Institute for Geotechnical Engineering
ETH Zurich – March 17 2011

Discontinuities in Soils

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Cardiff U.

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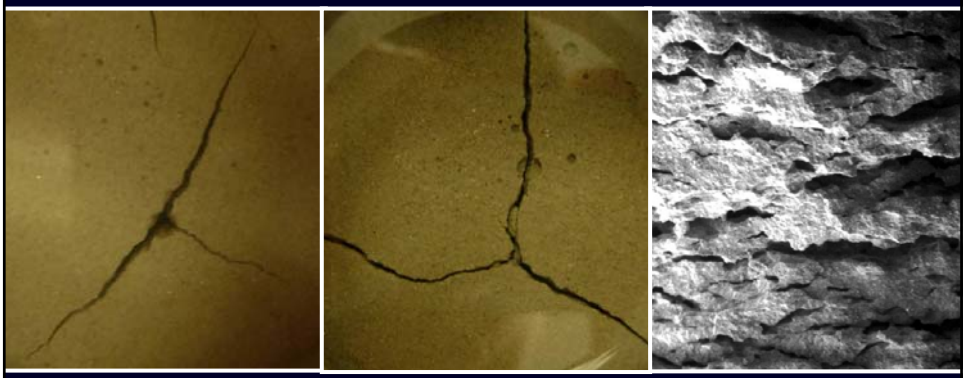
Hongik U.

M. Cha
GaTech

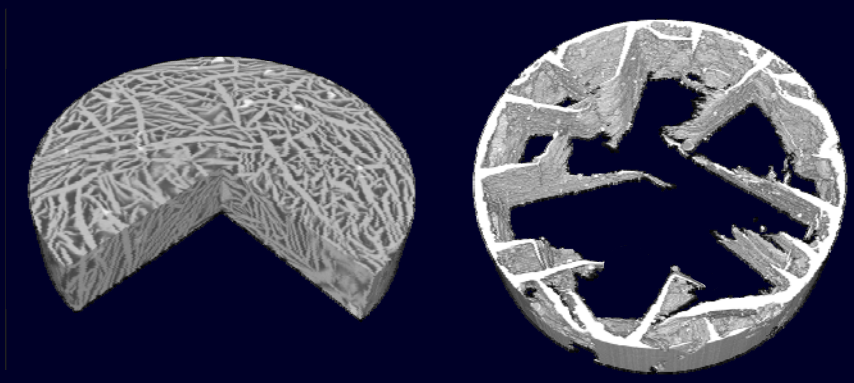
Desiccation Cracks

Forced Fluid Invasion



water *oil* *steam*

Ice Lenses

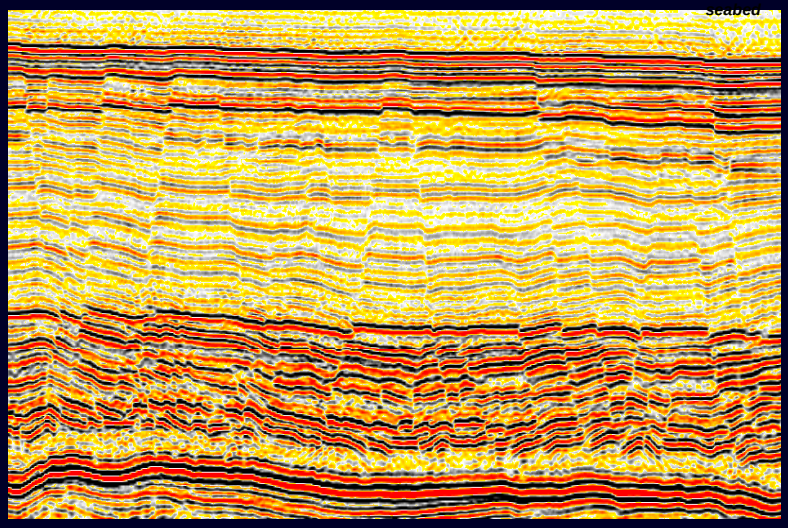


Bentonite *Kaolin*

Viggiani – Grenoble

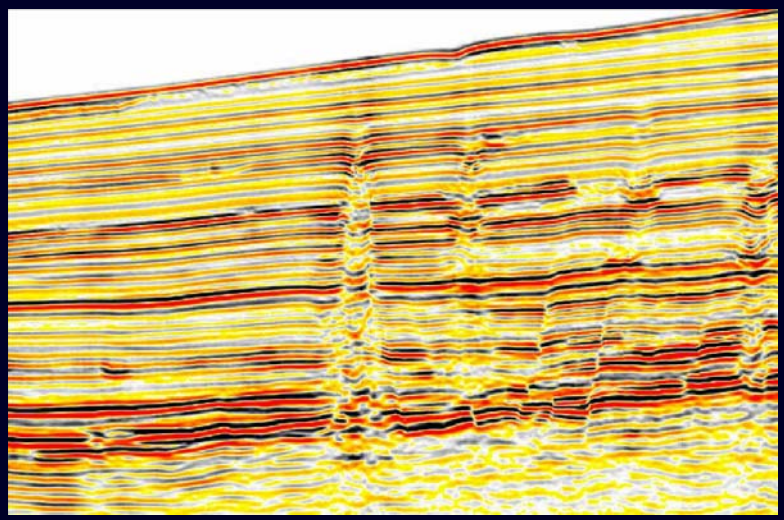
Roots?

Polygonal Faults in Marine Sediments

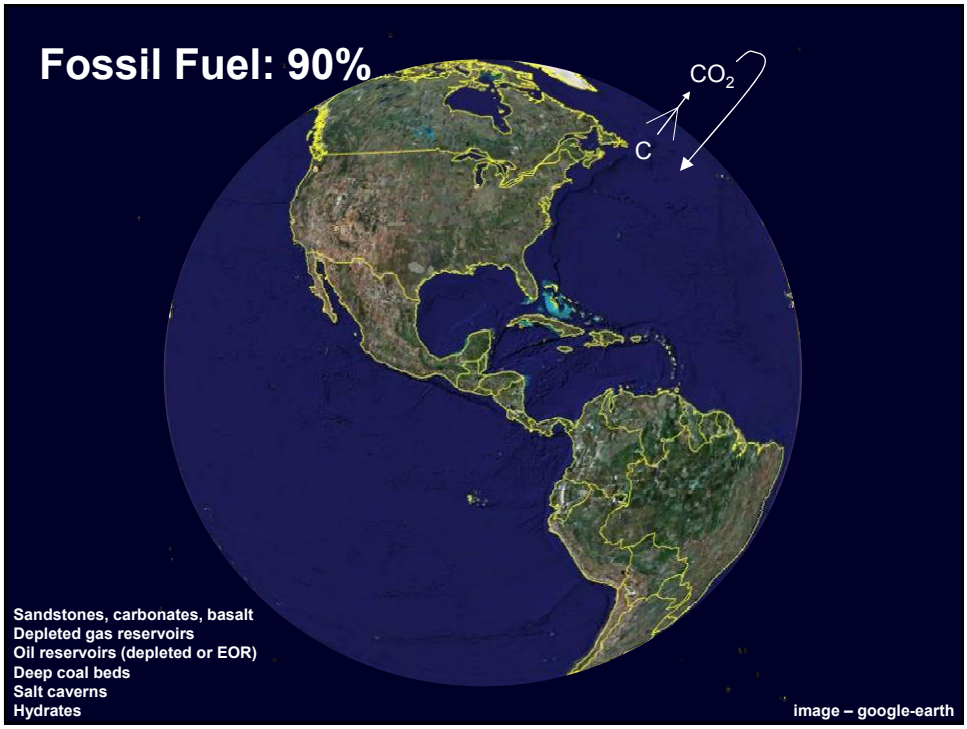


Cartwright (2005)

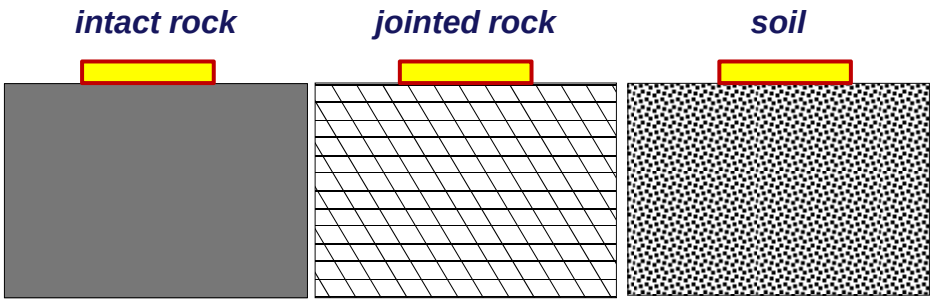
Pipes in Marine Sediments



Cartwright (2009)



Relative Length Scales: Footings

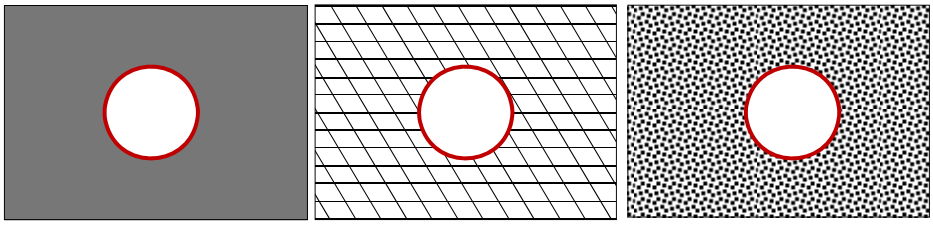


$\lambda/D>>1$	$\lambda/D\approx1$	$d/D<<1$
solid	*structured*	*granular*

Boussinesq (1885)

Relative Length Scales: Tunnels

intact rock | *jointed rock* | *soil*



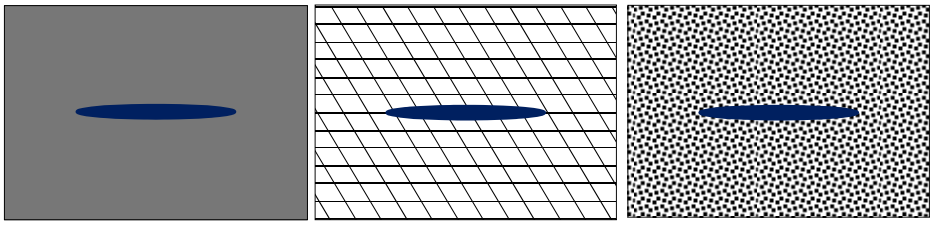
$\lambda/D>>1$ | $\lambda/D\approx1$ | $d/D<<1$

solid | *structured* | *granular*

Kirsch (1898)

Relative Length Scales: Fractures

intact rock | *jointed rock* | *soil*



$\lambda/D>>1$ | $\lambda/D\approx1$ | $d/D<<1$

solid | *structured* | *granular*

Griffith (1921)
Irwin (1957)

Discontinuities in SOILS

- Granular materials
- σ' dependent stiffness, strength, dilation
- Frictional $\tau_{ult} = \sigma' \tan\phi$
- No cohesion ➔ $\sigma' \geq 0$ everywhere

Effective stress compatible mechanisms

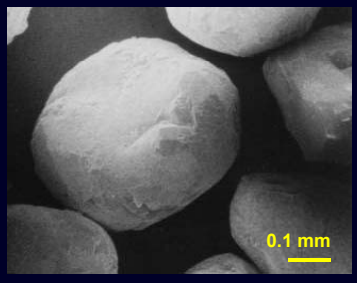
"… Coulomb… purposely ignored the fact that [soils] consist of individual grains

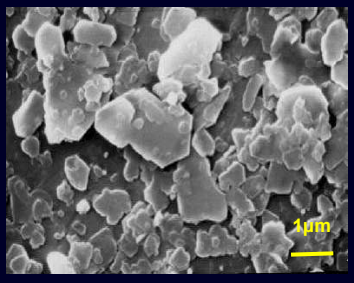
Coulomb's idea proved very useful as a working hypothesis …. but it developed into an obstacle against further progress as soon as its hypothetical character came to be forgotten by Coulomb's successors.

The way out of the difficulty lies in dropping the old fundamental principles and starting again from the elementary fact that [soils] consist of individual grains"

Terzaghi (1920)

Particle Forces F=ma





Particle Forces

Skeletal

Weight

Buoyant

Hydrodynamic

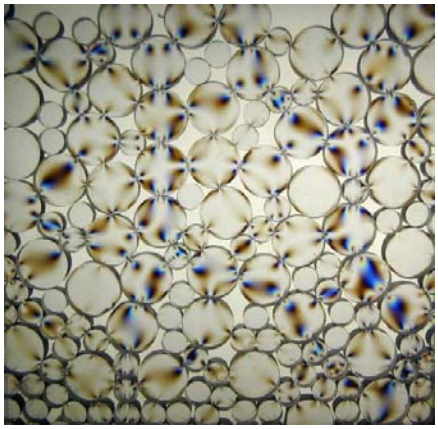
Capillary

Electrical

attraction

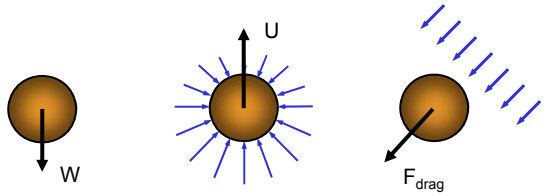
repulsion

Cementation



Particle Forces

- Skeletal
- **Weight**
- **Buoyant**
- **Hydrodynamic**
- Capillary
- Electrical
  - attraction
  - repulsion
- Cementation



Particle Forces

- Skeletal
- Weight
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- **Capillary**
- Electrical
  - attraction
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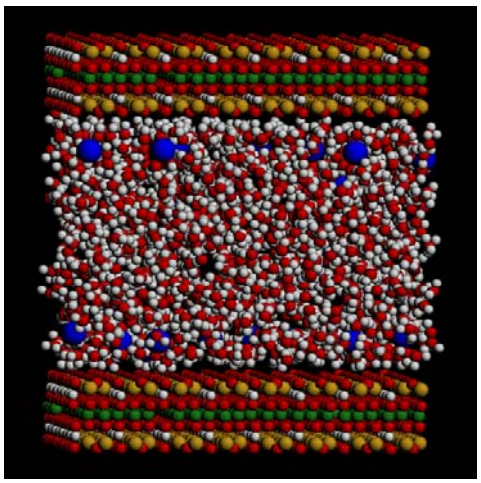
Particle Forces

- Skeletal
- Weight
- Buoyant
- Hydrodynamic
- Capillary
- **Electrical**
  - attraction
  - repulsion
- Cementation

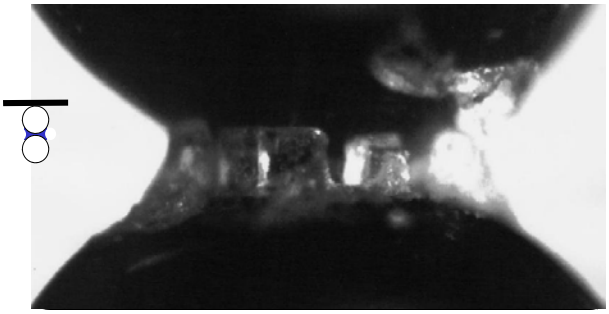
Laponite 1200 H_2O 24 Na^+



(N. Skipper - UCL)

Particle Forces

- Skeletal
- Weight
- Buoyant
- Hydrodynamic
- Capillary
- Electrical
  - attraction
  - repulsion
- **Cementation**



(passive)

Particle Forces – Spherical Particles

Skeletal	$\underline{N} = \sigma' d^2$	boundary-determined
Weight	$W = (\pi G_s \gamma_w / 6) d^3$	particle-level
Buoyant	$U = Vol \cdot \gamma_w = (\pi \gamma_w / 6) d^3$	
Hydrodynamic	$F_{drag} = 3\pi \mu v d$	
Capillary	$F_{cap} = \pi T_s d$	contact-level
Electrical		
attraction	$Att = \frac{A_h}{24 t^2} d$	
repulsion	$Re\,p = 0.0024 \sqrt{c_o}\ e^{-10^8 t \sqrt{c_o}}\ d$	
Cementation	$T = \pi \sigma_{ten} t d$	

Force Balance: Capillary Force

Skeletal

Weight

Buoyant

Hydrodynamic

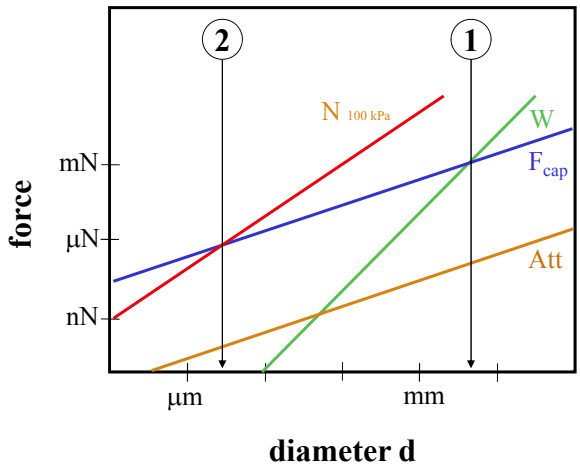
Capillary

Electrical

attraction

repulsion

Cementation



Force Balance: Viscous Drag

Skeletal

Weight

Buoyant

Hydrodynamic

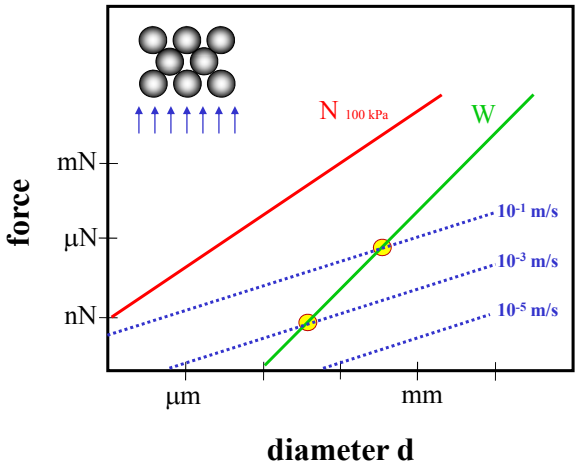
Capillary

Electrical

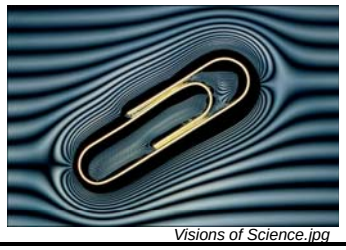
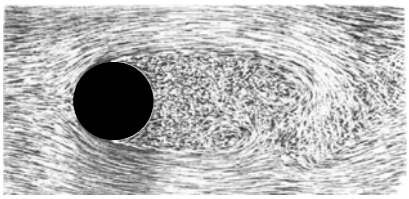
attraction

repulsion

Cementation

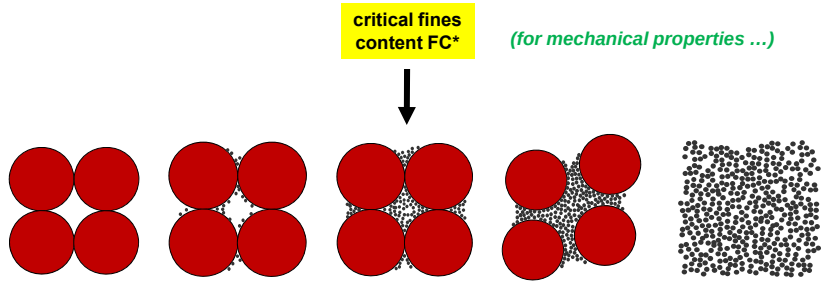


Forced Fluid Invasion

Immiscible fluid	Miscible fluid
 Visions of Science.jpg	

Effective stress compatible mechanisms

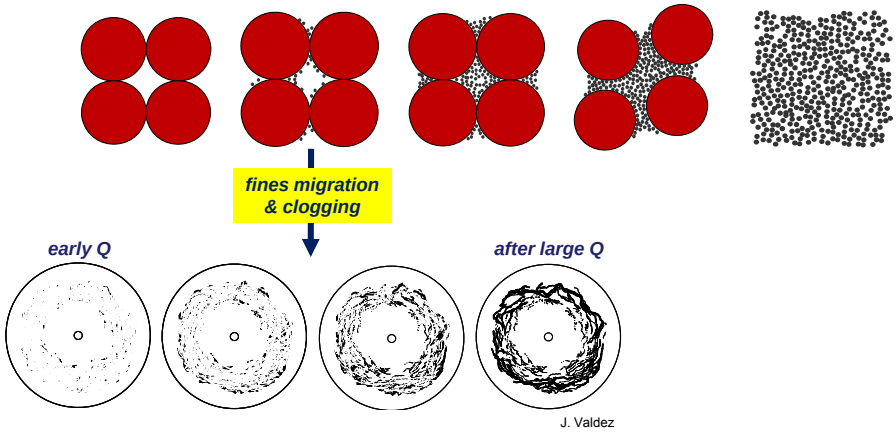
Grain Size Distribution: The Role of Fines



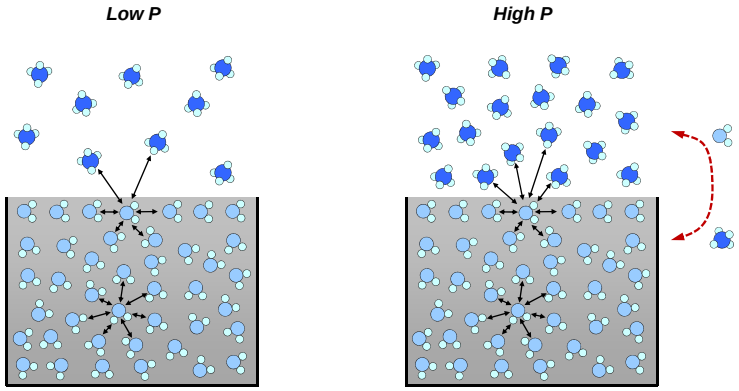
$$FC^* = \frac{M_{fine}}{M_{total}} = \frac{e_{coarse}}{1 + e_{coarse} + e_{fine}}$$

Sediment	e_{1kPa}	FC*
Silt	~0.7	~ 25 %
Kaolinite	~1.5	~ 20 %
Illite	~3.7	~ 11 %
Montmorillonite	~5.4	~ 8 %

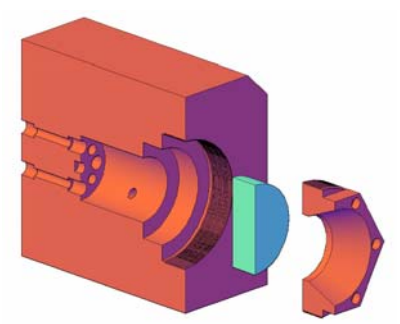
Fines Migration and Clogging

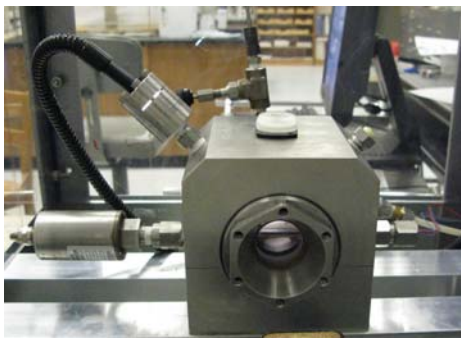


Gas-H_2O Interfacial Interaction

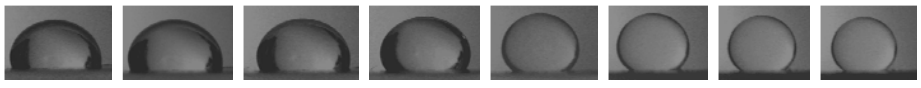


Caution: Surface Tension and Contact Angle





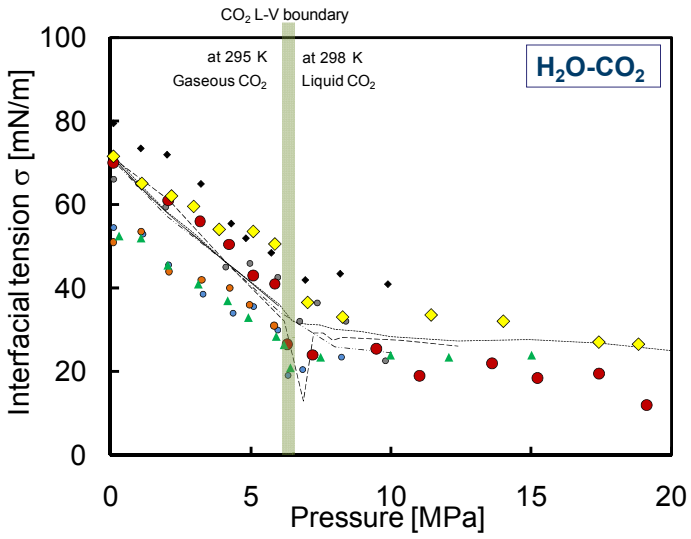
water droplet in CO2



atm → *gas* → *liquid* → 20 MPa

Espinoza - GT

Surface Tension = f(P)



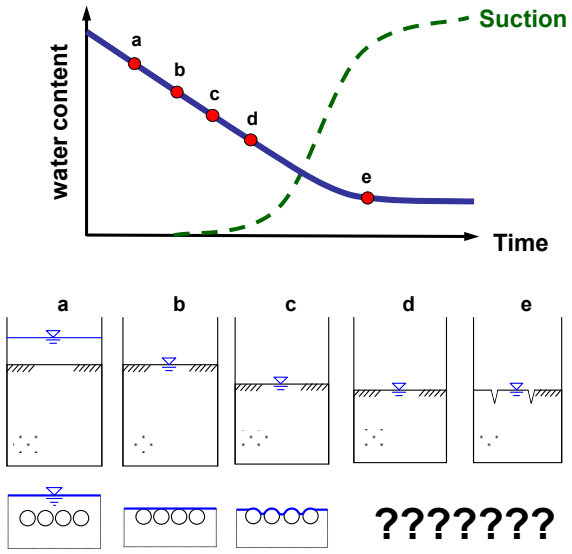
Espinoza - GT

Immiscible Fluids

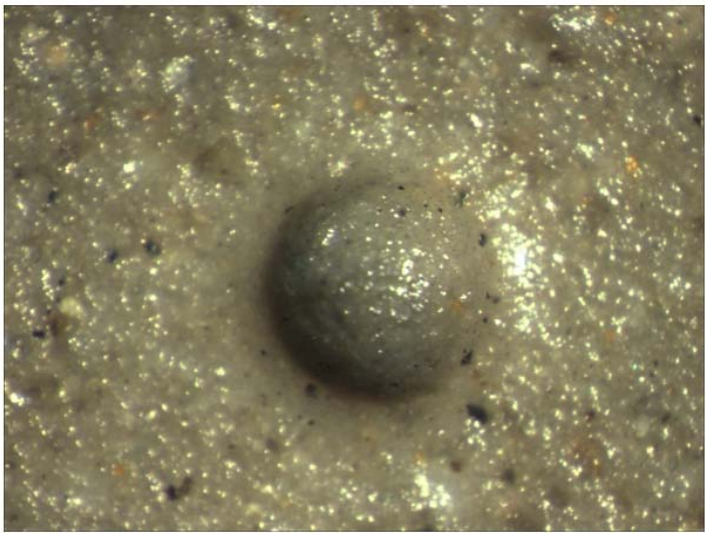
Desiccation Cracks

Forced invasion immiscible fluid

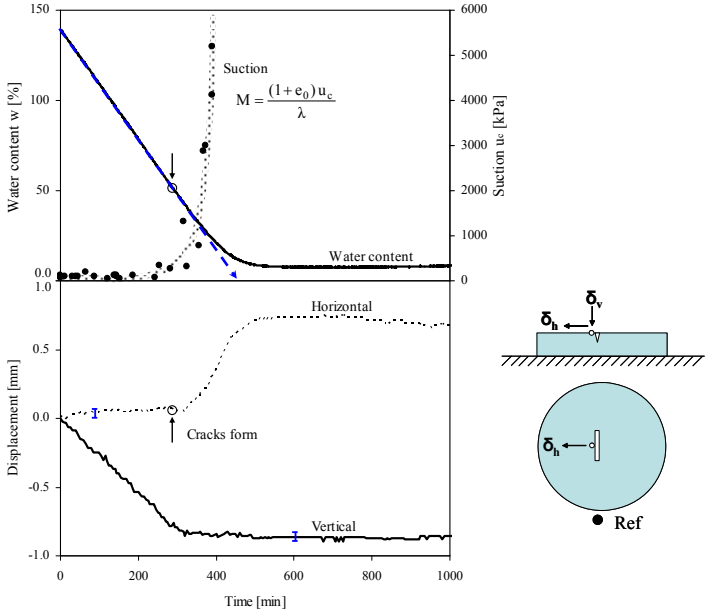
Desiccation and Crack Initiation



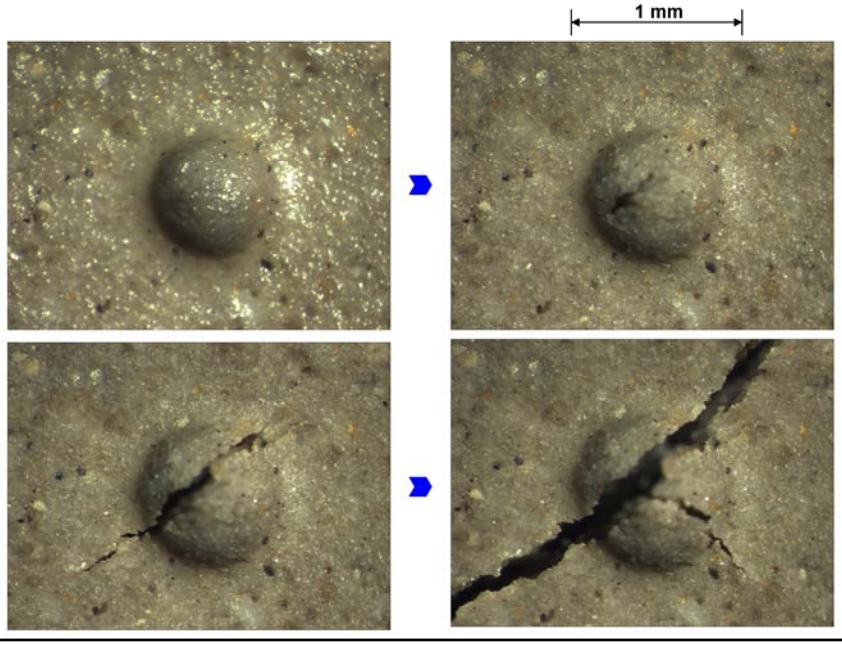
Crack Initiation



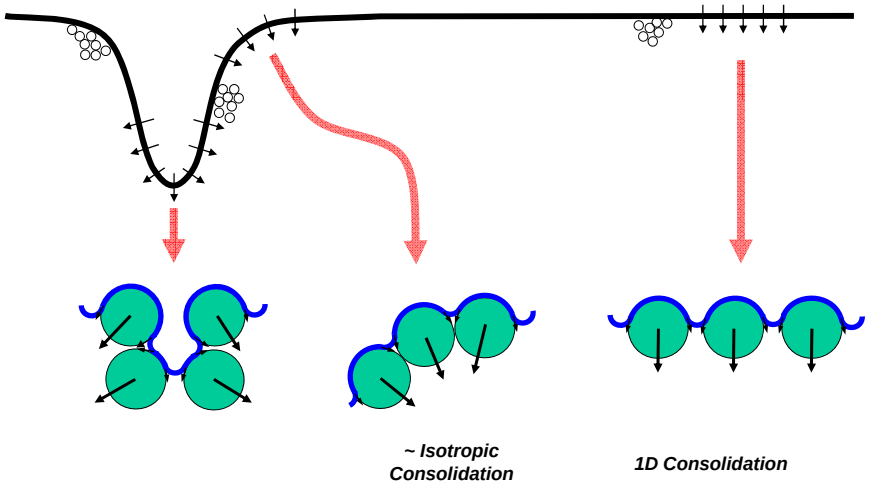
Crack Initiation Displacements



Crack initiation?

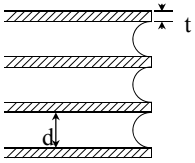


Crack Initiation: Capillary Forces



Soil is in compression EVERYwhere

Air entry line

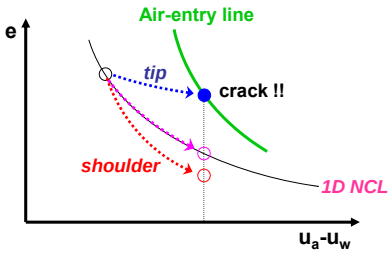


$e = d / t$

$S_S = 2 / (\rho\, t)$

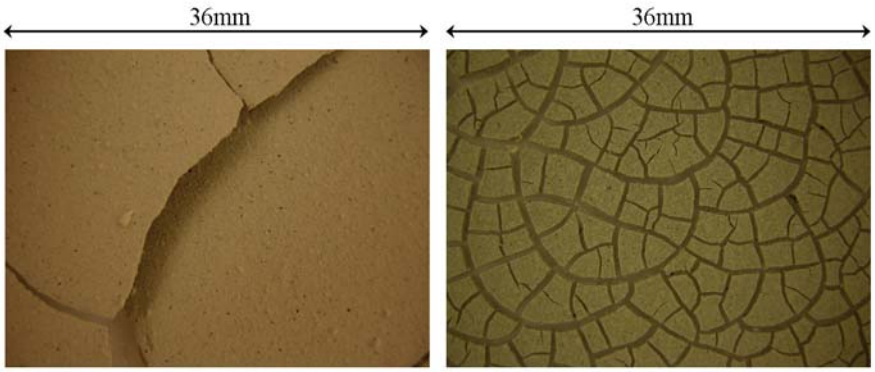
$u_c = 2\, T_S / d$

$$u_c^{AE} = \frac{\rho\, T_s\, S_s}{e}$$



Pore Size Distribution

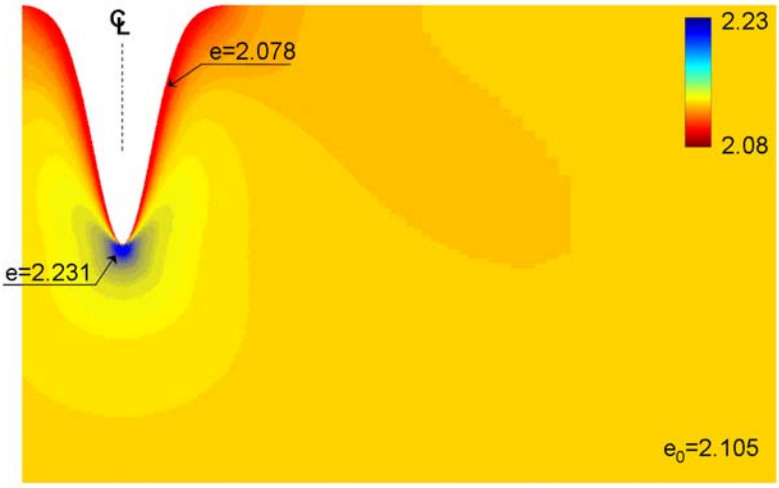
$$u_C = \frac{\rho T_S S_S}{e} \frac{1}{10^{\alpha\sigma^*}}$$



dispersed → *aggregated*

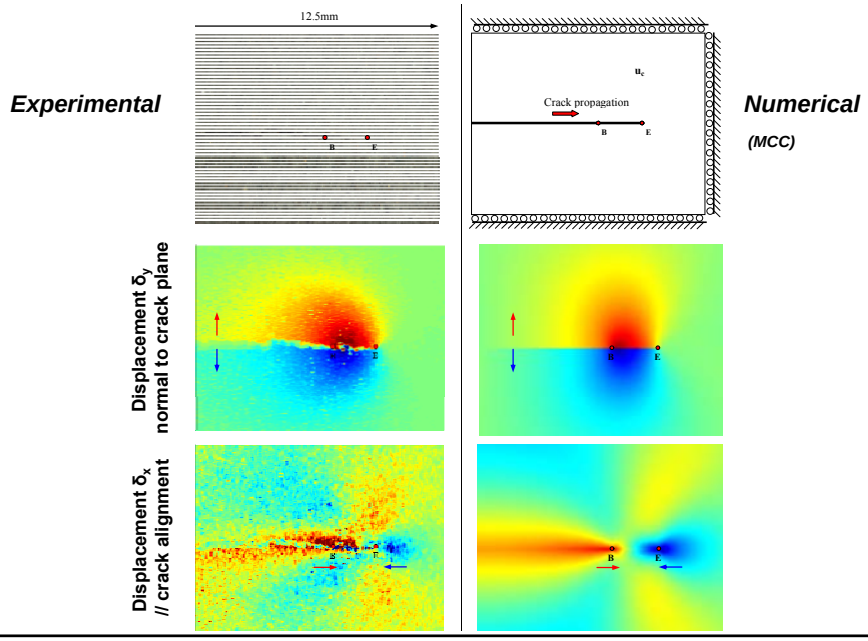
Tip Conditions

$$\Delta P = \frac{\rho \sigma_s S_s}{e}$$

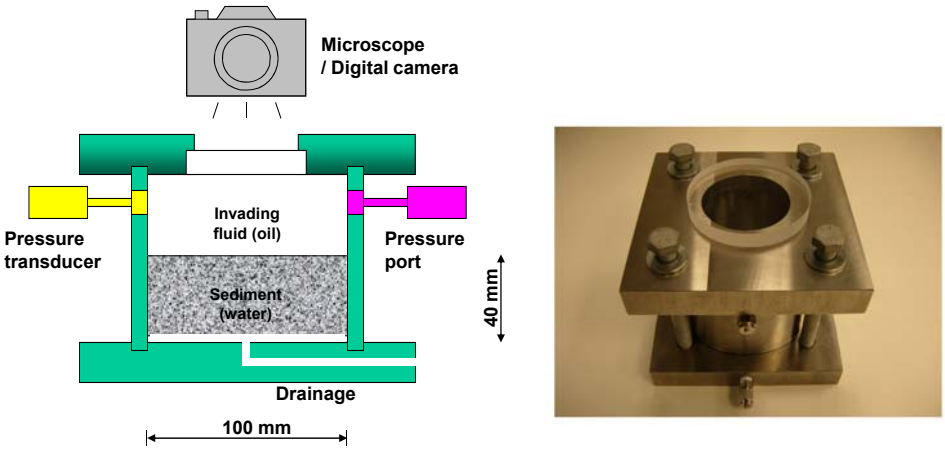


Sediment in compression EVERYwhere

Crack Propagation

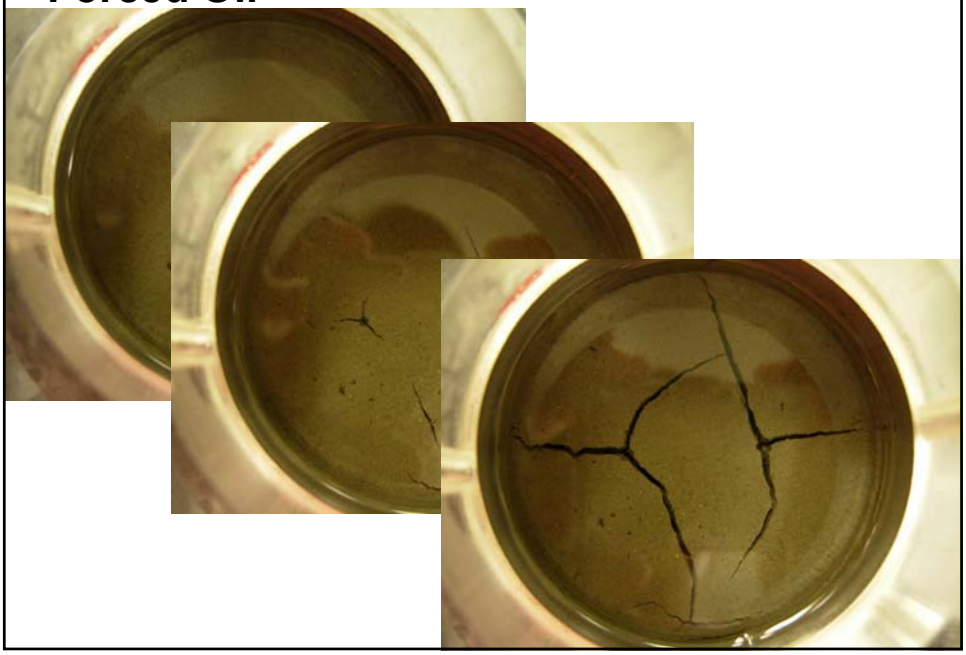


Forced Oil or Air - Device

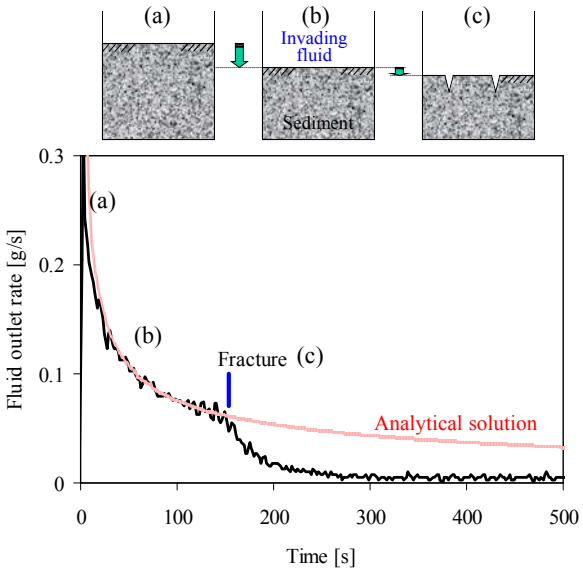


Forced Air

Forced Oil



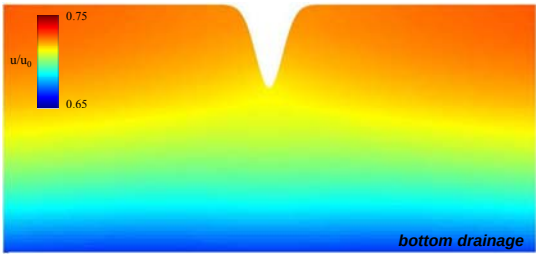
Effluent flow rate



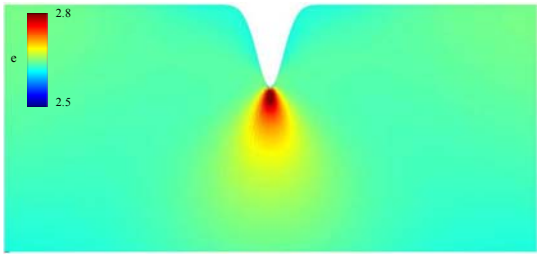
Surface defects: *forced invasion*

@ T=0.33

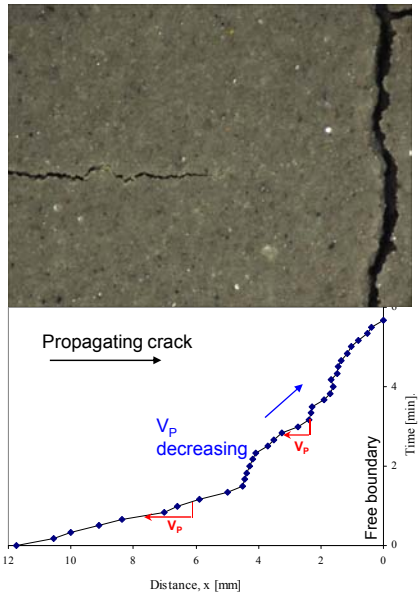
Fluid pressure



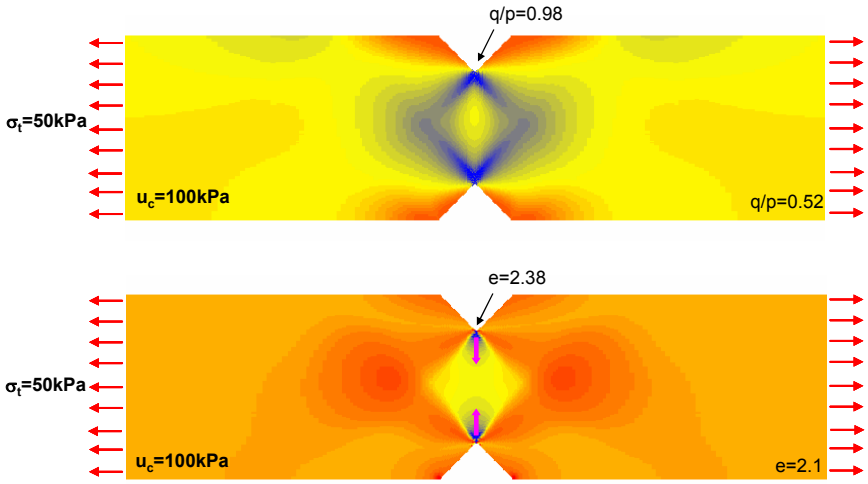
Void ratio



Crack Propagation Velocity

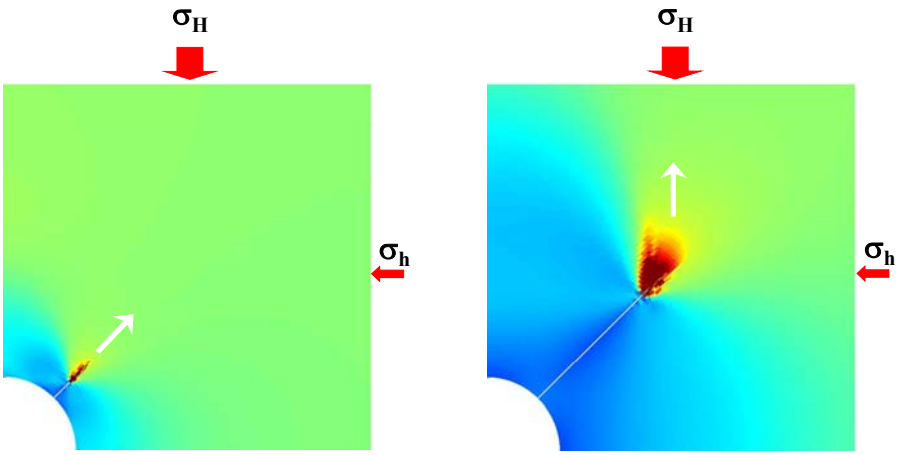


Apparent Tensile Strength



$$\sigma_T \le u_0 \frac{2\sin(\phi')}{1+\sin(\phi')}$$

Boreholes – Anisotropic Stress Field



$\sigma_h/\sigma_H=0.7$

Invasion vs. Open-mode Discontinuities

Invasion
Fluid invasion
Crystal growth in pores

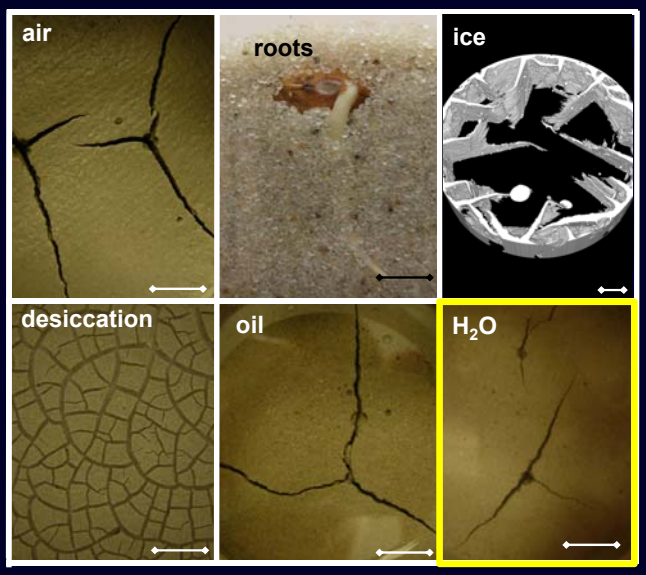
$$\frac{F_c}{N} = \frac{2\pi\sigma_{LV}}{\sigma' d}$$

DISCONTINUITIES
Lenses
Fractures
Roots

0.1 1.0 10

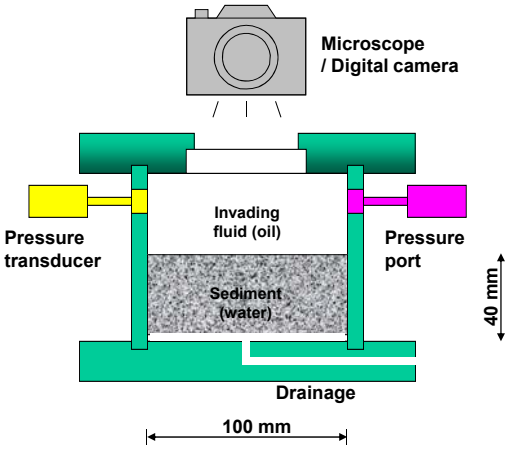
coarse grained soils
high effective stress

fine grained soils
low effective stress

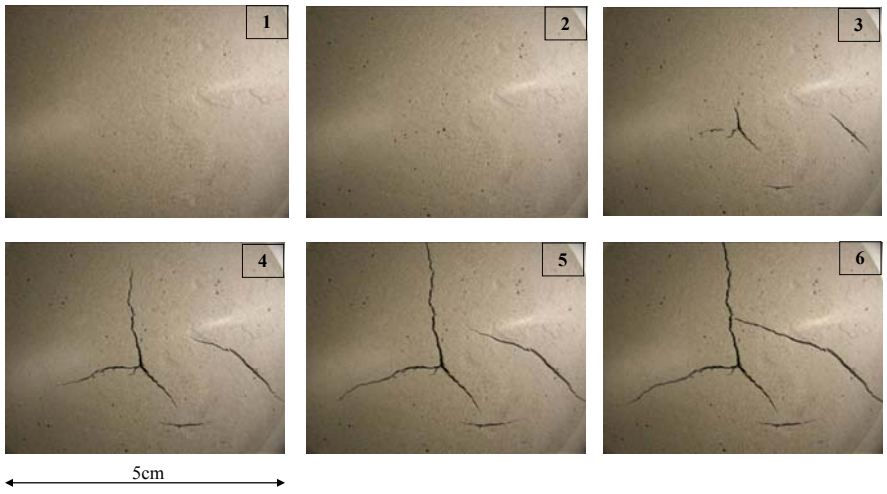


Miscible Fluids

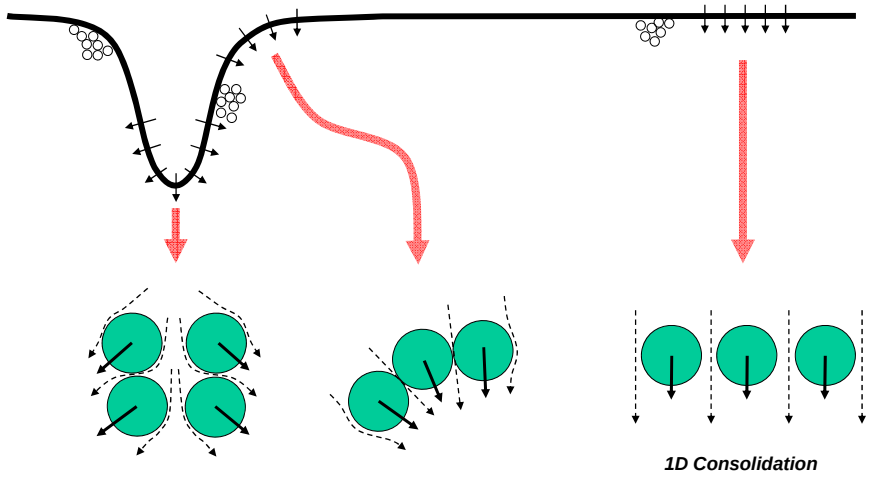
Forced Miscible Fluid - Device



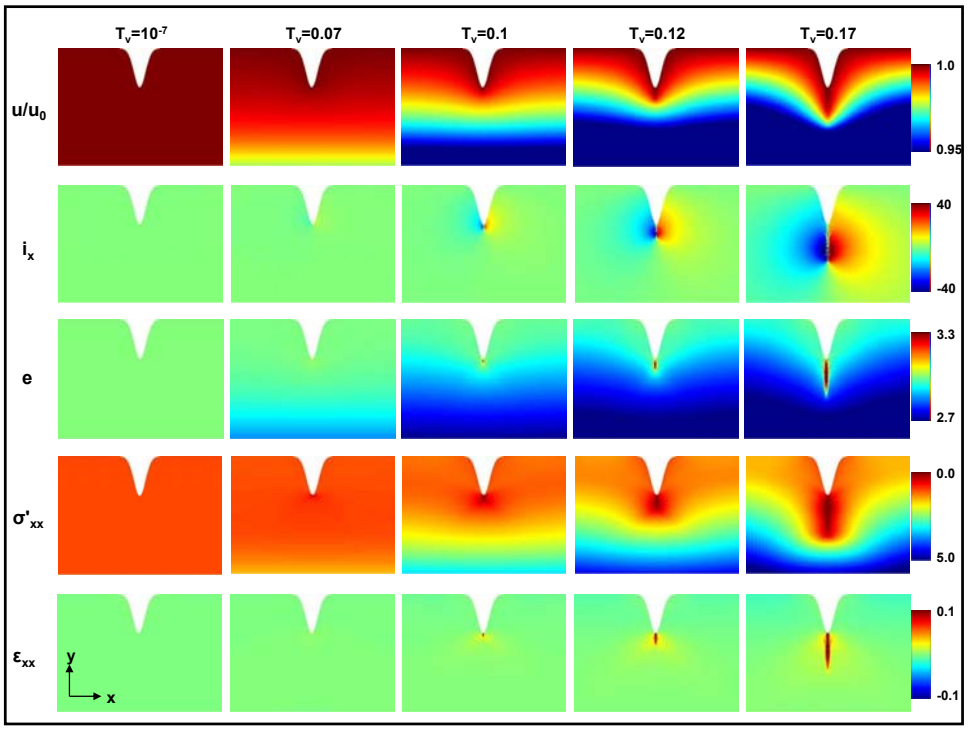
Forced Water



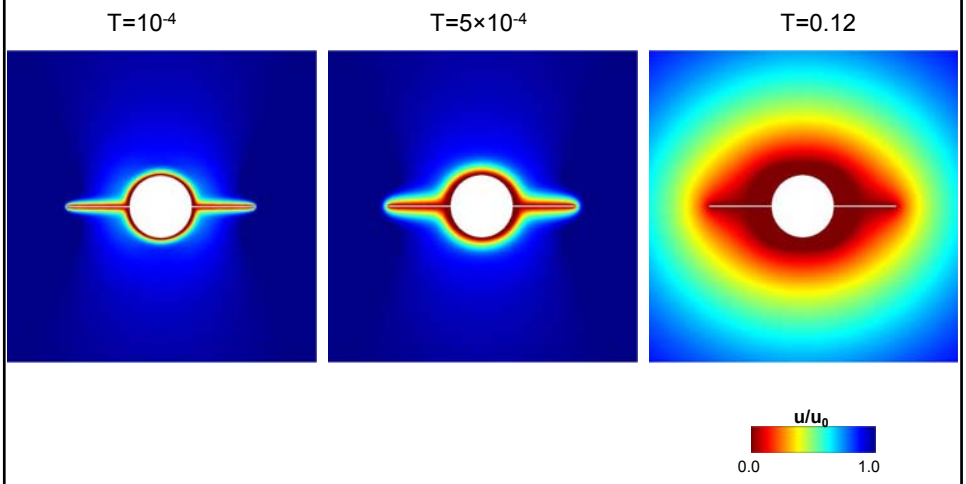
Crack initiation – Seepage Drag Forces



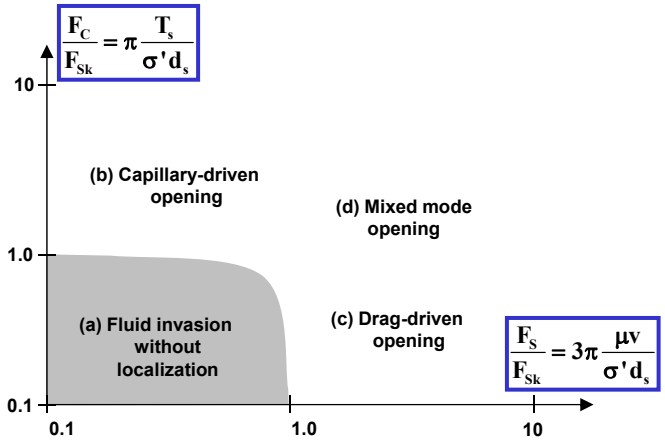
Soil is in compression EVERYwhere



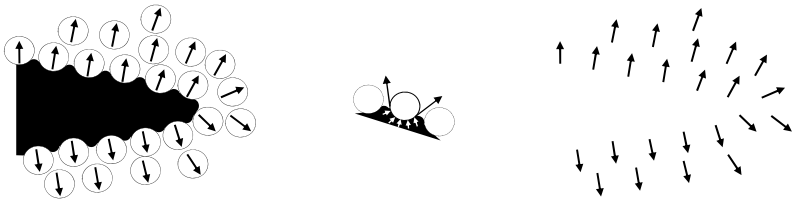
Pressure Diffusion



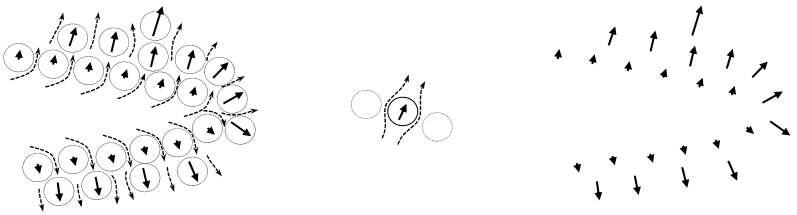
Miscible vs. Immiscible Fluid Invasion

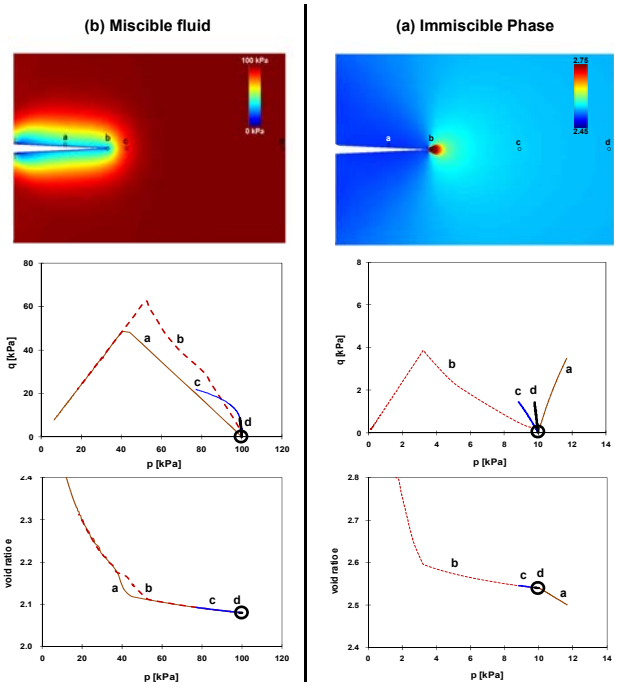


Immiscible (gas, ice, hydrates, roots)



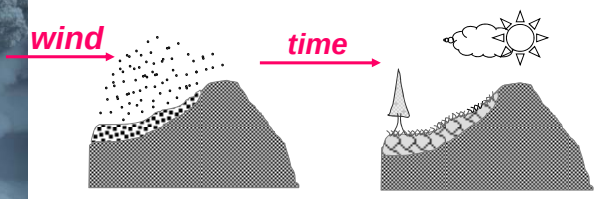
Miscible (classical hydraulic fracture)





Grain Dissolution

Volcanic Ash Soils: Formation



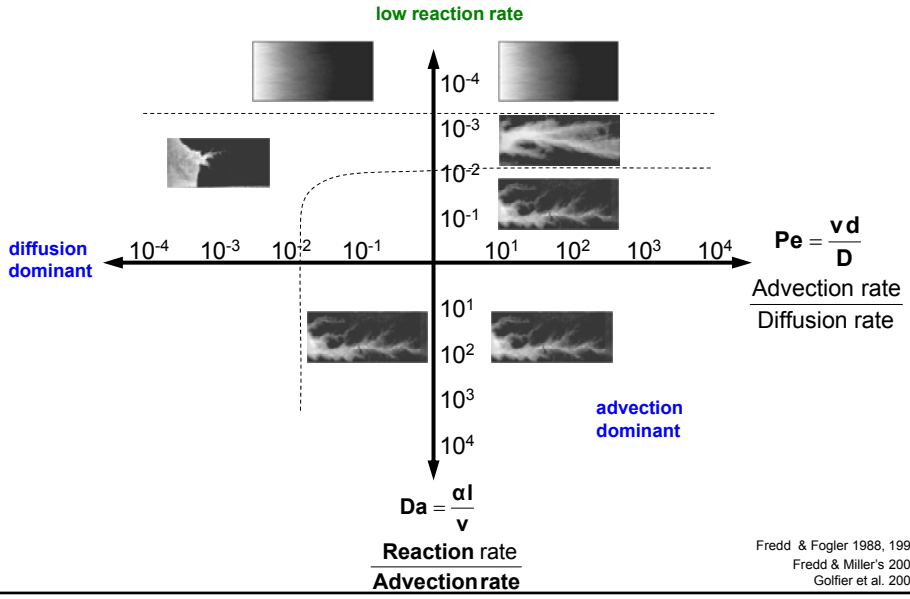
e= 0.8-1.5	e= 2.0-7.0
S_s~0.1-1 m^2/g	S_s=50-to-200 m^2/g
volcanic glass	hallosite imogolite alophane
$k_o=1-\sin\varphi$	k_o= ??

Dissolution

Evolution
- Distributed
  - Homogeneous
  - Pressure-solution
- Localized ➔ pipes/fingers

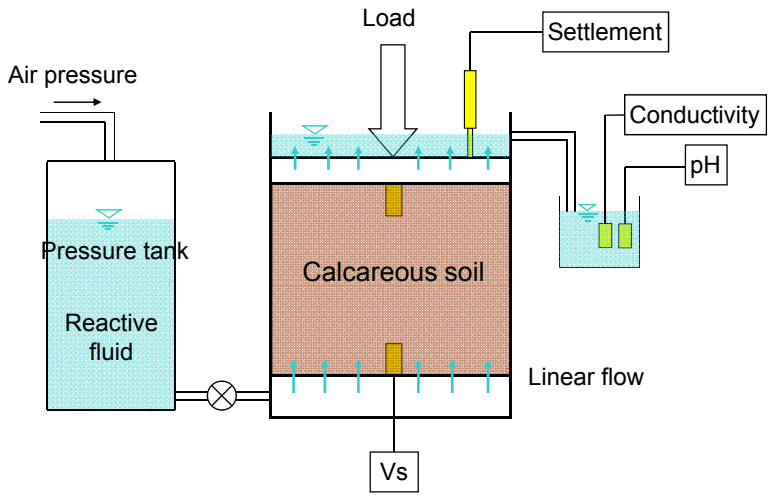
Questions:
- dissolution / rates
- porosity
- k_o
- shear strain localization
- flow & pressure field evolution
- pipes: exclusion distance
- detection: Vs, q_t
- healing (chemo, bio, others)
- …

Reactive Fluid Transport

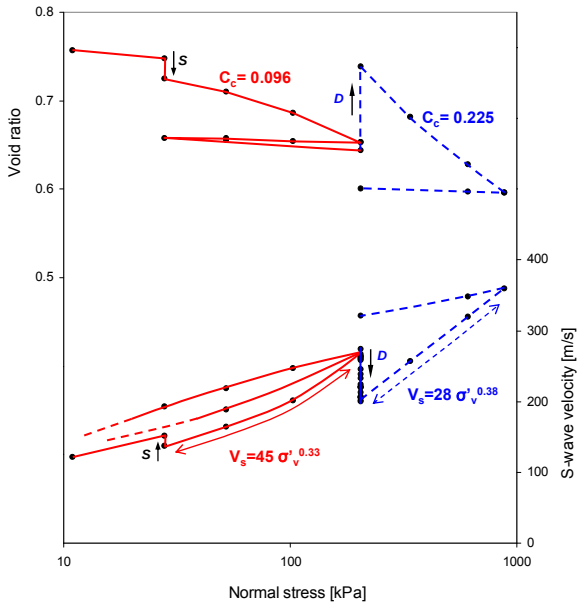


Fredd & Fogler 1988, 1998
Fredd & Miller's 2000
Golfier et al. 2002

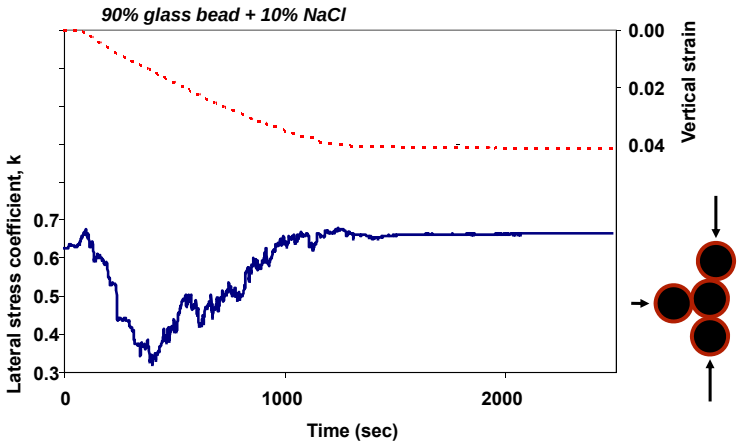
Experimental schematic



Soil Response Before & After Dissolution



Experimental Results



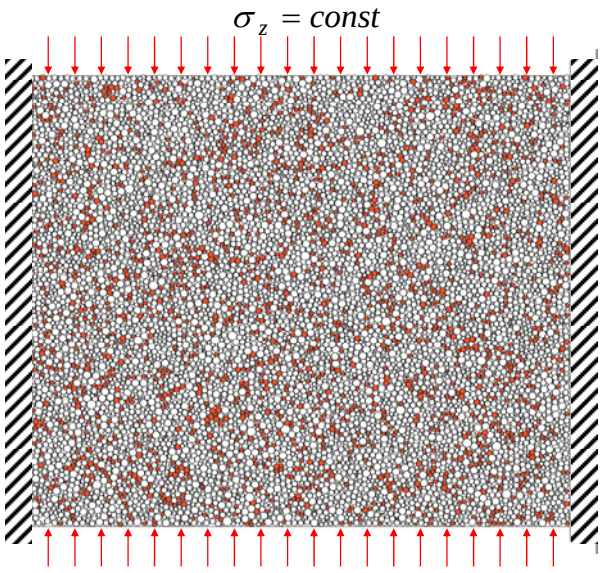
DEM Simulation

N= 9999 (in 2D) - 8000 (in 3D)

cov particle diameter: 0.25

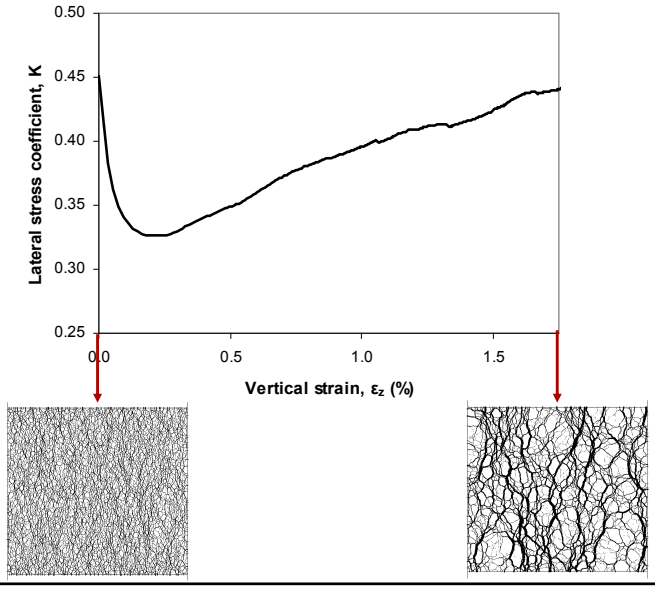
Interparticle friction: 0.5

Simulation: reduce D or G



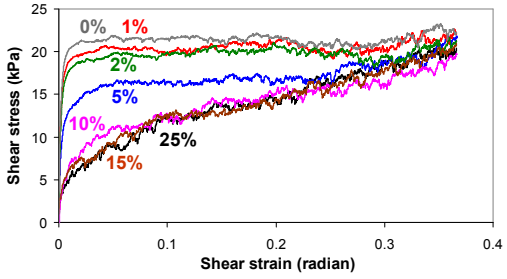
DEM Simulation

2D - diameter gradually reduced - 20% of particles

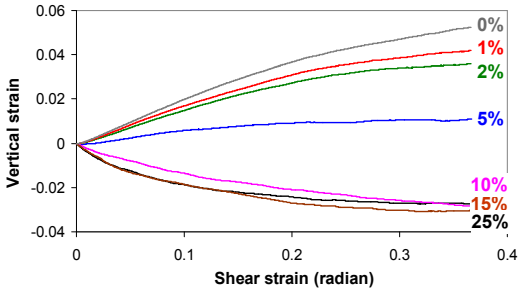


Post-dissolution simple shear

Shear stress

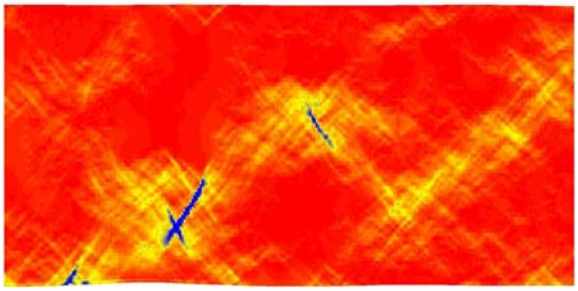


Vertical strain



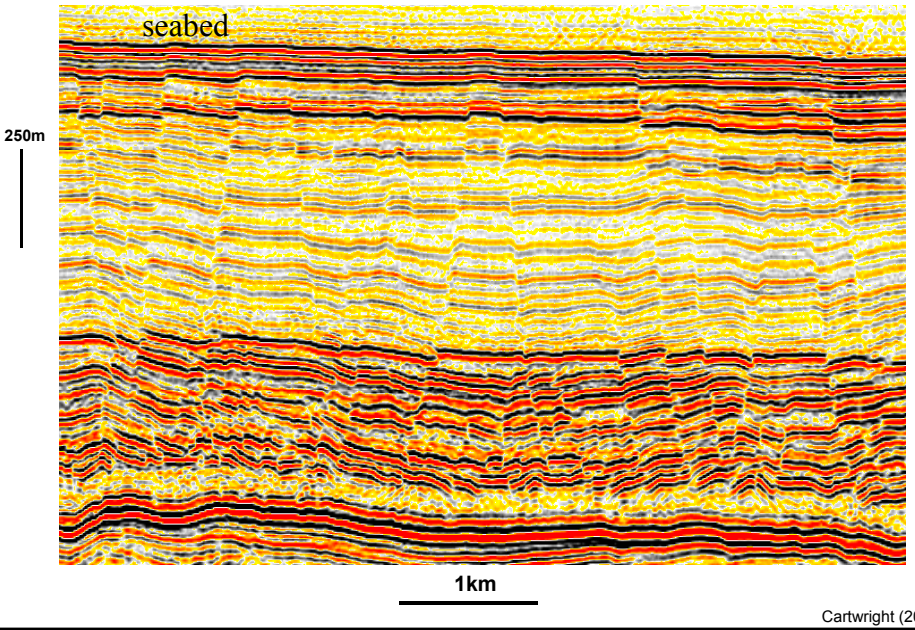
Shear Localization?

FEM simulation



natural sediments

Polygonal Fault Systems



Cartwright (2005)

The Man In A Red Turban
Jan van Eyck (1433 - Oil)