_w = T\left(\frac{1}{c} - \frac{1}{b}\right)$$

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

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

For β=53°, $c \equiv b$ ⇨ u_w-u_a = 0

Concept 5 – Integranular stress at meniscus contact

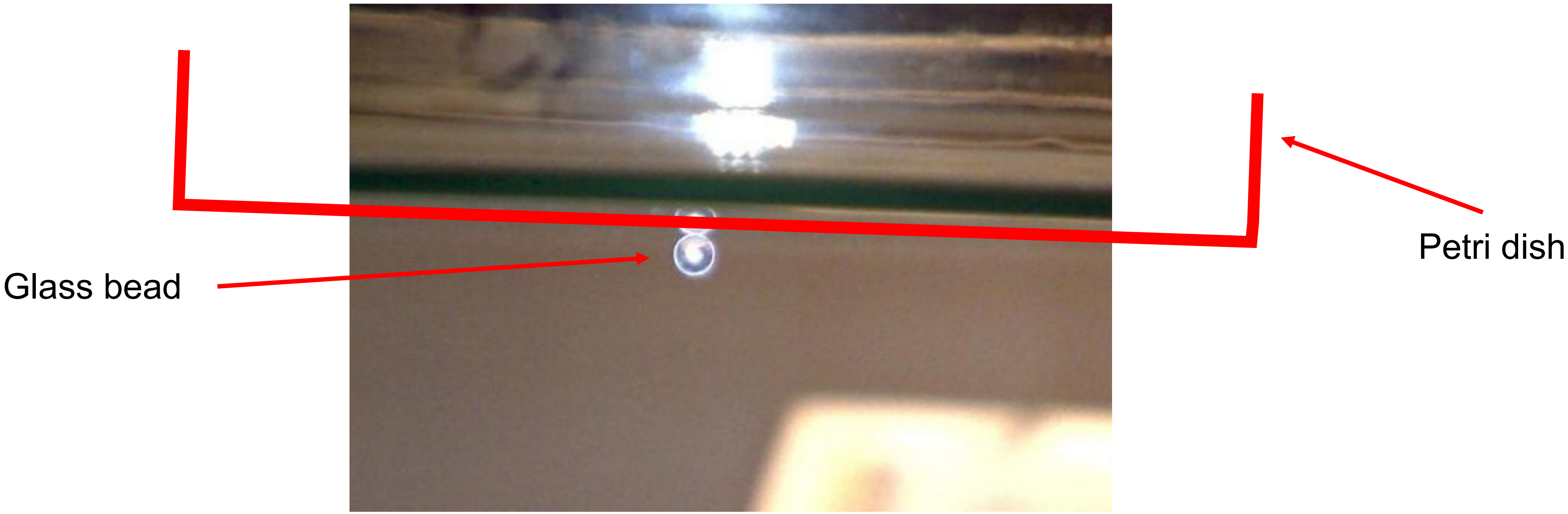


$$\sigma_i = \frac{N}{A} = (\sigma - u_a) + \underbrace{(u_a - u_w)\frac{A_w}{A} - T\frac{P_w}{A_w}}_{\sigma_i^{meniscus}}$$

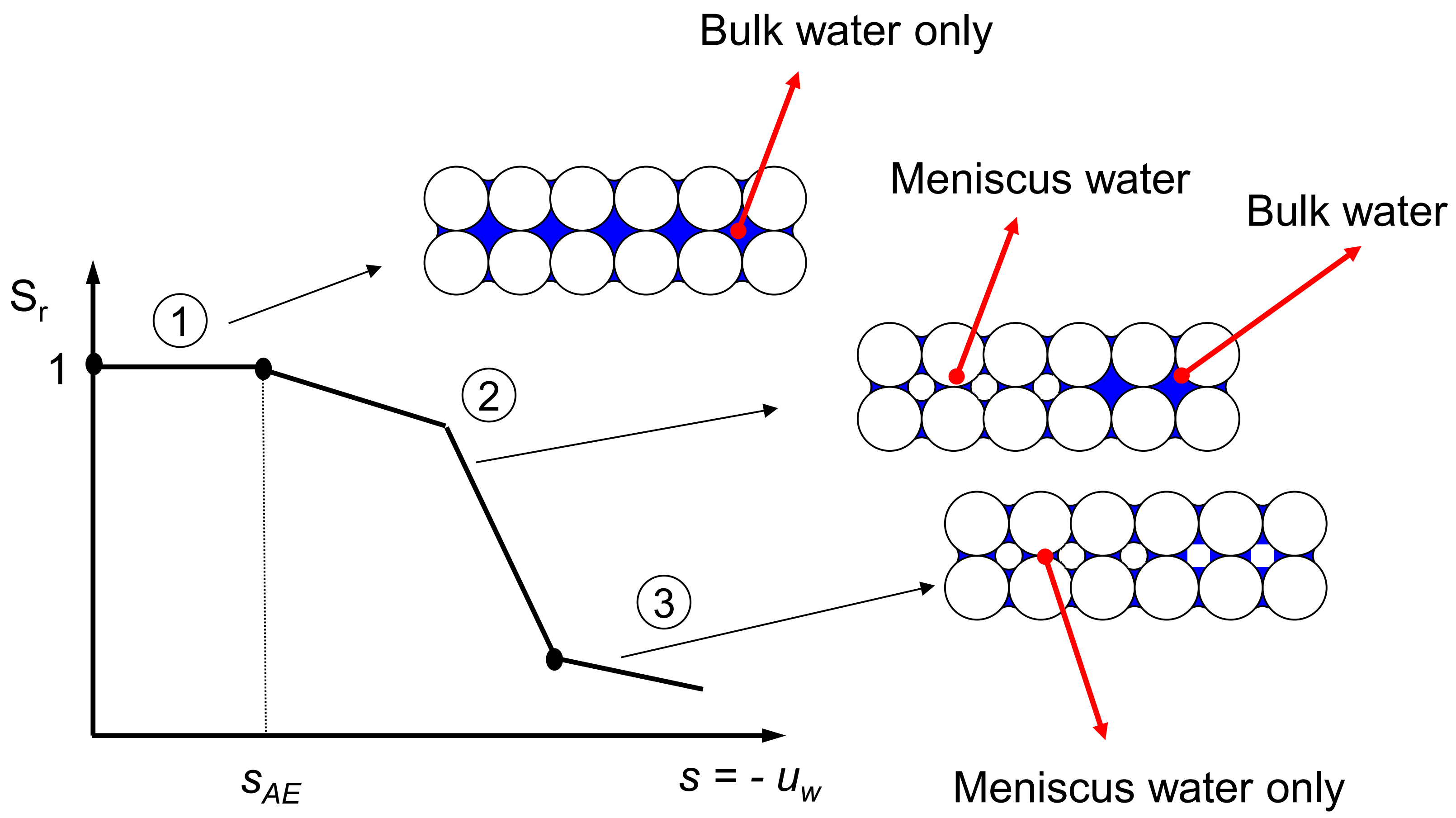
$\sigma_i^{meniscus} \cong$ constant (independent of suction)

Real-time experiment in the class: meniscus ‘bonding’

Glass bead 0.5 mm size ‘attached’ to the bottom of a Petri dish by capillary forces

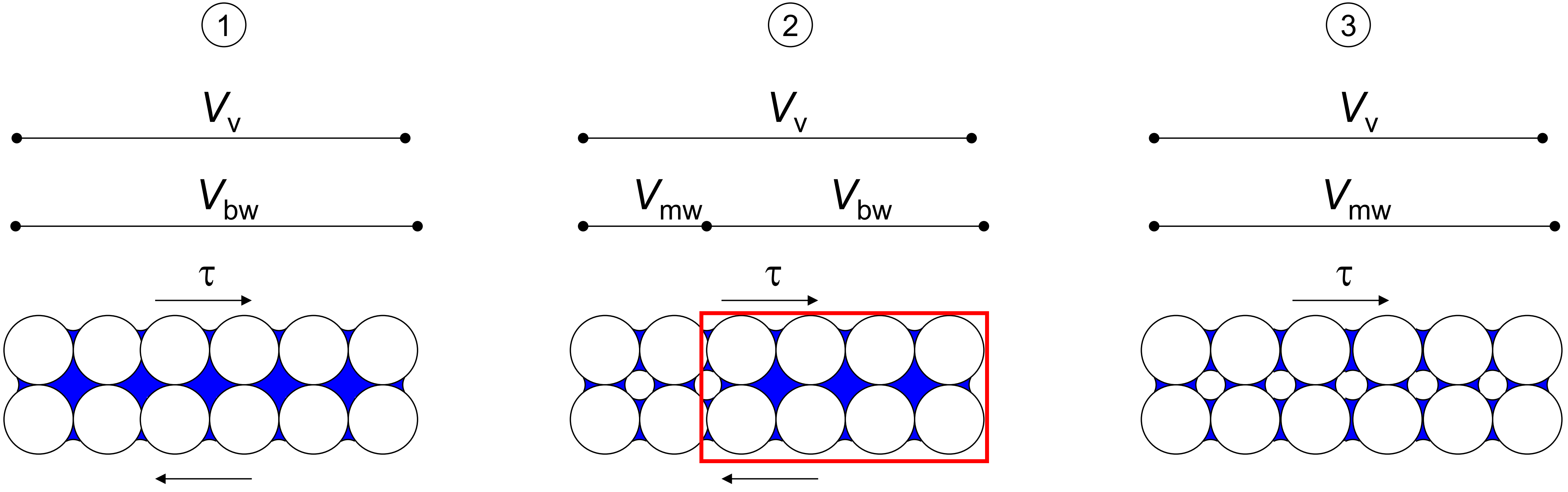


Concept 6 - Shear strength criterion – Differentiating saturation states



Concept 6 - Integranular stress at varying degrees of saturation

$$\tau = \sigma_i \tan\phi' = \sigma \tan\phi' + \sigma_{i,suction} \tan\phi'$$

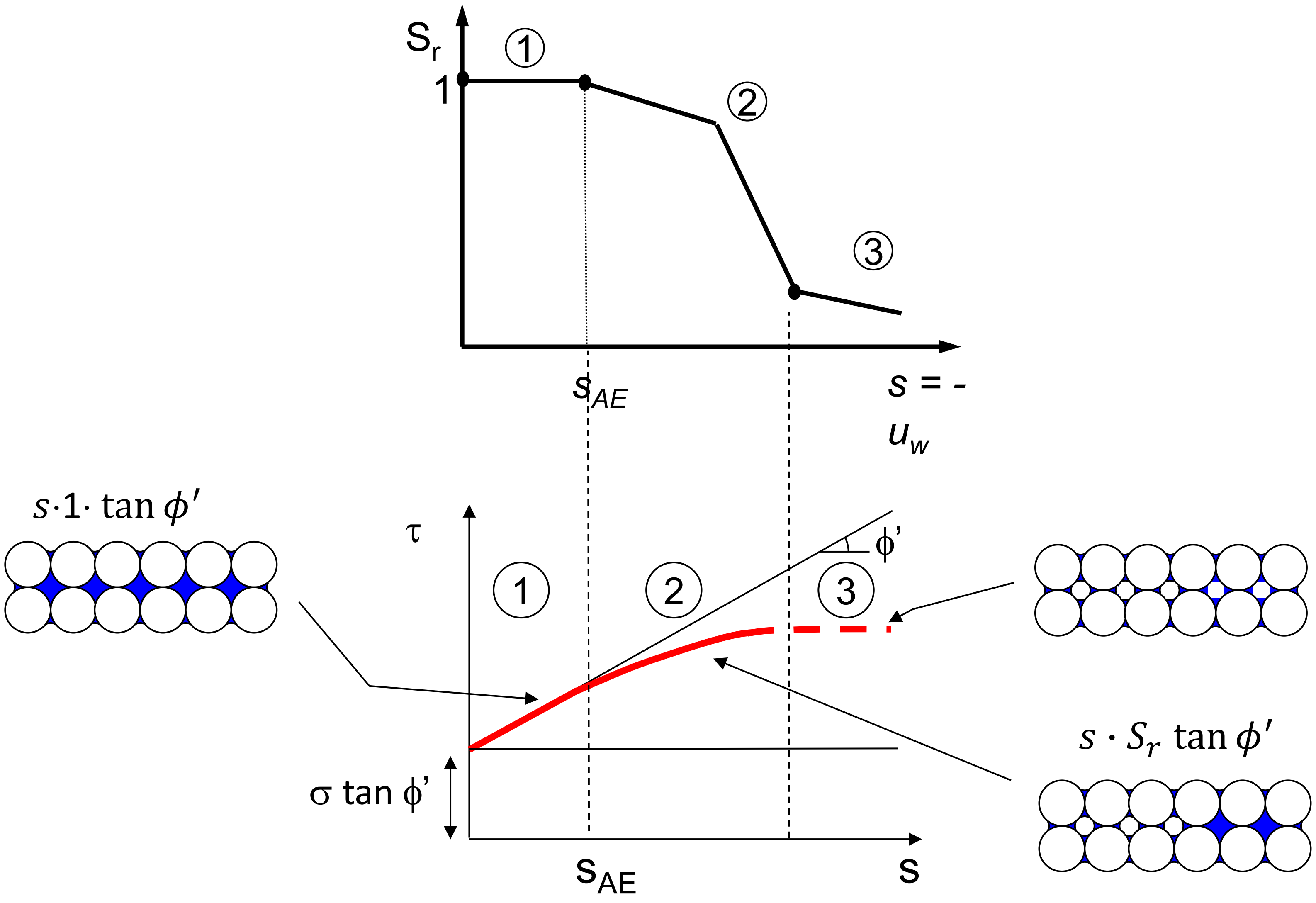


$\sigma_{i,suction} = s$

$\sigma_{i,suction} = s \, \frac{V_{bw}}{V} \cong s \cdot S_r$

$\sigma_{i,suction} = \sigma_{meniscus} = constant$

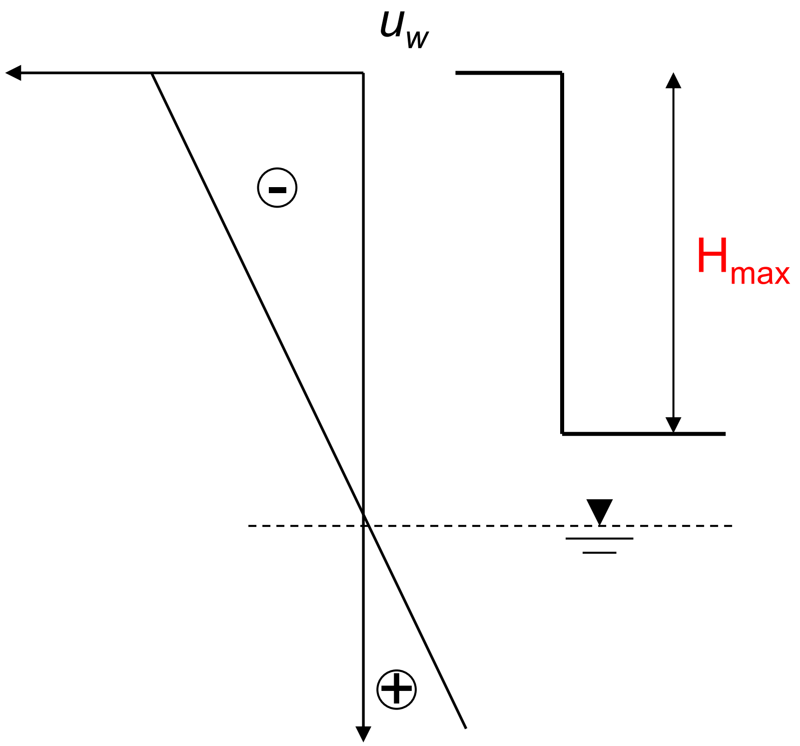
Concept 6 - Shear strength criterion



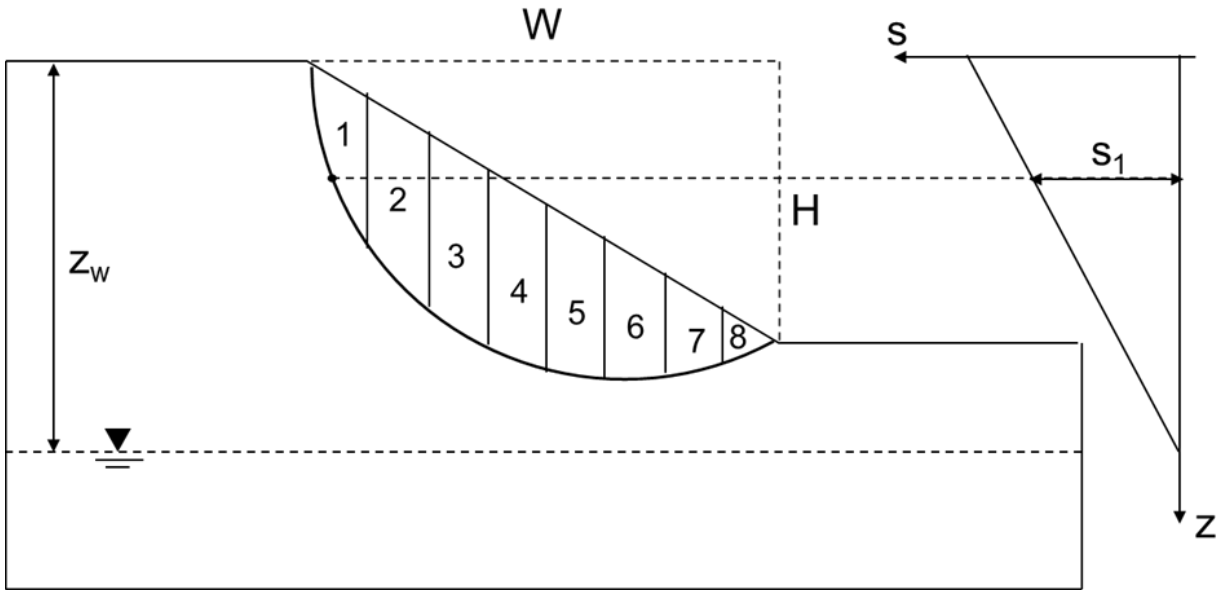
Step 7 – Stability Analysis

$$\tau = (\sigma + S_r s) \tan \phi' \qquad [S_r > 10 - 20\ \%]$$

Vertical cut and hydrostatic suction distribution



Slope stability and hydrostatic suction distribution



Step 7 – Stability Analysis

GEE 2025 - Geotechnical Engineering Education 2025
International Conference "Charting the path toward the future"
organized by TC306 - ISSMGE

Nancy, France
2-4 July 2025

Teaching of unsaturated soil mechanics: building on fundamental physical mechanisms to pave the way for geotechnical analyses

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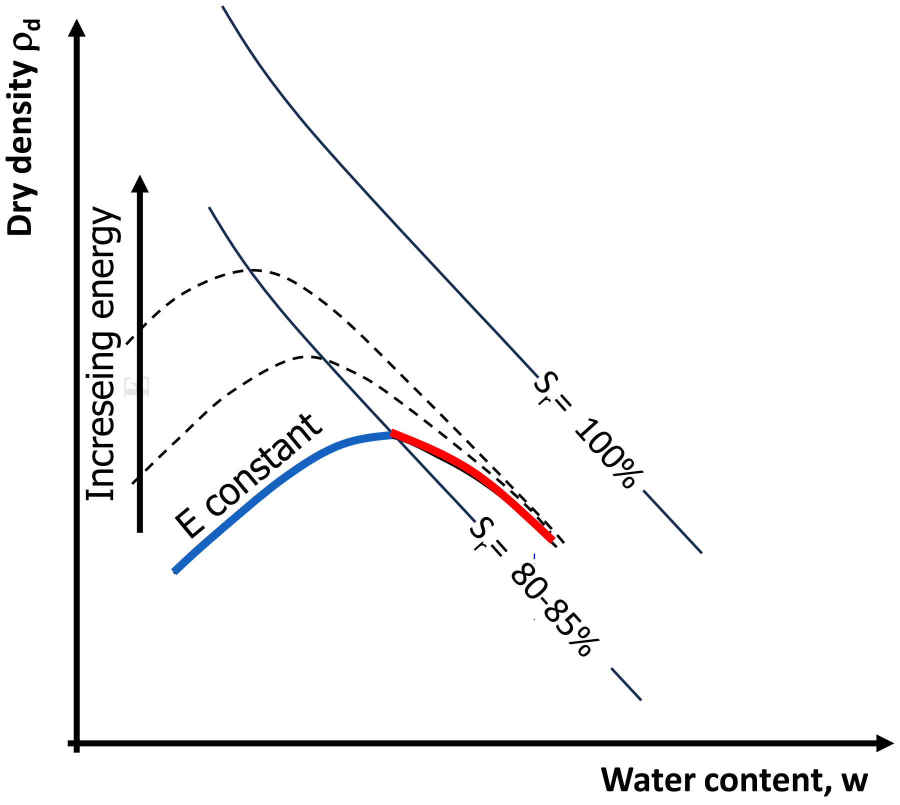
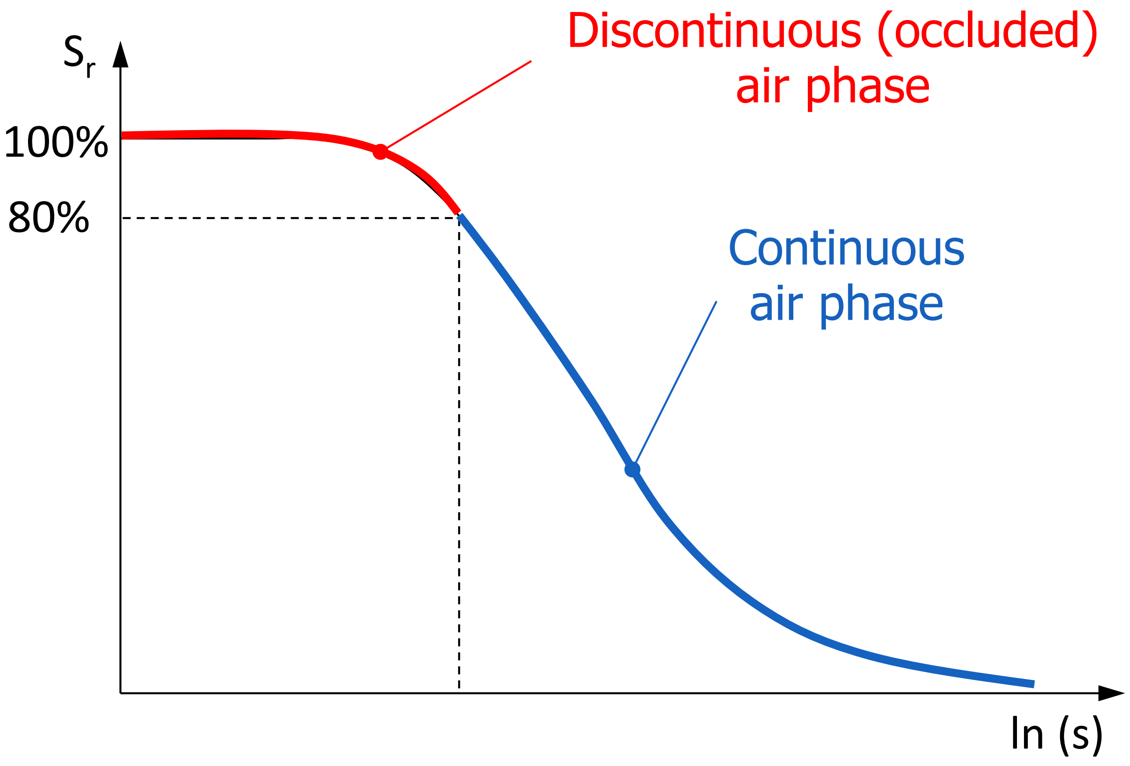
Compaction curve – An unsaturated soil mechanics perspective (compacted soils are unsaturated indeed!!)

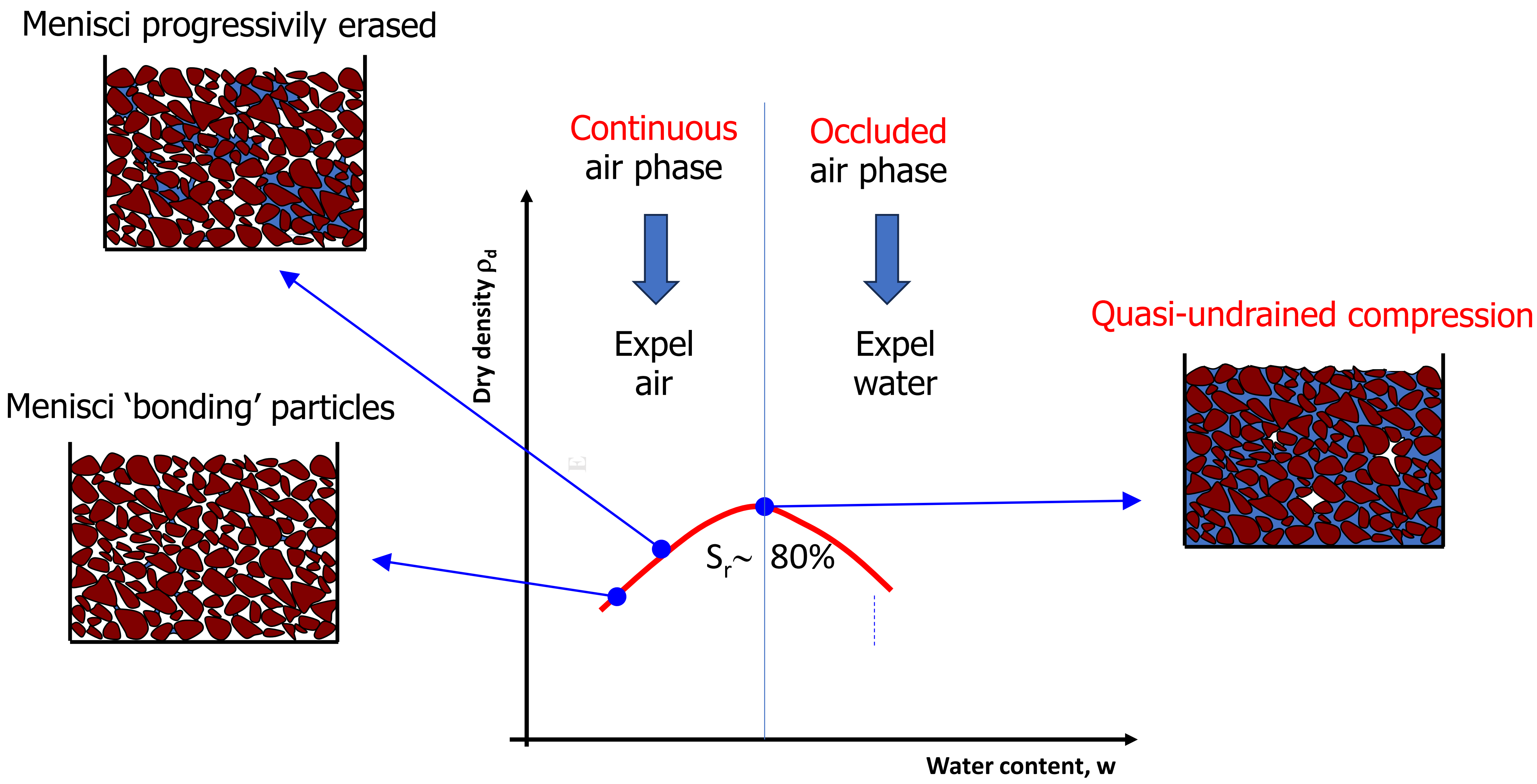


Two questions:

1. Why the bell shape?
2. Why optimum almost always at S_r ~80-85%?

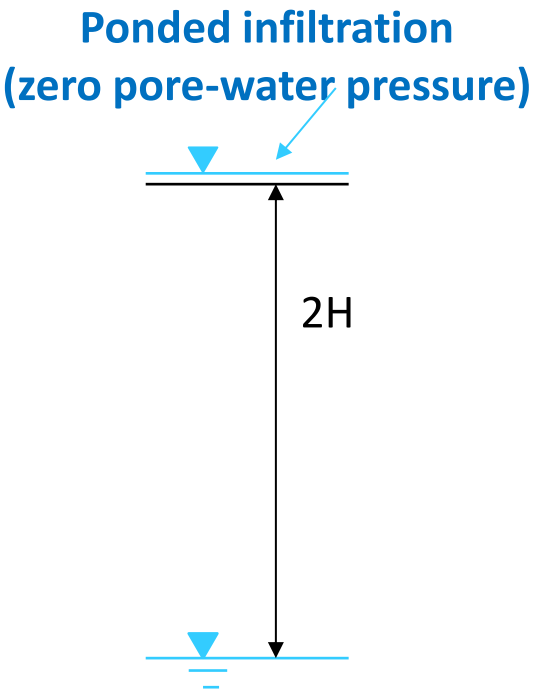


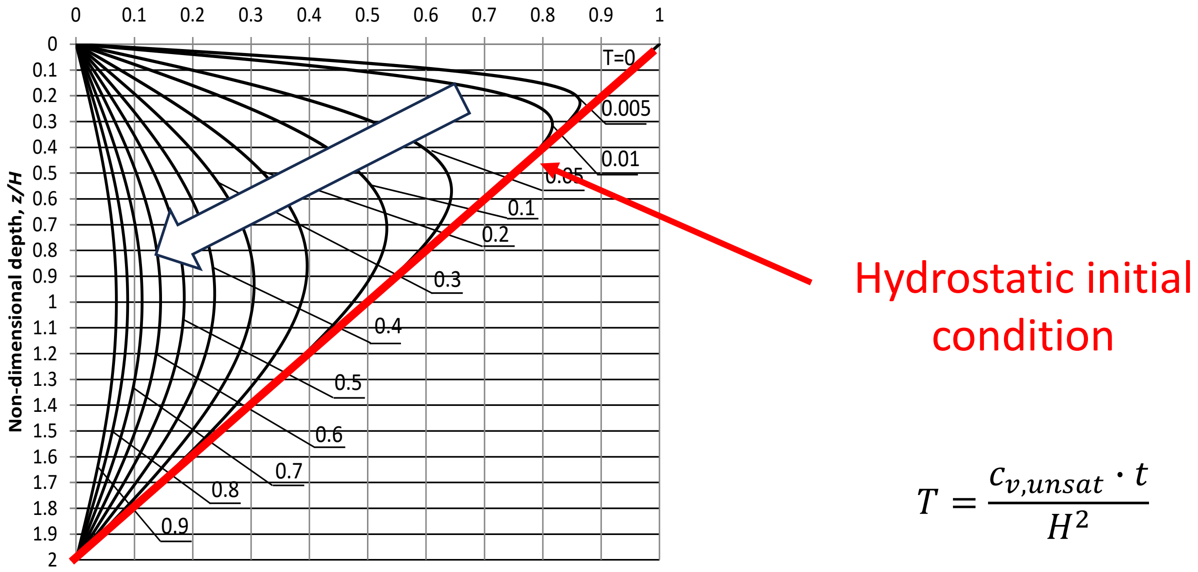
Compaction curve – An unsaturated soil mechanics perspective (compacted soils are unsaturated indeed!!)



Conclusions

- Can we teach elements of unsaturated soil mechanics at undergraduate level?
  Yes, we think we can
- This lecture took 30 min, if you go at slower pace and finalise the stability analysis exercise, it can take 2h, doable size for a lecture
- If you take another 2h, you can introduce hydraulic conductivity via a capillary tubes and model rainfall-induced transient flow using a language familiar to undergraduate students





$$T = \frac{c_{v,unsat} \cdot t}{H^2}$$

If I convinced the non-specialist instructor, further reading here

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Mechanics of unsaturated soils: simple approaches for routine engineering practice

Alessandro Tarantino,* Alice Di Donna**

Summary

A number of geotechnical structures involve the unsaturated upper portion of the soil profile, i.e. the zone above the phreatic surface where the pore-water pressure is negative and the degree of saturation is generally lower than unity. This zone is characterised by soil strength and stiffness higher than the saturated soil below the phreatic surface. In addition, its mechanical response is affected by the interaction with the atmosphere (rainfall and evapotranspiration). Engineers recognise more and more the importance of understanding and predicting the response of soils in the unsaturated portion of the soil profile. However, a gap still exists between research and engineering practice in unsaturated soil mechanics. This paper makes an attempt to serve fundamental concepts of unsaturated soil mechanics using a language as simple as possible. In particular, quantitative prediction tools are presented within the familiar framework of saturated soil mechanics. These include conventional 'saturated/dry' slope stability analysis and traditional 1-D consolidation analysis.

References not included in the accompanying paper

De Vita P, Angrisani AC, Di Clemente E (2008). Engineering geological properties of the phlegraean pozzolan soil (Campania region, Italy) and effect of the suction on the stability of cut slopes. Italian Journal of Engineering Geology and Environment, 2: 5-22. https://doi.org/10.4408/IJEGE.2008-02.O-01

Stanier SA and Tarantino A (2023). An approach for predicting the stability of vertical cuts in cohesionless soils above the water table. Engineering Geology, 158: 98-108. https://doi.org/10.1016/j.enggeo.2013.03.012.

Availability of Images and Figures

Non-copyrighted figures and images from the presentation and the accompanying paper will be provided in their original format upon request (alessandro.tarantino@strath.ac.uk)