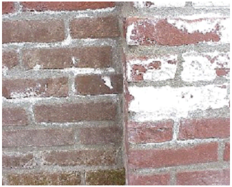
Porous media
–
How to describe them ?

Olivier Liot Petit

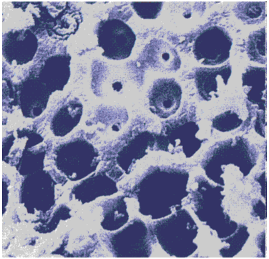
Where do we observe pores?

> Numerous examples: natural

Wood



Bricks

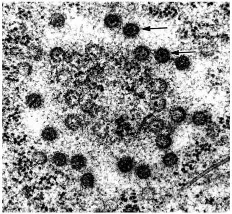


Limestone

Rocks

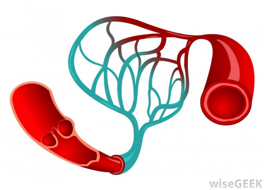
Where do we observe pores?

- Numerous examples: biological and artificial



Cell nucleus surface

Filter



Blood vessels

Fibreglass

Take your smartphone

How could we define a pore?

A. Crevice or cavity in a solid
B. Orifices coming out on a solid surface
C. Channel crossing a wall
D. All of them

#QDLE#S#ABCD##

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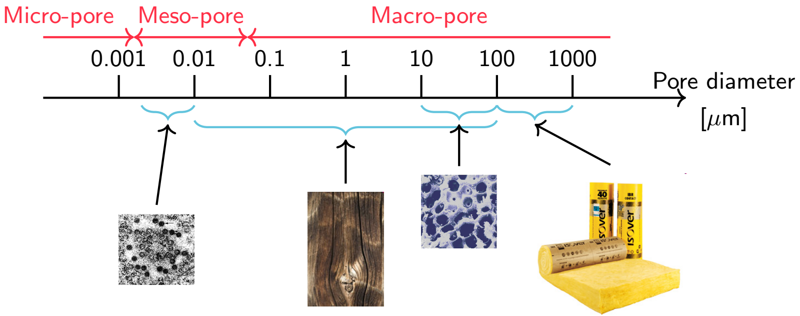
> Pore size classification (IUPAC)



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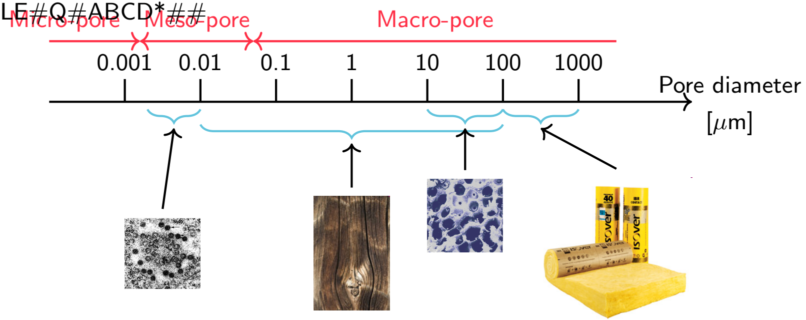
#QDLE#Q#ABCD*###



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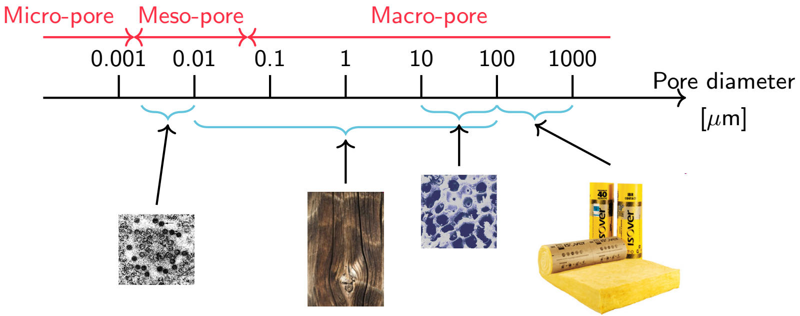
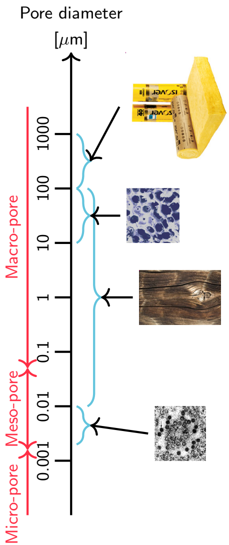
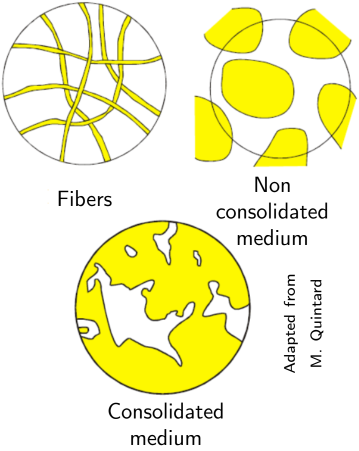
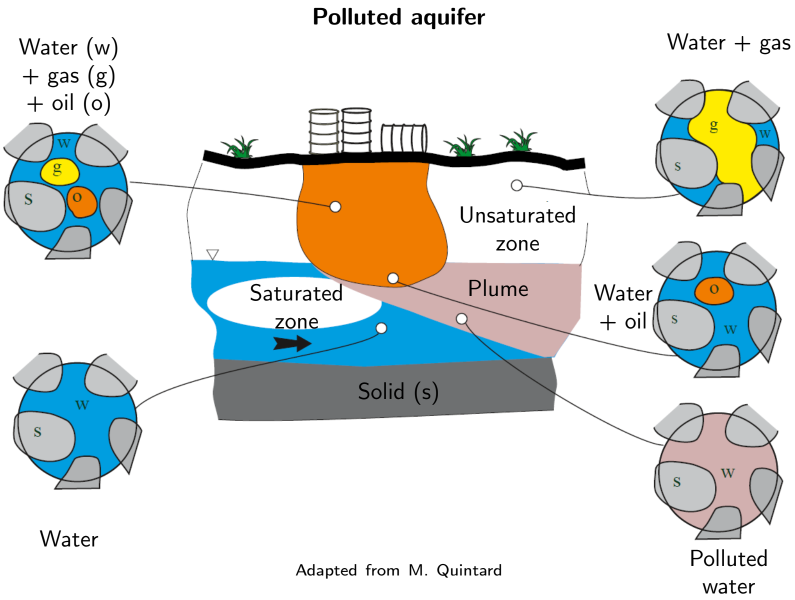


> Size (IUPAC)



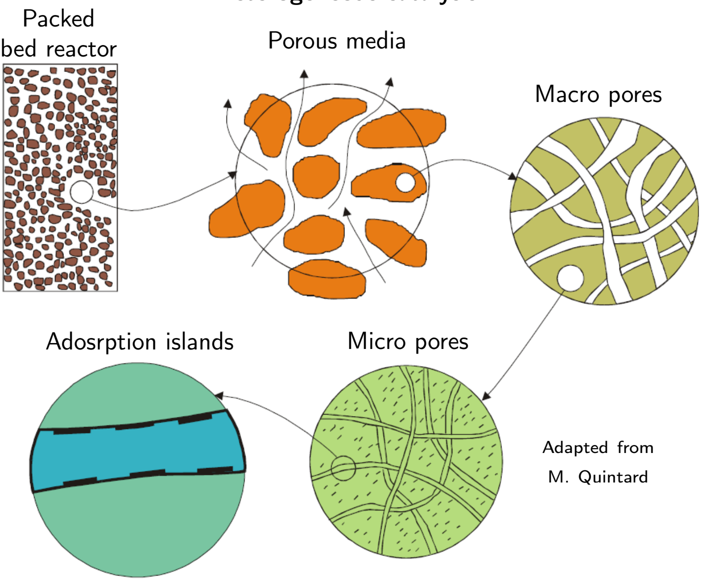
> Structure





Adapted from M. Quintard

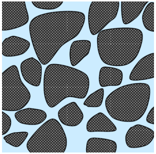
Heterogeneous catalysis



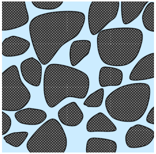
Adapted from
M. Quintard

Observations:

- Large variety of porous media (structure, size)
- Coexistence of different scales, with different properties
- Different solid phase properties (sand, rock, fibers)



How to have a quantitative approach of porous media properties?



Description of porous media and upscaling to porous media (two first parts):

A. **Definition of porous media scales, structures and properties**
B. **Averaging properties over the porous media**

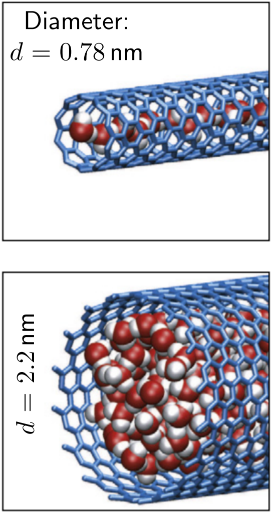
Description of and upscaling to porous media

At the end of the two first sections you should be able to:

- describe some natural and artificial porous media
- define and compute the Knudsen number
- define and explain the main properties of a porous media (porosity, tortuosity, saturation)

- define and describe the Representative Element Volume
- summarize the different upscaling methods for porous media
- compute the spatial average of a scalar field in a porous media

- Liquid in a porous media: Navier-Stokes and Stokes equations still valid
- Even for tiny pores (carbon nanotubes)



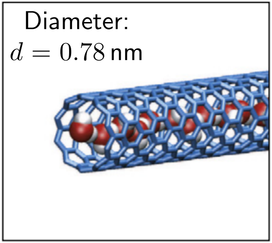
Adapted from Bonthuis *et al.* (2011)

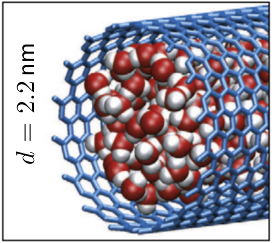
Physics at pore scale: influence of dimensions?

- Liquid in a porous media: Navier-Stokes and Stokes equations still valid
- Even for tiny pores (carbon nanotubes)

What happens with gas?

- Key value: Mean Free Path





Adapted from Bonthuis *et al.* (2011)

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What happens with gas?

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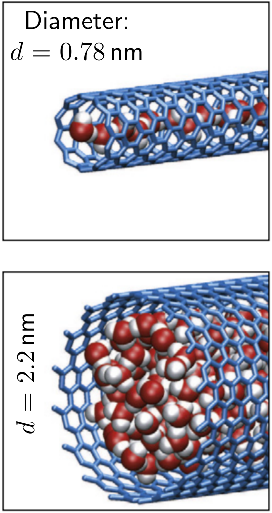
Mean Free Path (ideal gas)

$$\lambda = \frac{RT}{\sqrt{2}\pi d_{mol}^2 N_A P}$$



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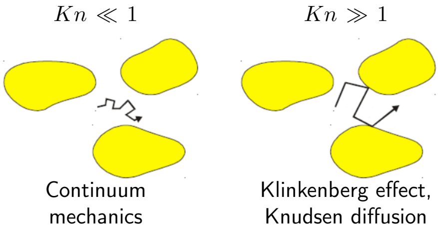
Physics at pore scale: Knudsen number for a gas

Knudsen number

$$Kn = \frac{\lambda}{d_{pore}} = \frac{RT}{\sqrt{2}\pi d_{pore} d_{mol}^2 N_A P}$$

Adapted from M. Quintard



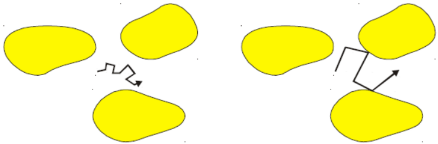
Exercise: numerical application for N_2 under atmospheric pressure and ambient temperature

Knudsen number

$$Kn = \frac{\lambda}{d_{pore}} = \frac{RT}{\sqrt{2}\pi d_{pore} d_{mol}^2 N_A P}$$

$Kn \ll 1$ $\qquad$ $Kn \gg 1$

Adapted from M. Quintard



Continuum mechanics

Klinkenberg effect, Knudsen diffusion

#QDLE#Q#ABC*##

Exercise: numerical application for N_2 under atmospheric pressure and ambient temperature

To have $Kn < 1$, the pore must be a...

A. Micro-pore

B. Meso-pore

C. Macro-pore

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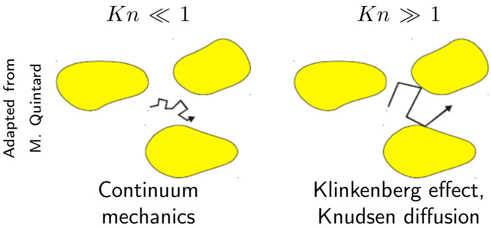

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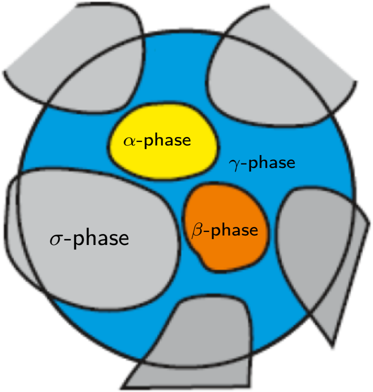
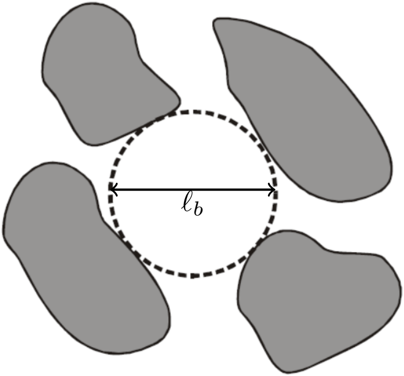
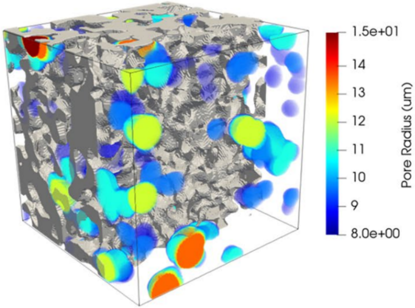


- σ-phase: solid phase
- Other phases: fluid phases (liquid or gas)
- Ψ_β: physical value relative to β-phase (temperature, velocity, ...)





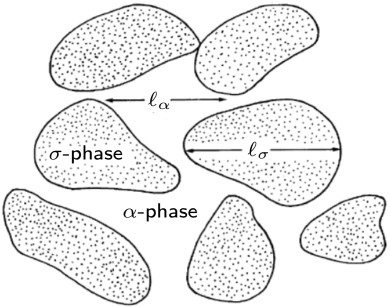
From Ávila *et al.* (2022)¶

> Measurement methods:
- image analysis (2D)
- RX tomography (3D)
- porosimetry (Hg, gas) – 3D

- Ratio between fluid phase volume and total volume

Porosity

$$\epsilon = \frac{V_\alpha}{V_\alpha + V_\sigma}$$



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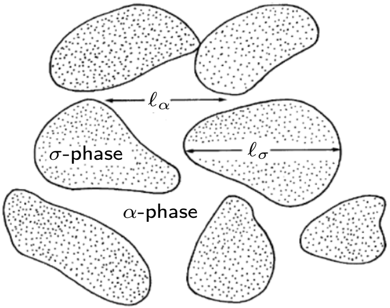
$$\epsilon = \frac{V_\alpha}{V_\alpha + V_\sigma}$$

- Surface of the solid phase

Specific surface

$$S_s = \frac{S_\sigma}{V_\alpha + V_\sigma}$$



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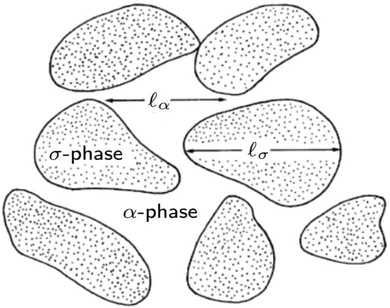

How to describe a porous media: specific surface and porosity

> Ratio between fluid phase volume and total volume

Porosity

$$\epsilon = \frac{V_\alpha}{V_\alpha + V_\sigma}$$

> Surface of the solid phase

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#QDLE#S#ABCD##

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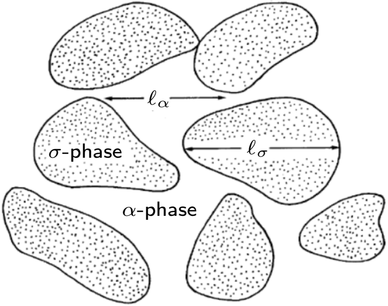
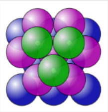
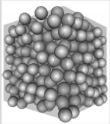
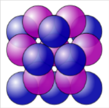


In your opinion, what packing has the lowest porosity?

A. 

B. 

C. 

D. 

Exercise: determine some specific surfaces and porosities

Take your smartphone

The relation between the specific surface and the porosity for an assembly of spheres is...

A. $S_v^{sph} = \frac{3\varepsilon}{a}$

B. $S_v^{sph} = \frac{3(1-\varepsilon)}{a}$

C. $S_v^{sph} = \frac{3a}{(1-\varepsilon)}$

#QDLE#Q#AB*C##

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#QDLE#Q#A*BC##

The equivalent radius for the capillary-like porous media writes...

A. $R_{eq} = \dfrac{2\varepsilon a}{3(1-\varepsilon)}$ B. $R_{eq} = \dfrac{3\varepsilon a}{2(1-\varepsilon)}$ C. $R_{eq} = \dfrac{2(1-\varepsilon)a}{3\varepsilon}$

Specific surface and porosity

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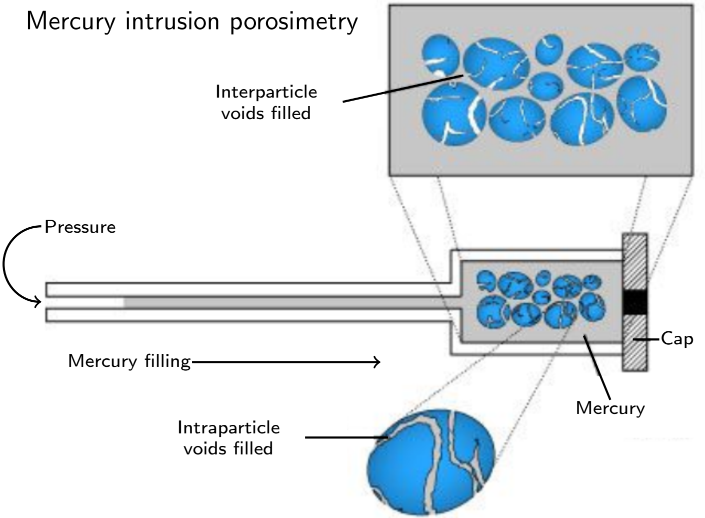
Porosity measurements

Mercury intrusion porosimetry



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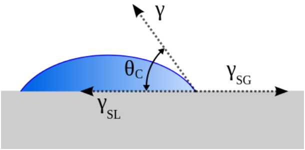
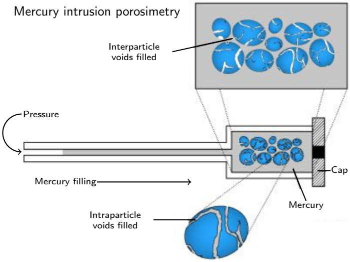




Contact angle

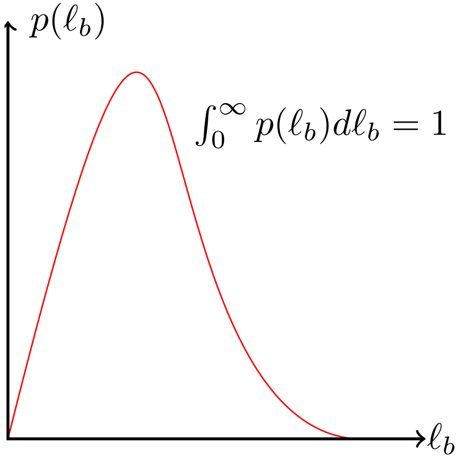
$$\gamma_{SG} = \gamma_{SL} + \gamma \cos\theta_c \Rightarrow \cos\theta_c = \frac{\gamma_{SG} - \gamma_{SL}}{\gamma}$$

Laplace pressure drop

$$P_L - P_G = -\frac{2\gamma \cos\theta_c}{R}$$

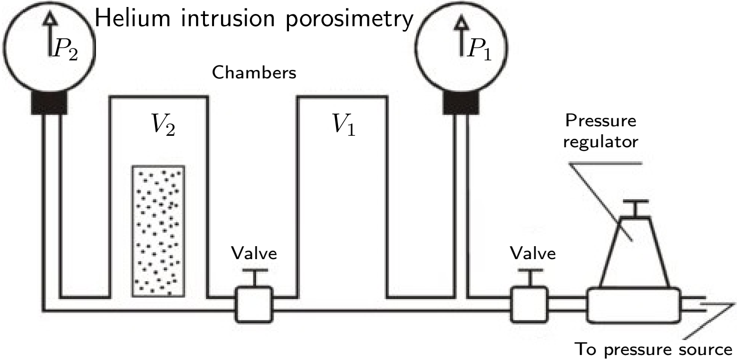
- Mercury: $\theta_c \approx 140°$ for various solids
- Given $P_L \Rightarrow$ allow invasion of pore down to ℓ_β
- Measurement of mercury volume evolution when increasing pressure from $P_{L,n}$ to $P_{L,n+1} \Rightarrow$ quantity of pores with radius in the range $[\ell_{\beta,n+1}, \ell_{\beta,n}]$

Porosity measurements



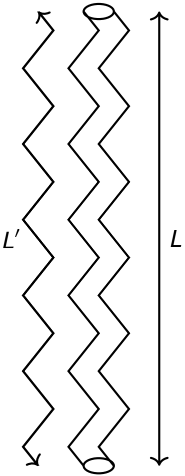
> Access to pore size distribution

Porosity measurements



Some typical porosities

Configuration	Porosity	Configuration	Porosity
Random packing	0.4	Granite	0.01
Cubic packing	0.48	Reservoir sandstones	0.15-0.35

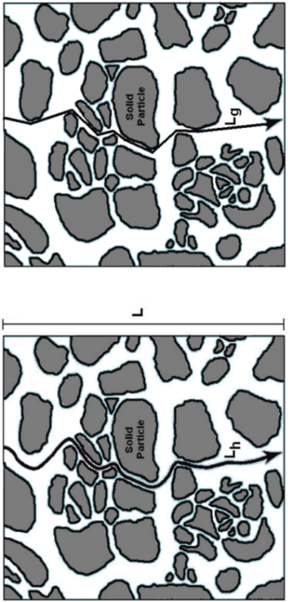


Tortuosity

$$\tau = \frac{L'}{L}$$

- Very basic definitions
- Numerous tortuosity model

How to describe a porous media: tortuosity



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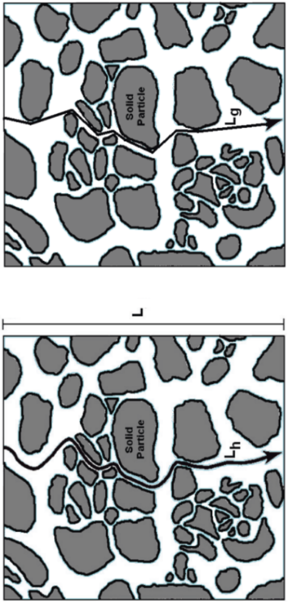

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Electric tortuosity

$$\tau_e = \epsilon F = \epsilon \frac{\rho_p}{\rho_f}$$

- ρ_p: electric resistivity of the saturated porous media
- ρ_f: electric resistivity of the fluid

How to describe a porous media: saturation

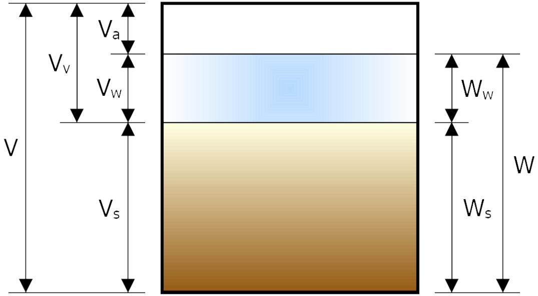
Content in fluid (water, oil, ...) inside the porous media: two definitions

Soil mechanics

$$w = \frac{W_w}{W_s}$$

Porous media physics

$$\theta = \frac{V_w}{V}$$



> Measurements using evaporation, satellites (micro-waves), chemical titration, ...

What did you remember ?

Take your smartphone

What did you remember?

Meso-pore range?

A. Less than 1 μm

B. 10 to 100 nm

C. More than 1 μm

D. 2 to 50 nm

#QDLE#Q#ABCD*#20#

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#QDLE#Q#A*BC#20#

Knudsen number concerns?

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B. Liquids in porous media

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#QDLE#50#ABC*#20#

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Porosity hierarchy?

A. Standstones<Granite<Random packing<Cubic packing

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