46TH IAH CONGRESS
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GROUNDWATER MANAGEMENT AND GOVERNANCE
COPING WITH WATER SCARCITY

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Induced land subsidence due to groundwater withdrawal compared to rising sea-levels in 'sinking cities'

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Hydrogeology
Environmental Geology

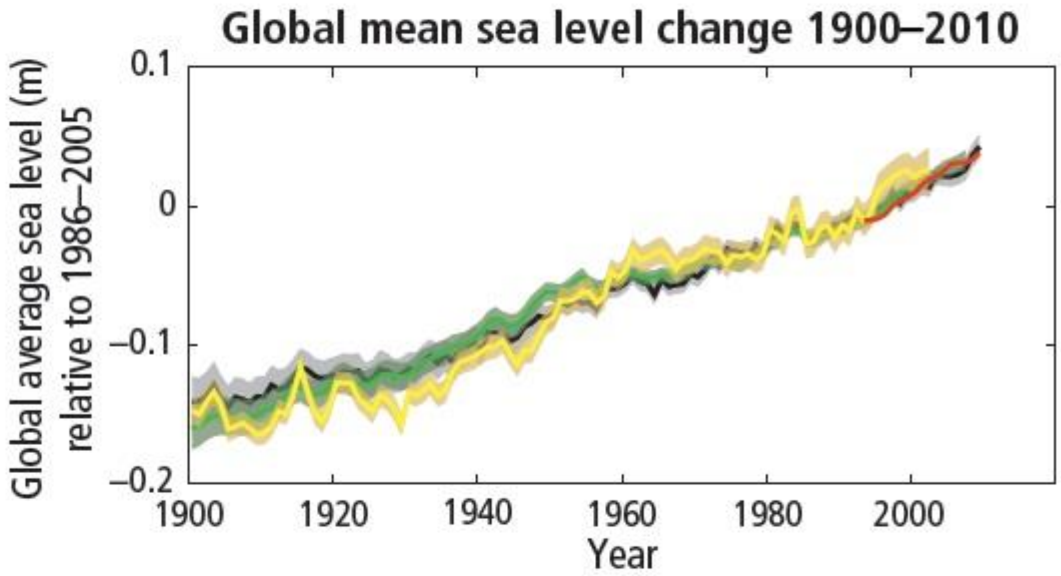
Introduction

Groundwater pumping and sinking cities: back to the forefront due to the sea level rise threats

(Showstack 2014, Gorelick and Zheng, 2015)

- *global warming has caused a global mean sea-level rise ranging from 17 to 21 cm from 1900 until 2010*

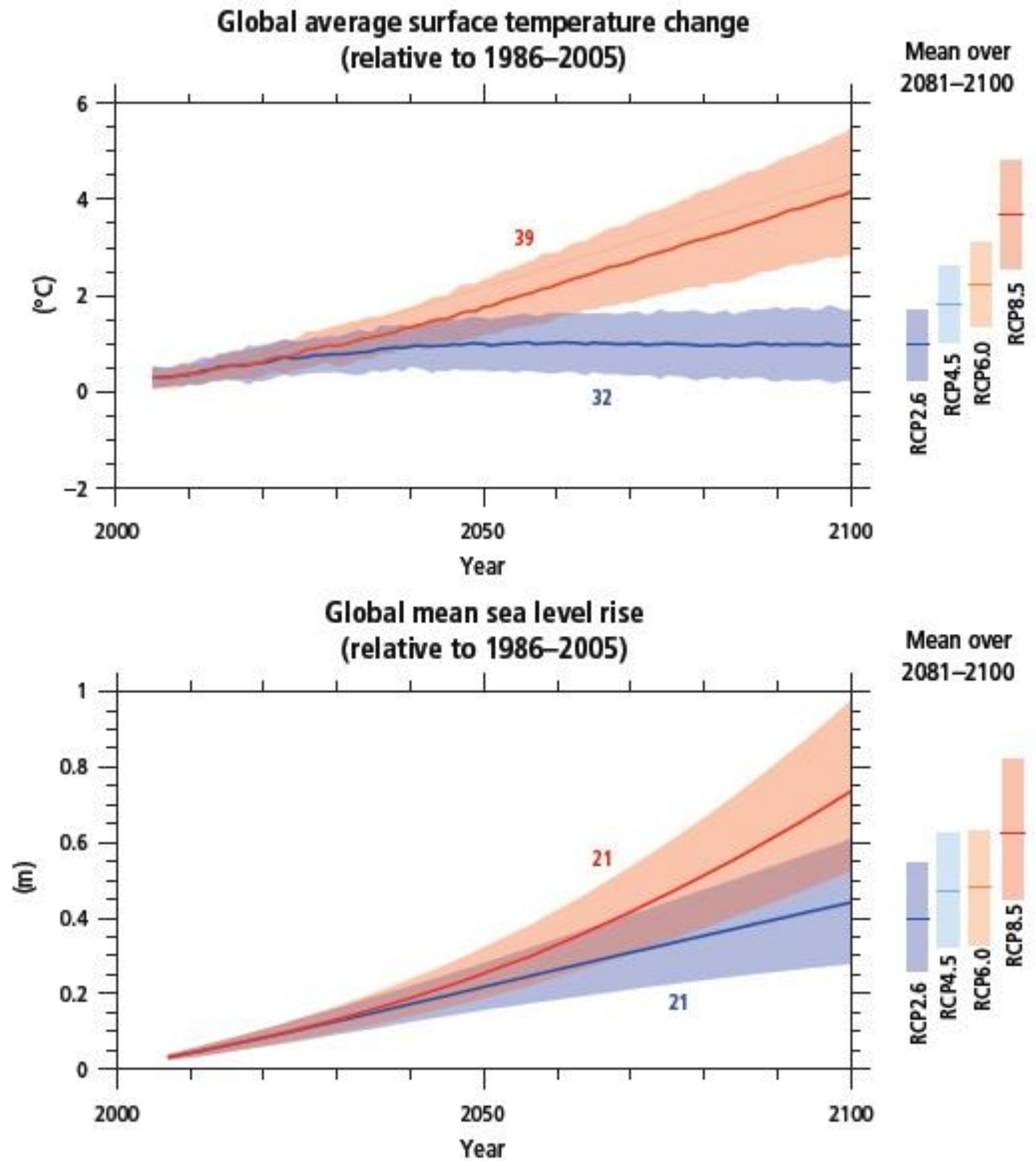
(IPCC report 2013)



Introduction

- *global warming will cause a sea-level rise ranging from 0.5 m to 0.9 m by 2100 (IPCC report 2013)*

  … in the worst case scenarios



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

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

even if consolidation processes are well known for a long time

(Terzaghi 1943, Biot 1941, …, Poland 1984,)

… they are still mostly ignored in every day life… as shown in many civil engineering works

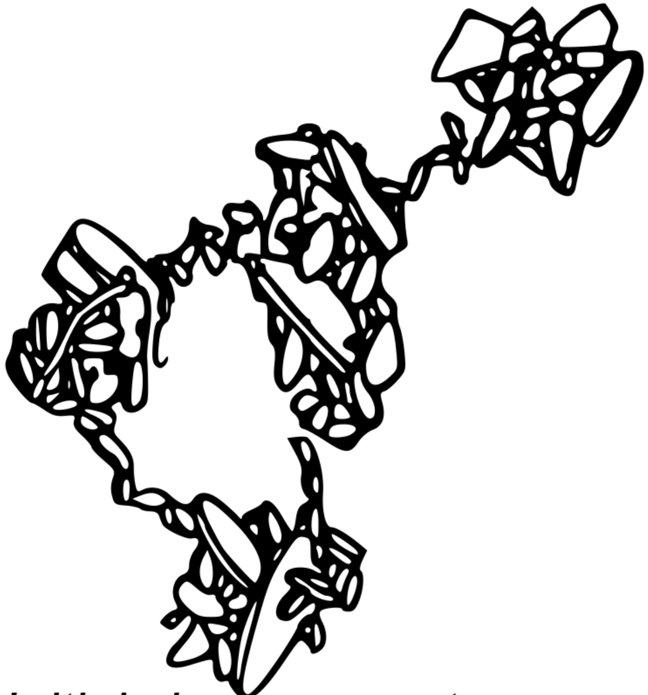
Cumulative values of man-induced subsidence … and present annual rates

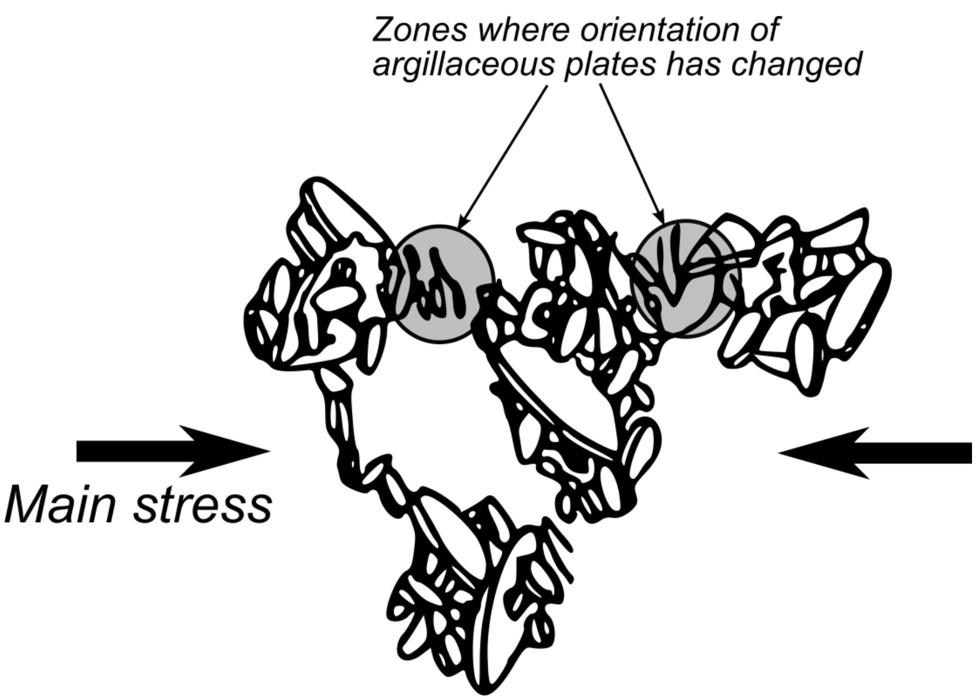
Venice:	*0.15 - 0.3 m*	*(1-2 mm/y)*
Mexico:	*13 m*	*(30 cm/y)*
Bangkok:	*2.1 m*	*(2 cm/y)*
Shanghai:	*2.6 m*	*(1.5 cm/y)*
Taipei:	*2.0 m*	*(-0.5 cm/y)*
Jakarta:	*4.1 m*	*(26 cm/y)*
Tehran:	*3.0 m*	*(15 cm/y)*
New Orleans:	*3 - 5 m*	*(8 mm/y)*
Houston:	*3.0 m*	*(2.5 cm/y)*
Tokyo:	*4.3 m*	*(-0.3 cm/y)*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

… to be added to rising sea-levels !
(about 20 cm during the last century, but about 1 m in 2100)

Consolidation

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


Initial clay aggregate

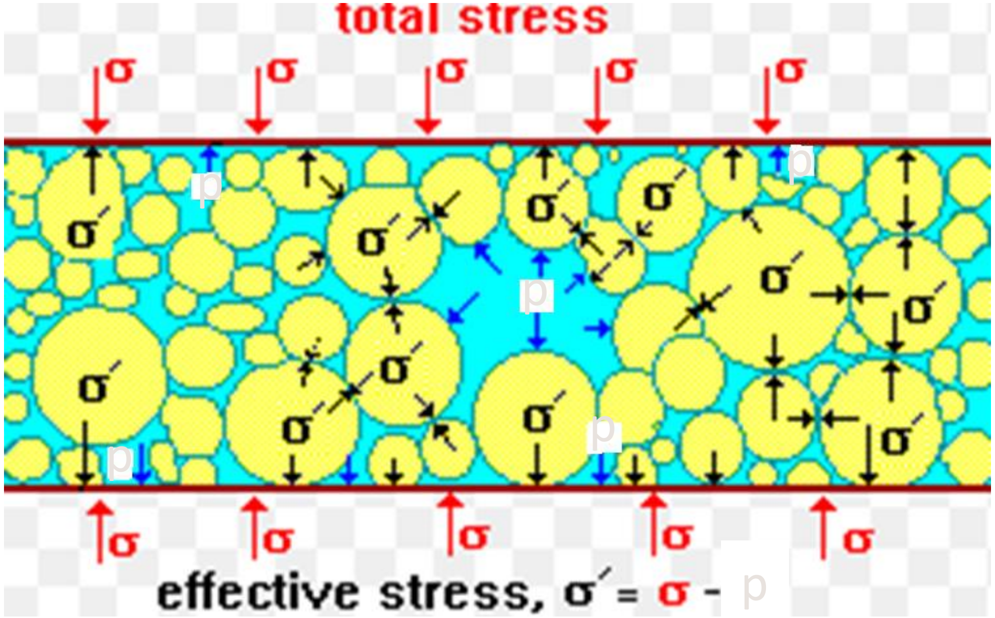


Aggregate after partial consolidation

Effective stress Terzaghi principle (1943)

… not the best but the more pragmatic concept…

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

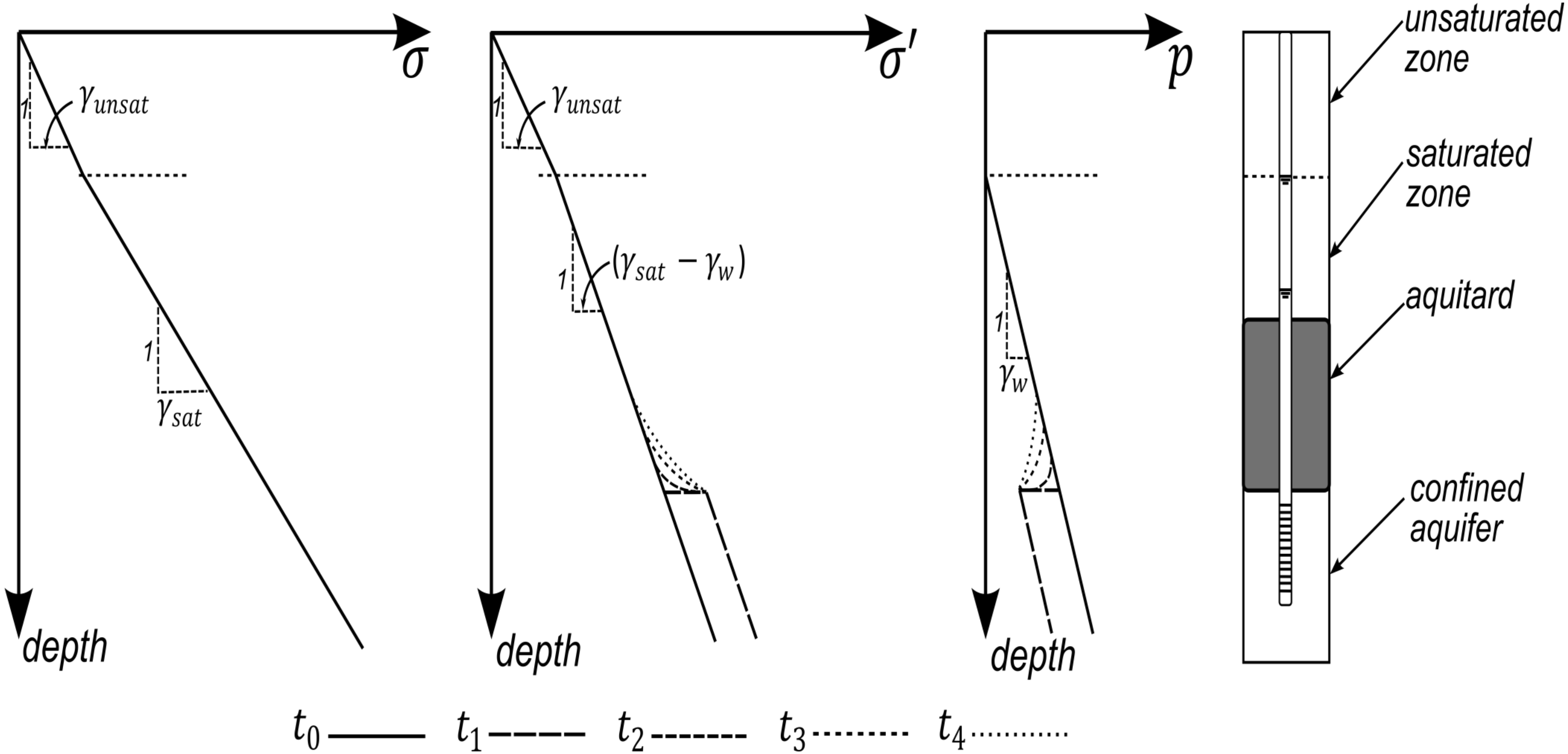


σ′ is the only responsible for consolidation process

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

Effective stress and water pressure variations in depth… in confined conditions

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



for unsaturated media:

$$\gamma_{unsat} = \rho_{unsat} g$$

for saturated media:

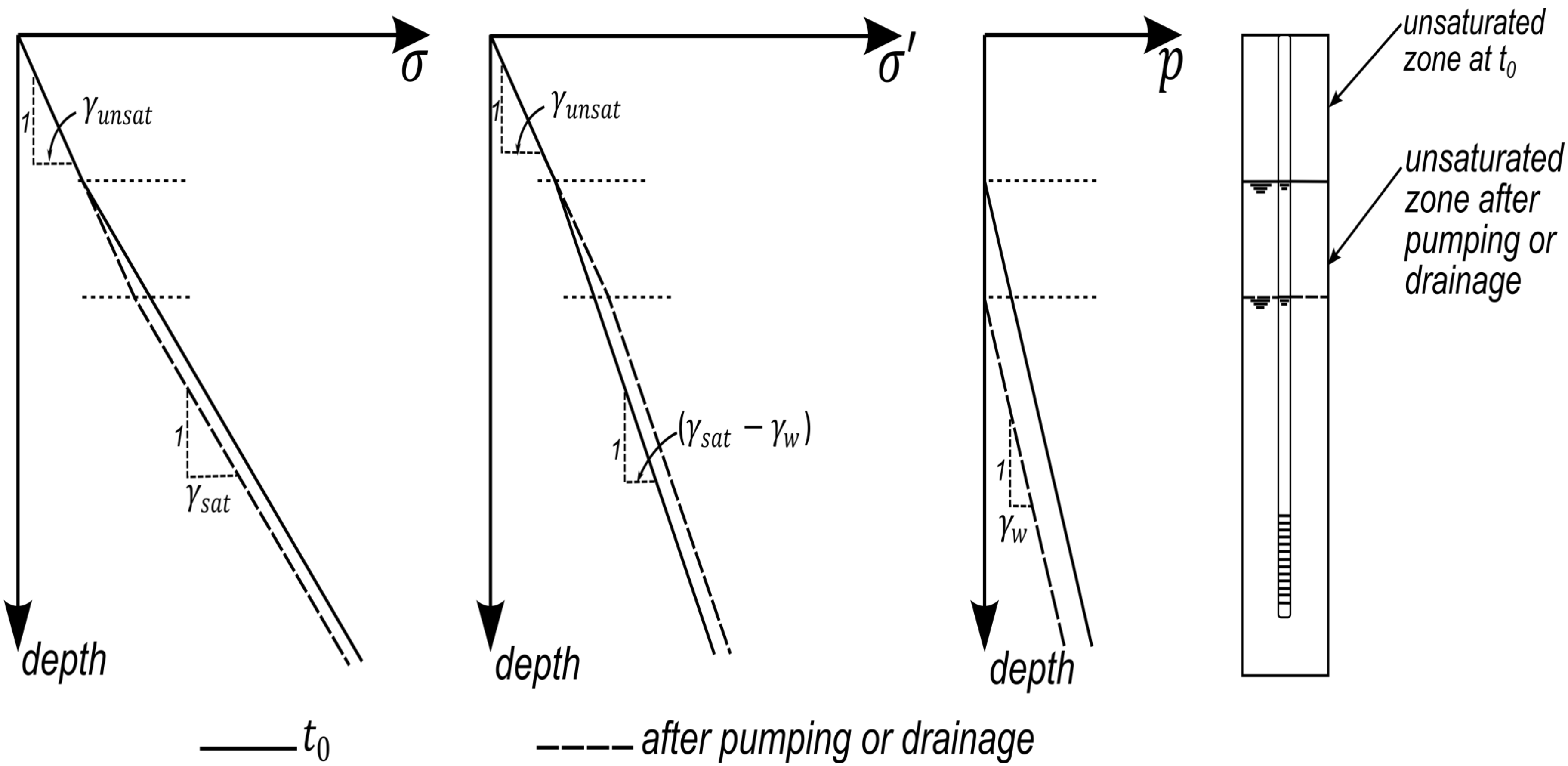
$$\gamma_{sat} = \rho_{sat} g$$

for water:

$$\gamma_w = \rho_w g$$

Effective stress and water pressure variations in depth… in unconfined conditions

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



Propagation of Δp and consolidation

➡ *transient and delayed processes*

➡ *evolution of the sediments*

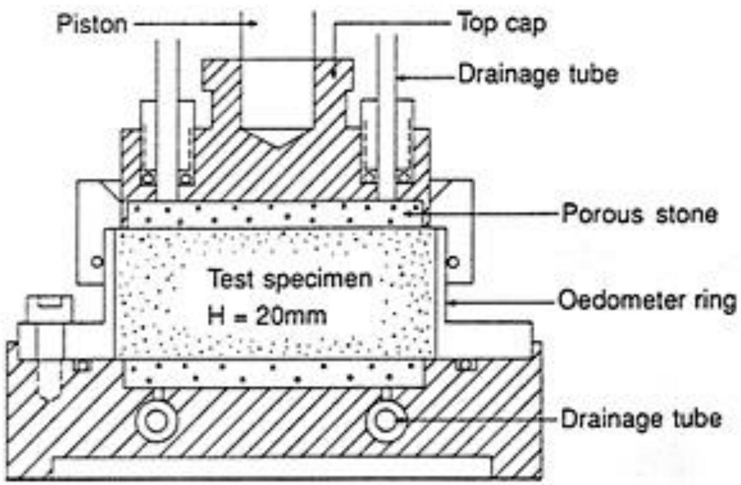
➡ *decreasing porosity by rearrangement of 'grains'*

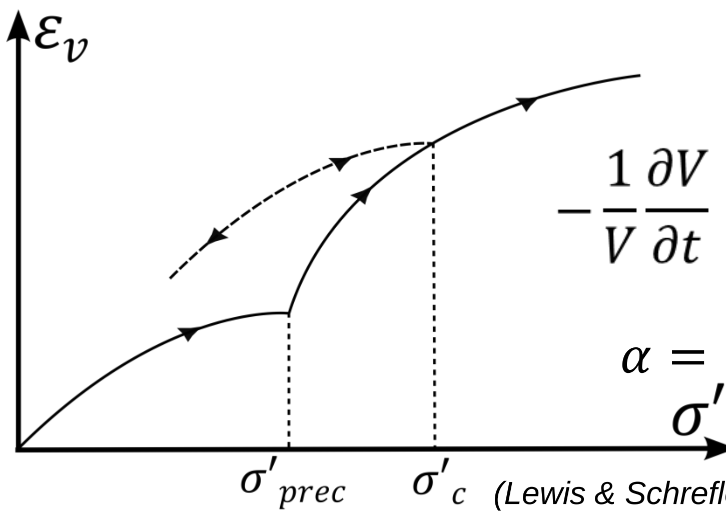
➡ *rheological models*
elasto-plastic and/or visco-elasto-plastic laws

➡ *clayey sediments characterized by a non-linear elasticity combined with progressive plasticity and viscosity*

➡ *models based on experimental laws*

Oedometer tests and coupling with groundwater flow in transient conditions





$$-\frac{1}{V}\frac{\partial V}{\partial t} = \alpha\frac{\partial \sigma'}{\partial t}$$

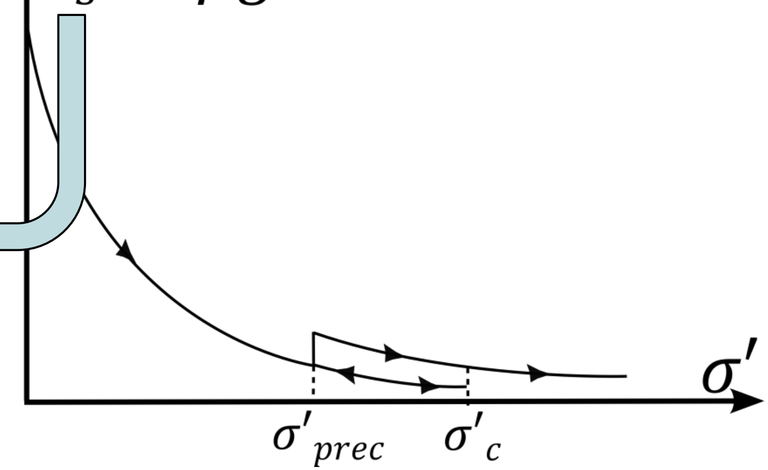
$$\alpha = -\frac{1}{V}\frac{\partial V}{\partial \sigma'}$$

(Lewis & Schrefler, 1987)

Flow equation in saturated media:

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

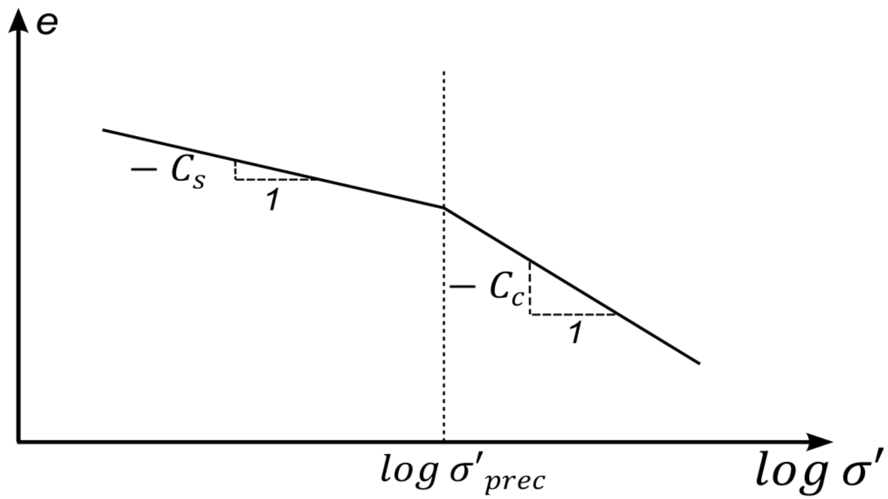
$$S_s = \rho g \alpha$$



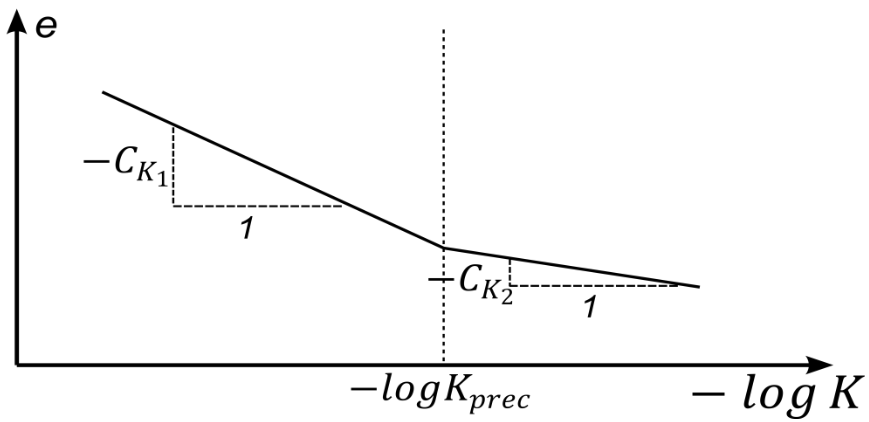
Additional non-linearity due to permeability variation

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

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



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

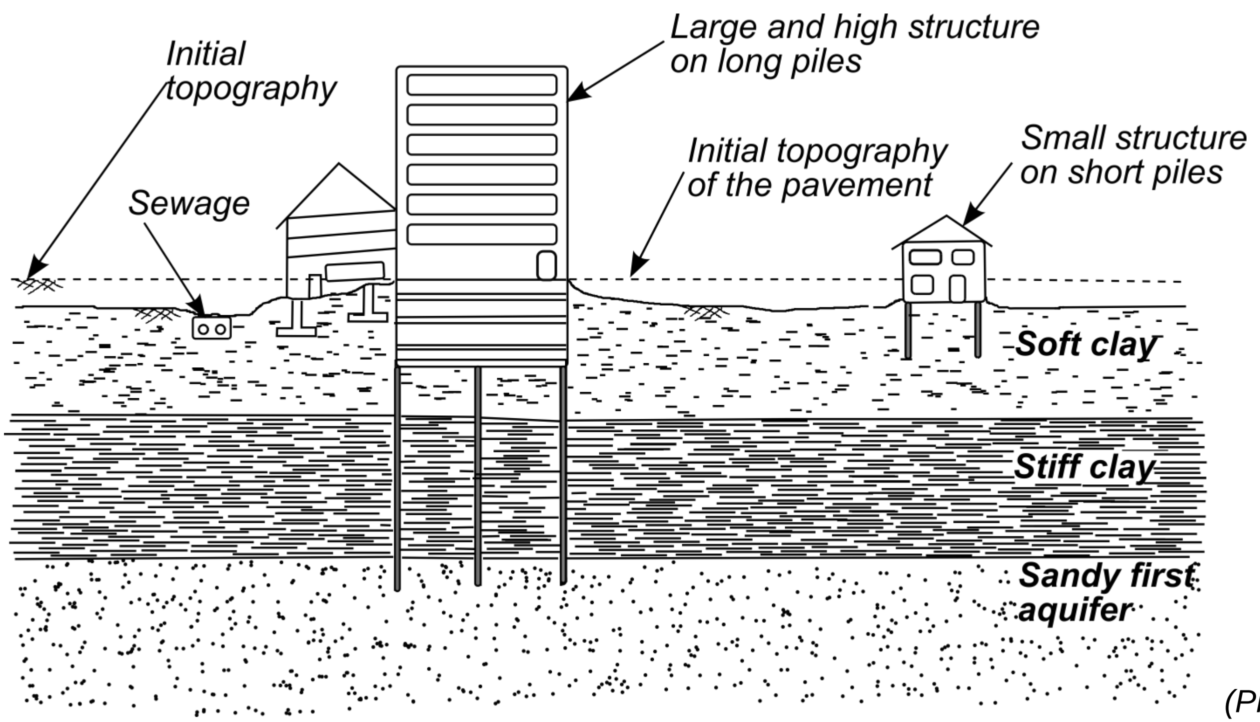


(Dassargues 1995, 1997, 1998)

Bangkok

- thick (> 2000 m) sequence of recent sediments
- top layer (15-20m thick) of clay highly compressible
- then: a stiff clay layer and a first sandy aquifer

- groundwater production still increasing > 2 10^6 m^3/d



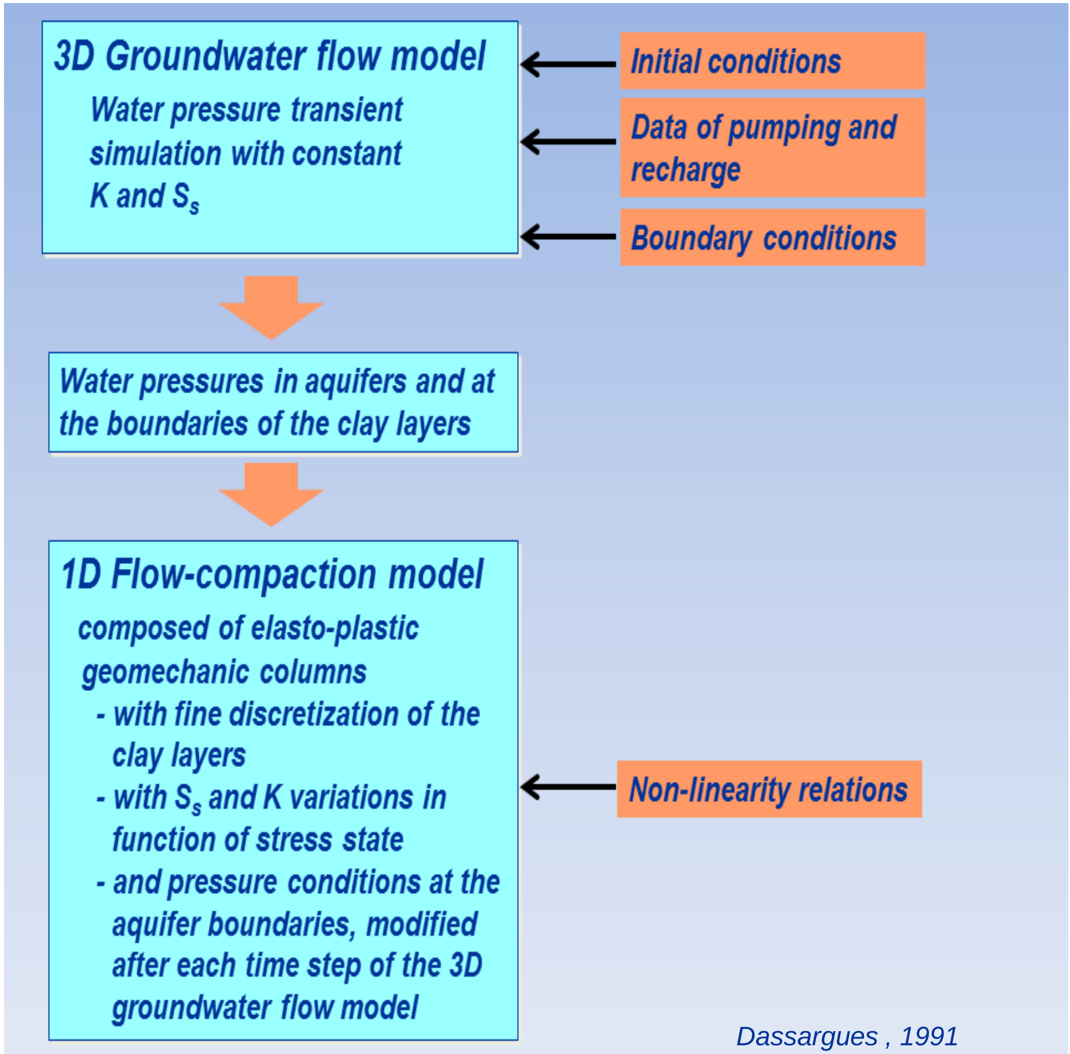
- different and differential settlements
- due to heterogeneity, different building foundations
- cumulative subsidence: 2.30 m

(Phien-wej et al. 2006)

Shanghai

- *coastal lowlands, compressible sediments, transition from an estuarine to a fluvial system*
- *absence in some zones of DGSC (over-consolidated)*
- *2.5 m in 1962 and a maximum yearly rate of 98 mm between 1956 and 1959*
- *since 1962, recharge main exploited aquifers led to elastic rebound*

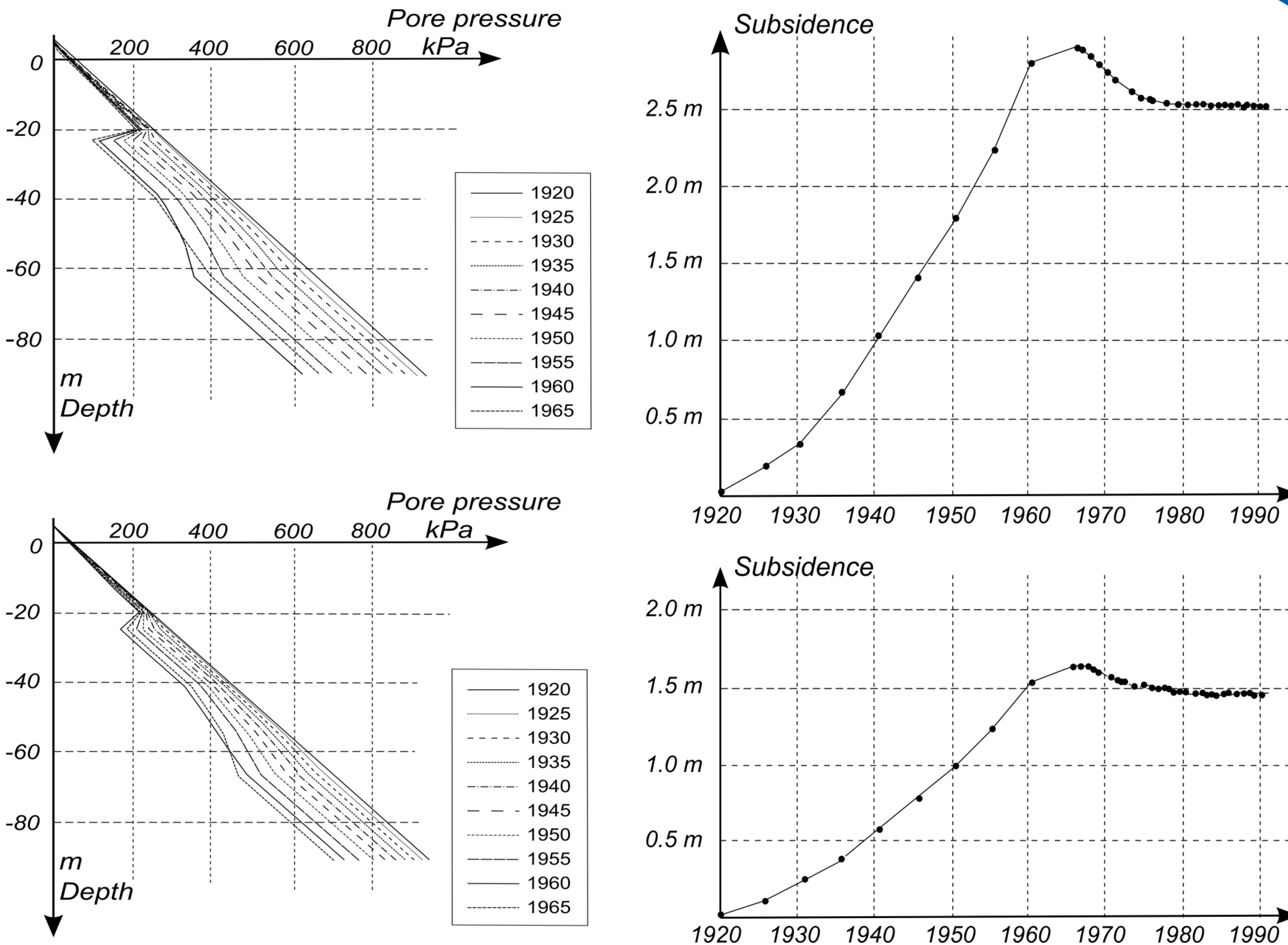
- *now again 18 mm/y essentially in suburbs*



(Zhang et al. 2007, Wu et al. 2010)

Shanghai

(Dassargues et al. 1993)



Conclusions / perspectives

- *during the last century, induced land subsidence > sea-level rise (17 to 21 cm from 1900 until 2010)*
- *but sea-level rise ranging from 0.5 m to 0.9 m by 2100 (IPCC report 2013)*
- *no miracle for remediation of land subsidence except to stop and restore pore pressures*
- *injection of water*
  - *elastic rebound only*
  - *in deep confined saline aquifers*
  - *physico-chemical reactions*
  - *many uncertainties*
- *better measurements with SAR (interferometric synthetic aperture radar) and D-GPS techniques (Bock et al. 2012)*
- ***more consideration of the hydrogeological conditions in the land use planning***

  …

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