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Sciences Appliquées

Land subsidence due to induced water pressure changes in aquifers and confining layers

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'Quantum gravimetry in space and ground'

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Outline

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- *Piezometric heads and water pressure*
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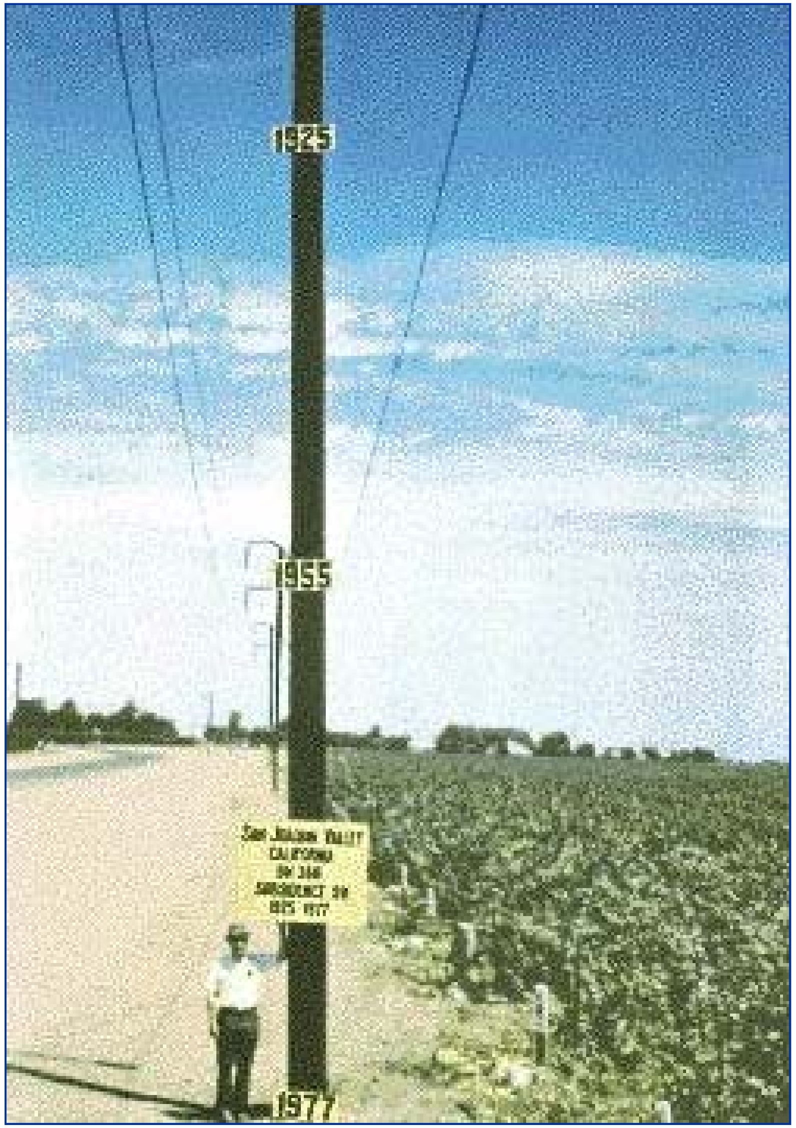
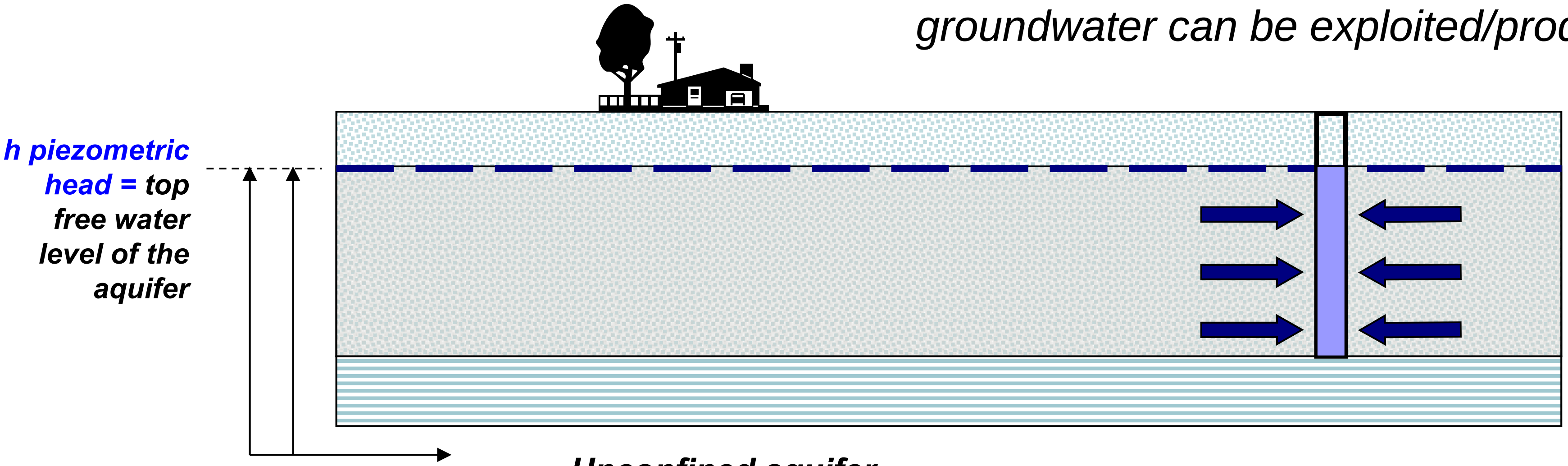
Introduction



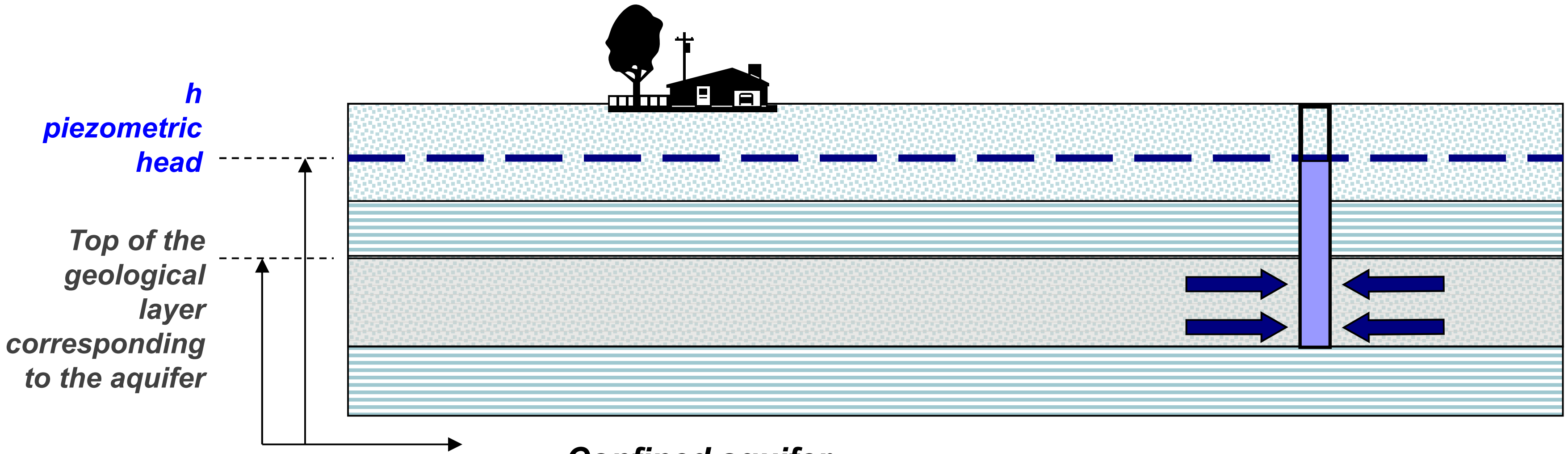
(Poland 1984)

Definitions of aquifers and confining layers

Aquifer = geological medium where groundwater can be exploited/produced

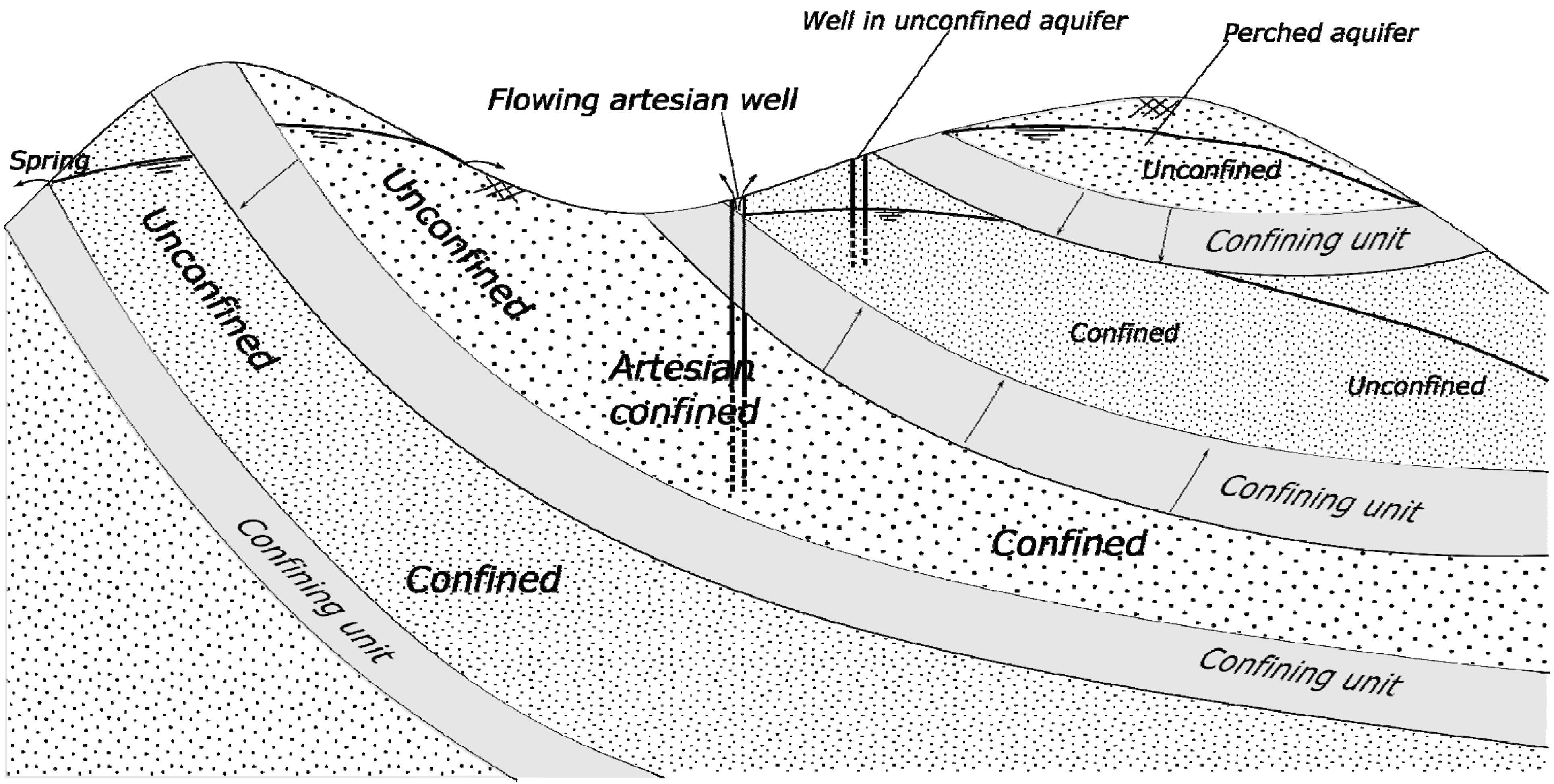


Unconfined aquifer



Confined aquifer

Hydrogeological definitions of aquifers and confining layers



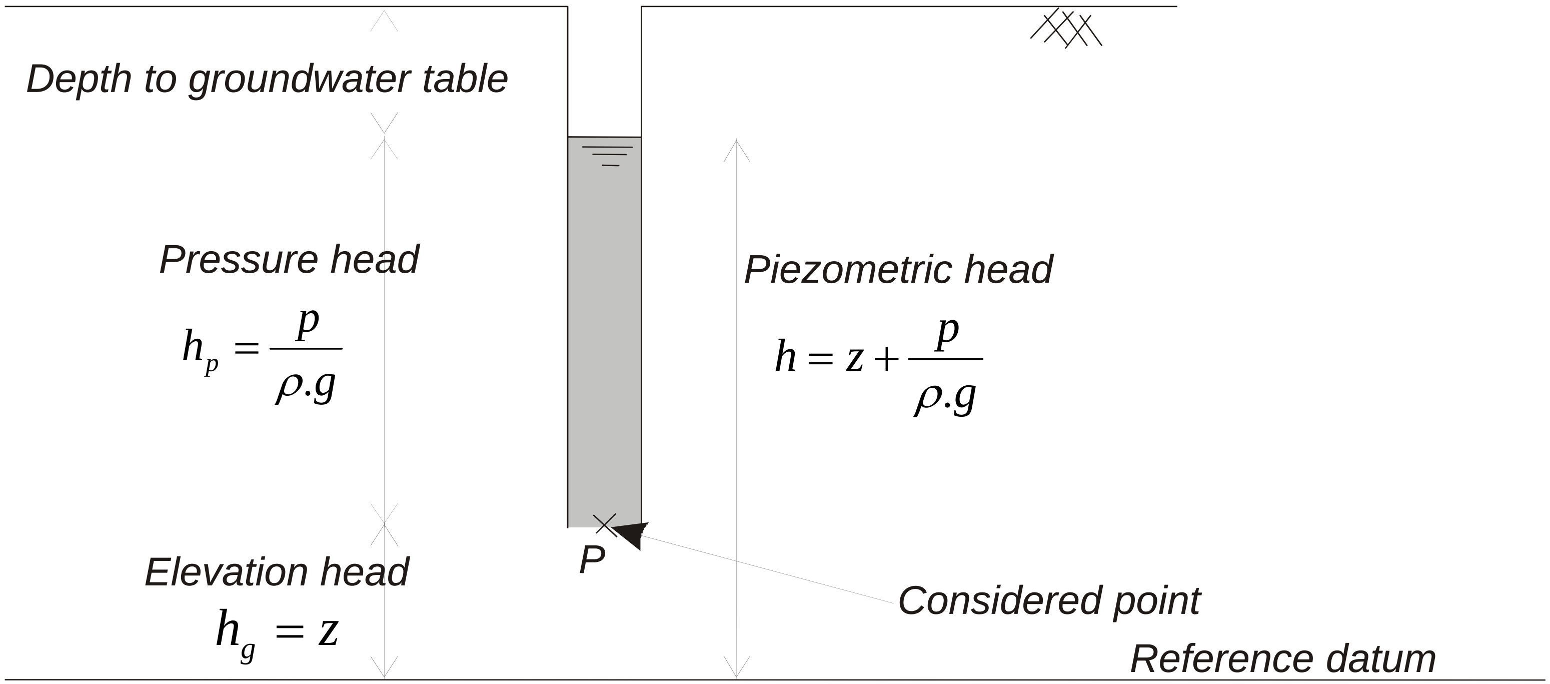
(Dassargues 2018, 2020)

Piezometric heads and water pressure in the geological layers

$$h = z + p/\rho g$$

$$p = \rho g(h - z)$$

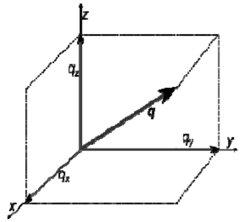
$$\frac{\partial p}{\partial t} = \rho g \frac{\partial h}{\partial t}$$



(Bear & Cheng 2010)

Groundwater flow and properties

$$\boldsymbol{q} = -\boldsymbol{K} \cdot \nabla h = -\frac{\boldsymbol{k}\rho g}{\mu} \cdot \nabla h = -\frac{\boldsymbol{k}}{\mu} \cdot (\nabla p + \rho g \nabla z)$$



Hydraulic conductivity

$$\boldsymbol{K} = \begin{bmatrix} K_{xx} & K_{xy} & K_{xz} \\ K_{yx} & K_{yy} & K_{yz} \\ K_{zx} & K_{zy} & K_{zz} \end{bmatrix}$$

In most cases: $K_{xx} = K_{yy} = K_h$ **and** $K_{zz} = K_v$

$$div(\boldsymbol{q}) = \nabla \cdot \boldsymbol{q} = \left(\frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} + \frac{\partial q_z}{\partial z}\right)$$

$$-\nabla \cdot \rho \boldsymbol{q} + \rho q' = \frac{\partial(n\rho)}{\partial t} = \rho S_s \frac{\partial h}{\partial t}$$

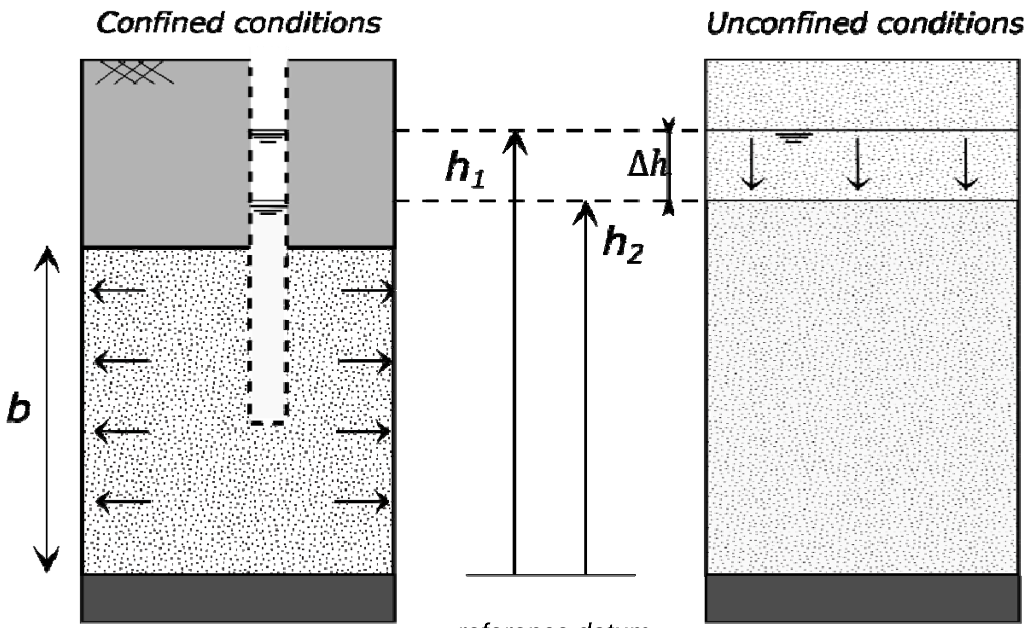
S_s =Specific storage coefficient

corresponds to the water volume (m^3) liberated or stored per volume unit of saturated porous medium (m^3) for a unit change of piezometric head (m)

→ *link to the compressibility* $S_s = \rho g \alpha$

Different storage variation in confined and in unconfined aquifers

Storage coefficient = integral of the specific storage coefficient on the saturated thickness



Consolidation and expulsion of water

$S = S_s b = \rho g \alpha b$

S < 0.005

reference datum = bottom of the aquifer layer

Drainage

$S \cong n_e = S_y$

S = 0.02 – 0.30

corresponds to the water volume (m³) liberated or stored per surface unit (m²) for a unit change of piezometric head (m)

$$S = n_e + \int_0^h S_s dz$$

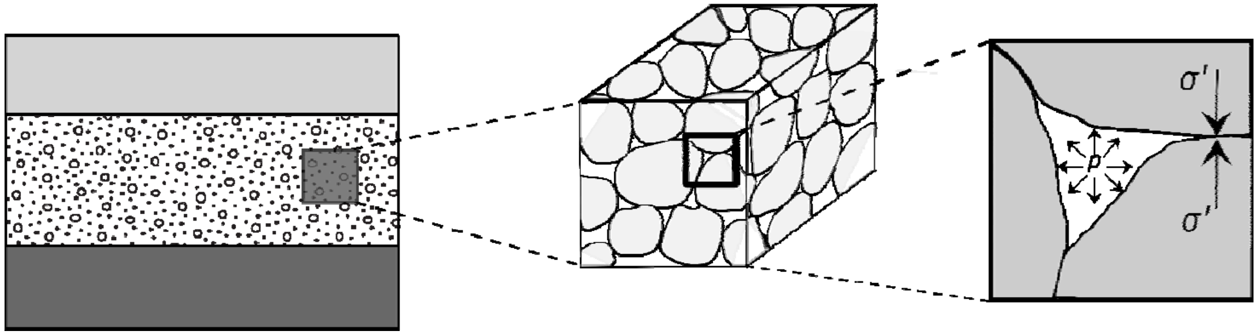
in fully saturated aquifers and confining layers, S_s is directly proportional to the compressibility

$$S_s = \rho g \alpha$$

volumic compressibility of the saturated medium

$$\alpha = -\frac{1}{V}\frac{\partial V}{\partial \sigma'}$$

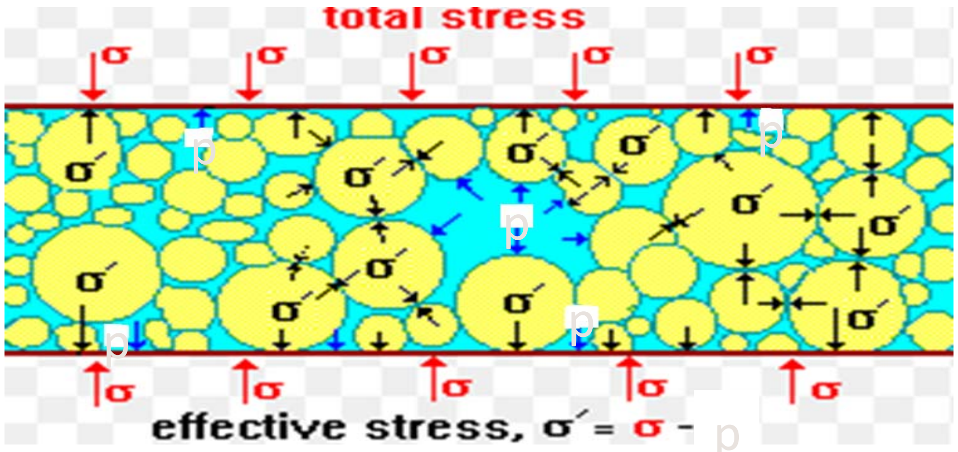
Stresses in the saturated underground: Terzaghi principle



$$\sigma = \sigma' + p$$

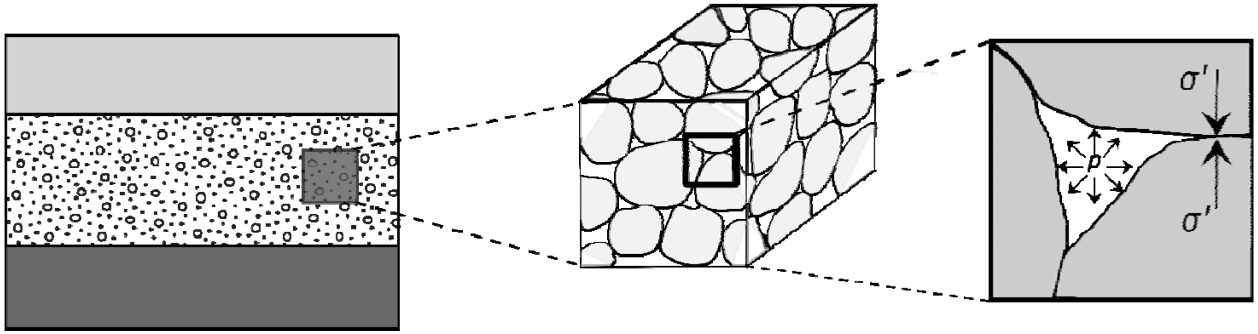
(Terzaghi 1943, Biot, 1941, Verruijt 1982, Dassargues 2018, 2020)

Total stress: σ *= total force / surface (N/m²)*
Effective stress: σ' *= 'grain to grain', solid matrix stress, the only source of any deformation (for geotechnical engineers)*
Water pressure: p *= water pressure linked to piezometric head*



(acceptable if volume compressibility > 20 solid and water compressibility)

Volume compressibility



$$\sigma = \sigma' + p$$

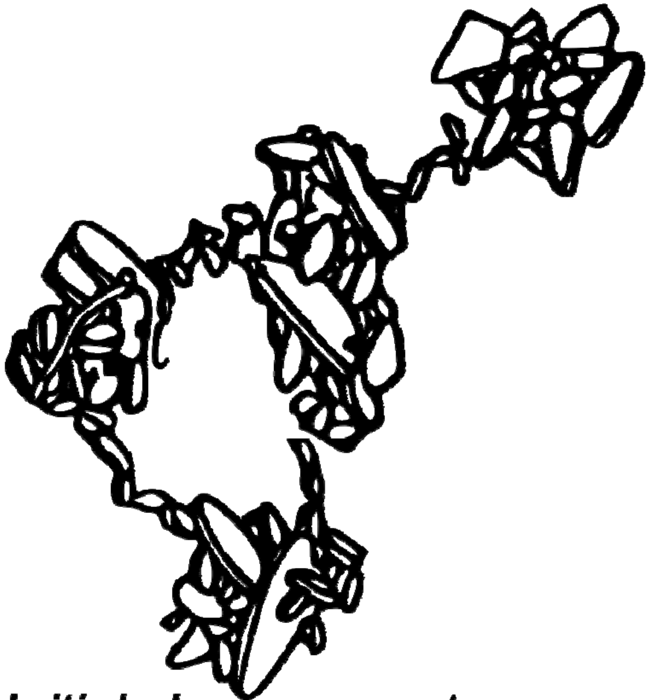
volume compressibility (Pa^{-1}): $$\alpha = -\frac{1}{V}\frac{\partial V}{\partial \sigma'}$$

Lithology	Volume compressibility α (Pa^{-1})
Highly organic alluvial clays and peats, underconsolidated clays	1.5×10^{-6} – $1.\ x10^{-6}$
Normally consolidated alluvial clays	$1.\ x10^{-6}$ – $3.\ x10^{-7}$
Clays of lake deposits/outwash, normally consolidated clays at depth, weathered marls	$3.\ x10^{-7}$ – $1.\ x10^{-7}$
Tills and marls	$1.\ x10^{-7}$ – $5.\ x10^{-8}$
Over-consolidated clays	$5.\ x10^{-8}$ – $1.\ x10^{-8}$
Sand	$5.\ x10^{-7}$ – $1.\ x10^{-9}$
Gravel	$5.\ x10^{-8}$ – $1.\ x10^{-10}$
Fractured rock	$5.\ x10^{-8}$ – $1.\ x10^{-10}$
Hard rock	$5.\ x10^{-9}$ – $1.\ x10^{-11}$

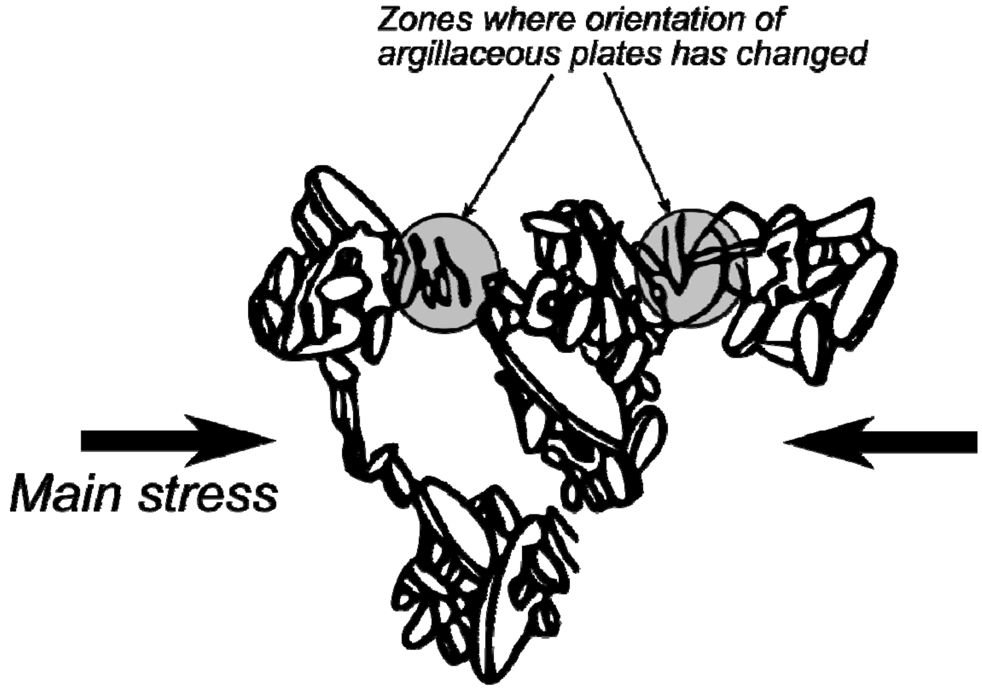
(modified from Freeze and Cherry 1979, Carter and Bentley 1991)

Consolidation process

- a drained process
- supposed essentially 1D
- by rearrangement of the grains/matrix
- essentially in loam, clay and peat



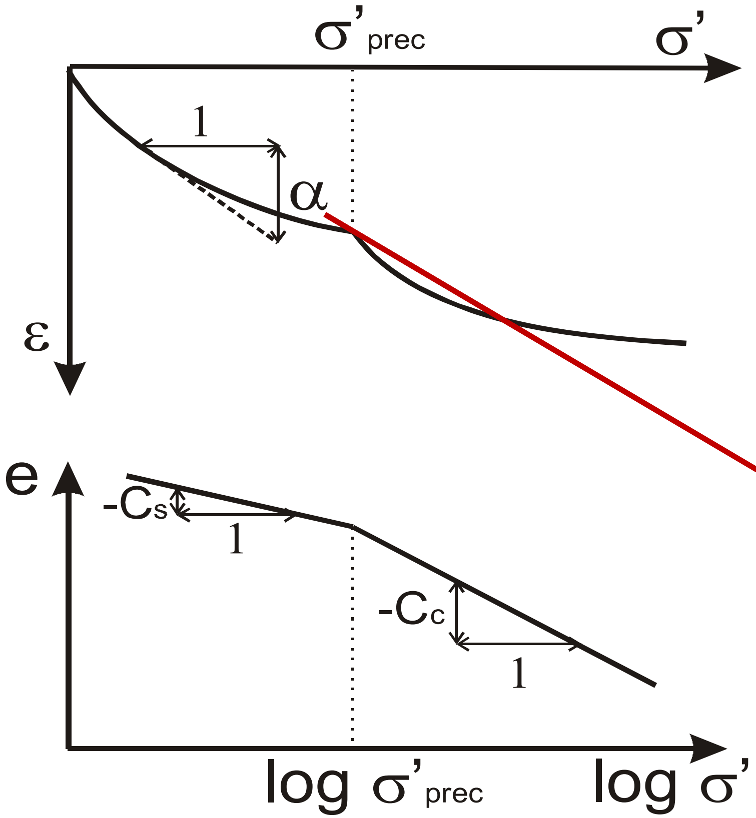
Initial clay aggregate



Aggregate after partial consolidation

(as schematically seen at the Scanning Electron Microsope scale _____ 10µm)

Consolidation process

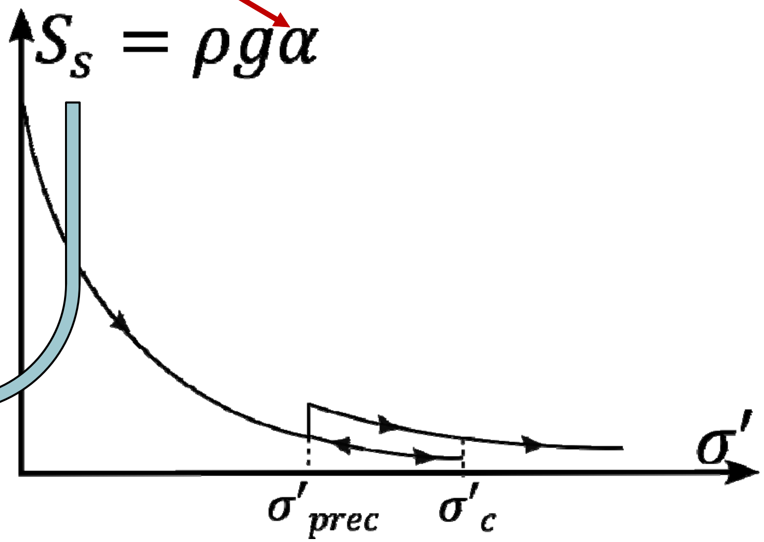


- a drained process
- supposed essentially 1D
- by rearrangement of the grains/matrix
- essentially in loam, clay and peat

- supposed elasto(visco)plastic behaviour of the medium
- C_s = swelling index (reversibility of the elastic behaviour)
- C_c = compression index
- e = void ratio
- σ'_{prec} = effective preconsolidation stress

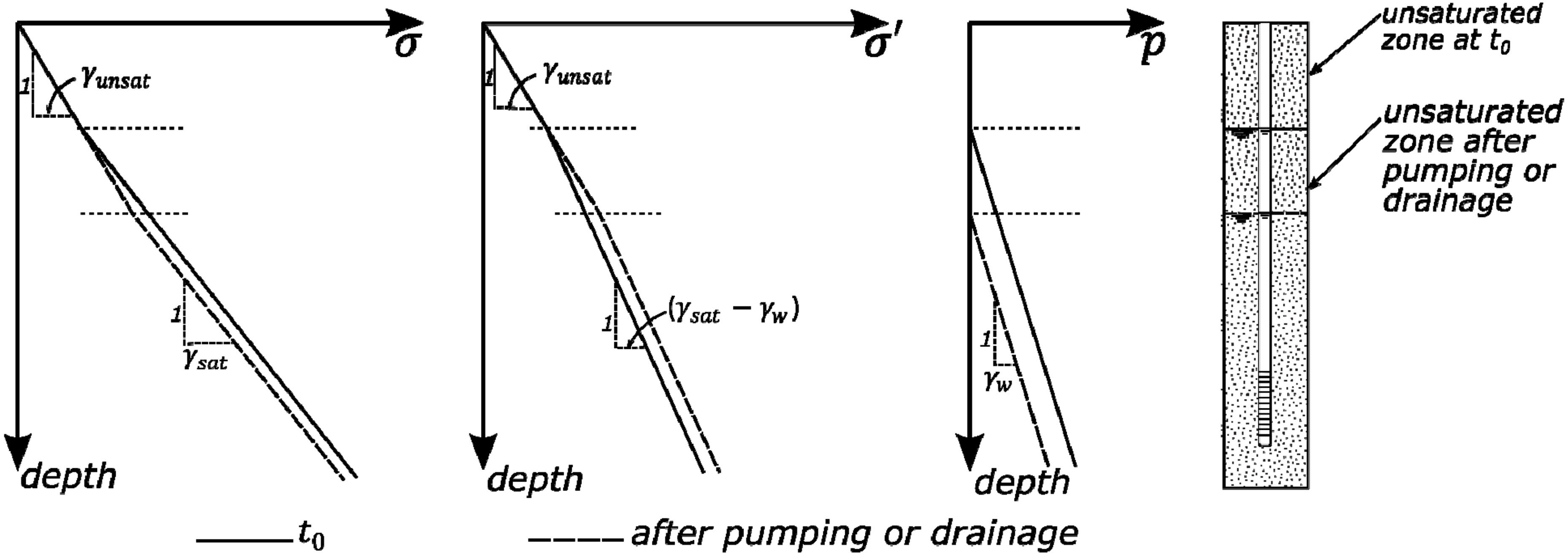
$$S_s = \rho g \alpha$$

$$-\nabla \cdot \rho \boldsymbol{q} + \rho q' = \rho S_s \frac{\partial h}{\partial t}$$



Changes of total stress (σ), of effective stress (σ') and water pressure (p) if you pump in an unconfined aquifer

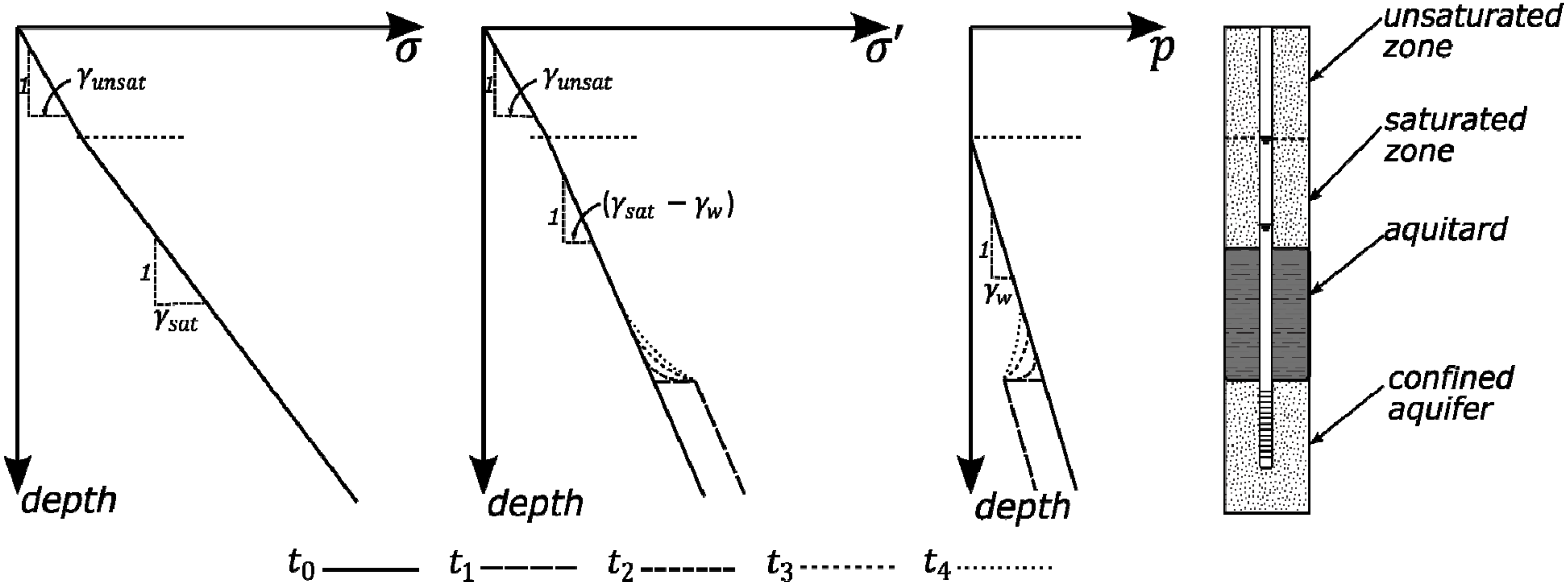
$$\sigma = \sigma' + p$$



Land subsidence induced by pumping in water table aquifers is due mainly to a increase of effective stress in potentially compressible zones/parts of the aquifer layers:
Exemple: in alluvial aquifers

Changes of total stress (σ), of effective stress (σ') and water pressure (p) if you pump in a confined aquifer

$$\sigma = \sigma' + p$$



Land subsidence induced by pumping in confined aquifers is due mostly to a slow increase of effective stress in the compressible confining layers (above and below the pumped aquifer):
Exemples: in many sinking cities (Shanghai, Tokyo, New Orleans, Bangkok, Mexico, …)

Low propagation of Δp and consolidation

- ***transient processes***

- ***evolving properties of the sediments***

  (further compressiblity is lower for a consolidated sediment)

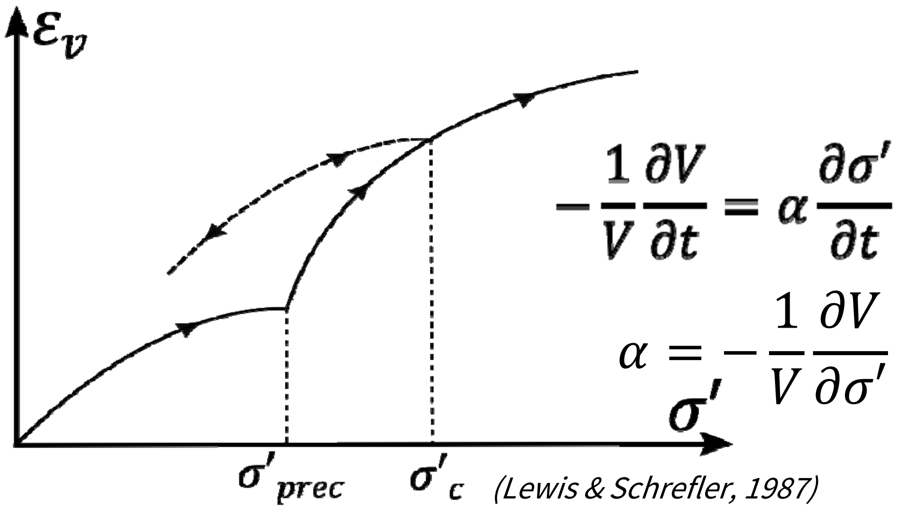
- ***experimental (data based) rheological models involving non linear elasticity, plasticity and viscosity behaviours***

- ***loams, clays and peats are the most compressible***

- ***most often characterized/considered with elasto-plastic (but actually elasto-visco-plastic) behaviours***

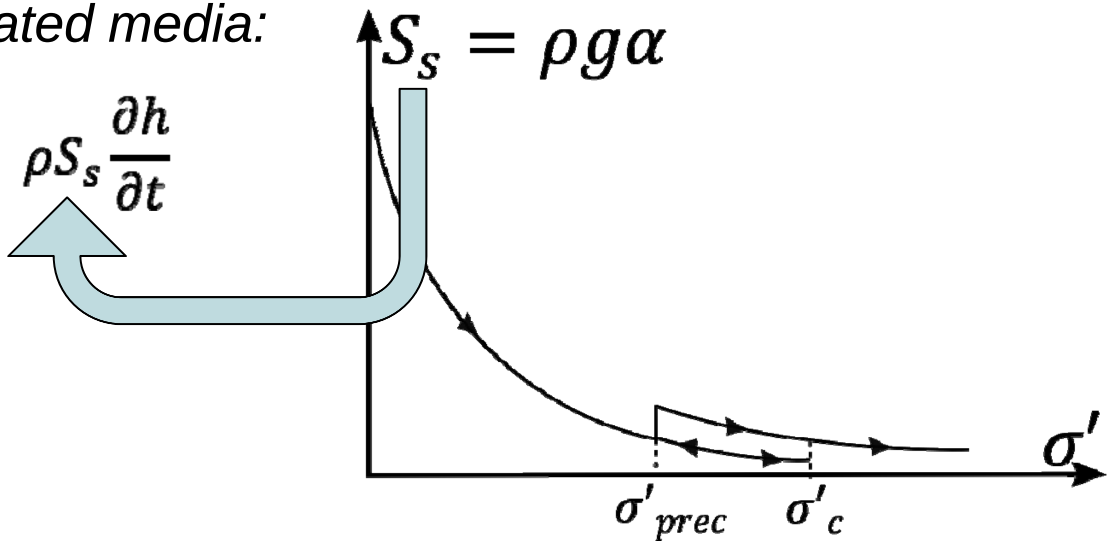
Non linear effects on the hydrogeological and physical properties

Change of S_s due to the evolution of the compressibility with the new effective stress conditions



Flow equation in saturated media:

$$\nabla \cdot \rho(\boldsymbol{K} \cdot \nabla h) + \rho q' = \rho S_s \frac{\partial h}{\partial t}$$



Non linear effects on the hydrogeological and physical properties

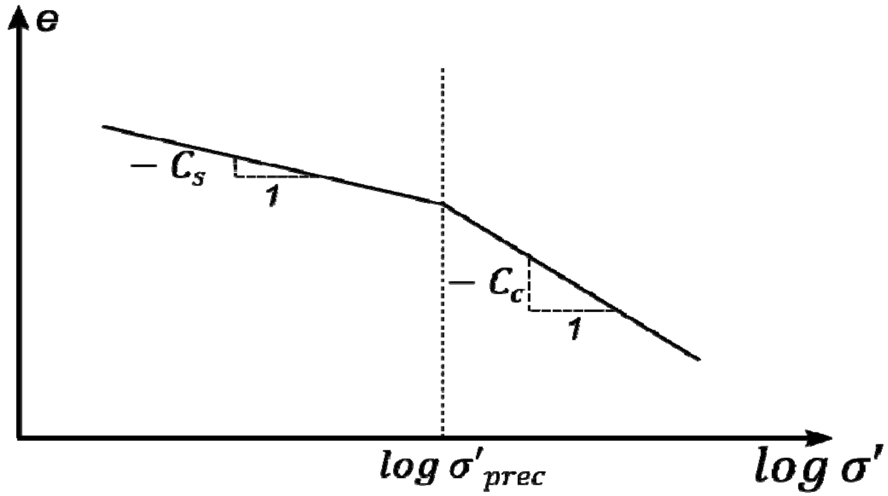
for practical reasons: easier to handle a bi-linear law

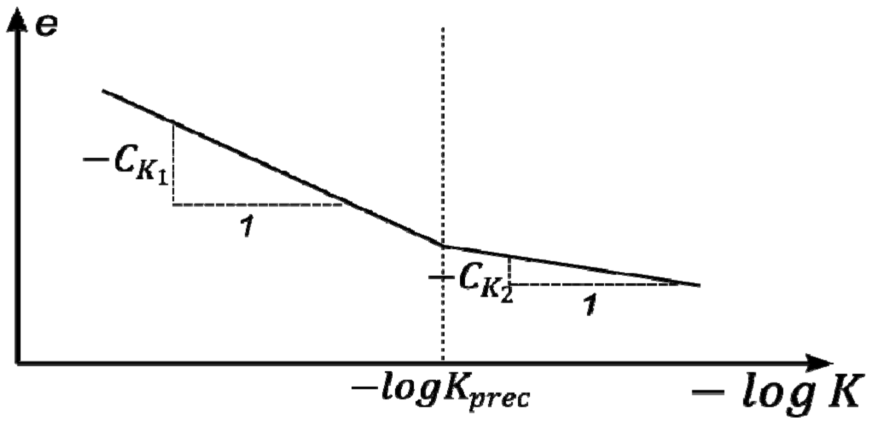
Change of K due to the evolution of the void ratio with the new effective stress conditions

$$\log K = f(e)$$

$$\nabla \cdot \rho(\boldsymbol{K} \cdot \nabla h) + \rho q' = \rho S_s \frac{\partial h}{\partial t}$$

$$\frac{dK}{K} = \begin{cases} -\dfrac{C_s}{C_{K1}} \dfrac{d\sigma'}{\sigma'} & K > K_{prec} \\ -\dfrac{C_c}{C_{K2}} \dfrac{d\sigma'}{\sigma'} & K \leq K_{prec} \end{cases}$$





(Dassargues 1995, 1997, 1998)

Effect on the gravity measurements ?

Consolidation =
- **slow process**
- **can be natural**
- **drained process**
- **dry density of soil increases but water content decreases**

➡ **change in water storage**
➡ **change the relative gravity position**

Not to be confused with

Compaction =
- **Civil Engineering Technique by rapid mechanical methods like tamping, rolling and vibration applied to soils**
- **instant process**
- **always artificial**
- **expulsion and compression of air**
- **dry density of soil increases but water content remains same**

Other causes of land subsidence

- ***natural consolidation of underconsolidated (recent) sediments***
- ***oxydation of peats***
- ***any overload inducing an increase of total stress that will induce an increase of effective stress***
- ***consolidation in backfill materials in artificial soils/embankments/dams***

Examples:

Venice, Mexico, Bangkok, Shanghai, Taipei, Jakarta, Tehran, New Orleans, Houston, Tokyo,
Ho Chi Minh City, Hanoi, …

Venice:	***0.15 - 0.3 m***	***(1-2 mm/y)***
Mexico:	***13 m***	***(30 cm/y)***
Bangkok:	***2.1 m***	***(2 cm/y)***
Shanghai:	***2.6 m***	***(1.5 cm/y)***
Taipei:	***2.0 m***	***(-0.5 cm/y)***
Jakarta:	***4.1 m***	***(26 cm/y)***
Tehran:	***3.0 m***	***(15 cm/y)***
New Orleans:	***3 - 5 m***	***(8 mm/y)***
Houston:	***3.0 m***	***(2.5 cm/y)***
Tokyo:	***4.3 m***	***(-0.3 cm/y)***
Ho Chi Minh:	***0.5 m***	***(4 cm/y)***
Hanoi:	***0.6 m***	***(7 cm/y)***

are only a few examples among the numerous 'sinking cities'

…to be added to rising sea-levels !

Sinking cities: the crucial truth

- ***Example of Bangkok:***
  - ***global warming has caused a global mean sea-level rise ranging from 17 to 21 cm from 1900 until 2010***
  - ***groundwater pumping has caused a land subsidence of 2.1 m***

- ***no miracle for remediation except to stop and restore pore pressures***

- ***injection in the consolidated layers but limitation factors:***
  elastic rebound only
  in deep confined saline aquifers
  physico-chemical reactions
  many uncertainties

Most of this content is coming from chapter 6 of my book:

Dassargues, A. 2018. *Hydrogeology: groundwater science and engineering*, 472p. Taylor & Francis CRC press, Boca Raton.
Dassargues, A. 2020. *Hydrogéologie appliquée : science et ingénierie des eaux souterraines*, 512p. Dunod. Paris.

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