10th G.A. Leonards Lecture
April 13, 2012 - Purdue U.

Understanding

Soil Properties and Behavior
- Recent Developments -

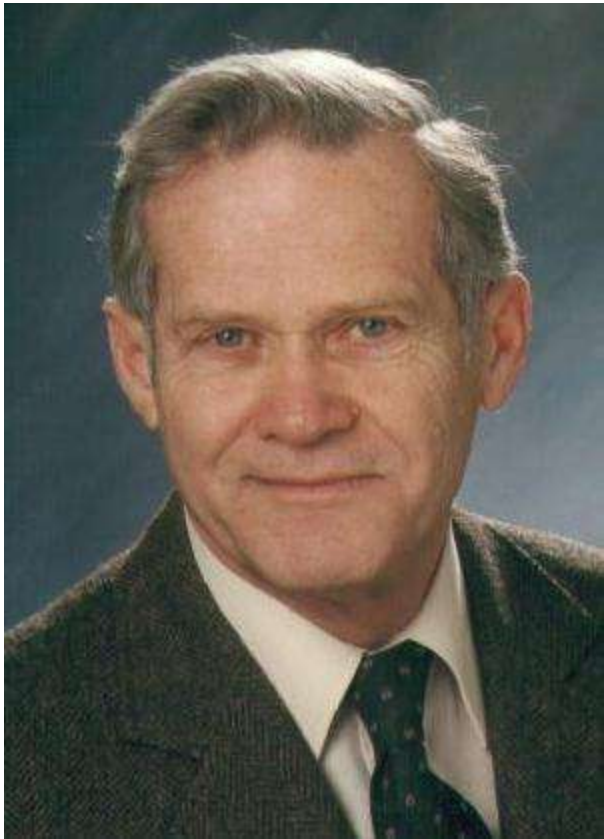
A personal journey inspired in Jerry Leonards

J. Carlos Santamarina
Georgia Institute of Technology

1921	Born (April 29, Montreal)
1943	BSc (McGill University)
1944	Army @ McGill
44-45	Canadian Mines & Resources
1945	Married
45-46	Canadian DoT
1948	MSc (Purdue)
1952	PhD (Purdue): Compacted clay
1952	Assistant Professor
1955	Associate Professor
1958	Full Professor
1960	US Citizen
1965	Norman Medal
1976	"Best CE Teacher"
1980	Terzaghi Lecture – Failures
1985	Workshop Dam Failures
1989	Member NAE
1991	Professor Emeritus
1997	Died (February 1)

Taught Mechanics & Drafting
"MUD-LAB" (compaction and shear tests)
6 week trip in the USA (Shannon, Casagrande)

Harvard? Caltech? Purdue?



1921 Born (April 29, Montreal)	
1943 BSc (McGill University) 1944 Army @ McGill 44-45 Canadian Mines & Resources 1945 Married 45-46 Canadian DoT 1948 MSc (Purdue)	Frozen ground Pavements
1952 PhD (Purdue): Compacted clay 1952 Assistant Professor 1955 Associate Professor 1958 Full Professor	Clays: σ-history
1960 US Citizen 1965 Norman Medal	Friction (and vibration) Clays - Repeated loading Cracking Earth Dams Shallow Foundations
1976 "Best CE Teacher"	Sands: σ-history; vibration; dynamic compaction Fly Ash Failures Pile Foundations
1980 Terzaghi Lecture – Failures 1985 Workshop Dam Failures 1989 Member NAE	Slope Stability – Landfills – Dam failures Weak seams Lateral Earth Pressure Culverts Undrained loading – Liquefaction of sands Tower of Pisa
1991 Professor Emeritus 1997 Died (February 1)	Hydraulic conductivity, piping, erosion

1921 Born (April 29, Montreal)	
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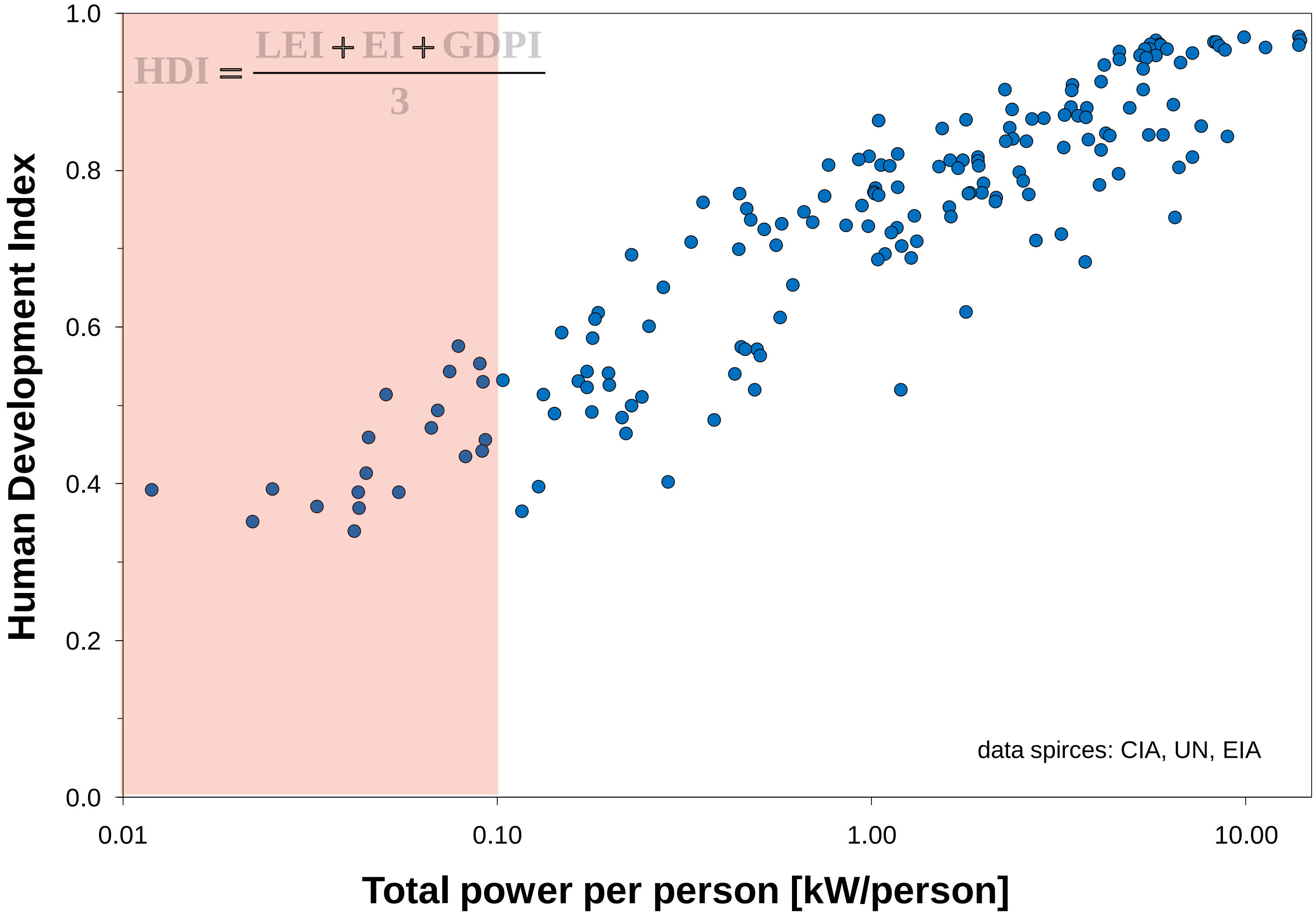
1952 PhD (Purdue): Compacted clay 1952 Assistant Professor 1955 Associate Professor 1958 Full Professor	Clays Sands Fly Ash
1960 US Citizen 1965 Norman Medal	Frozen ground Discontinuities - Weak seams Friction Hydraulic conductivity Piping, erosion
1976 "Best CE Teacher"	Pavements - Culverts Shallow and Deep Foundations Slopes and dams Lateral Earth Pressure
1980 Terzaghi Lecture – Failures 1985 Workshop Dam Failures 1989 Member NAE	Failures
1991 Professor Emeritus 1997 Died (February 1)	*Energy Geotechnology*

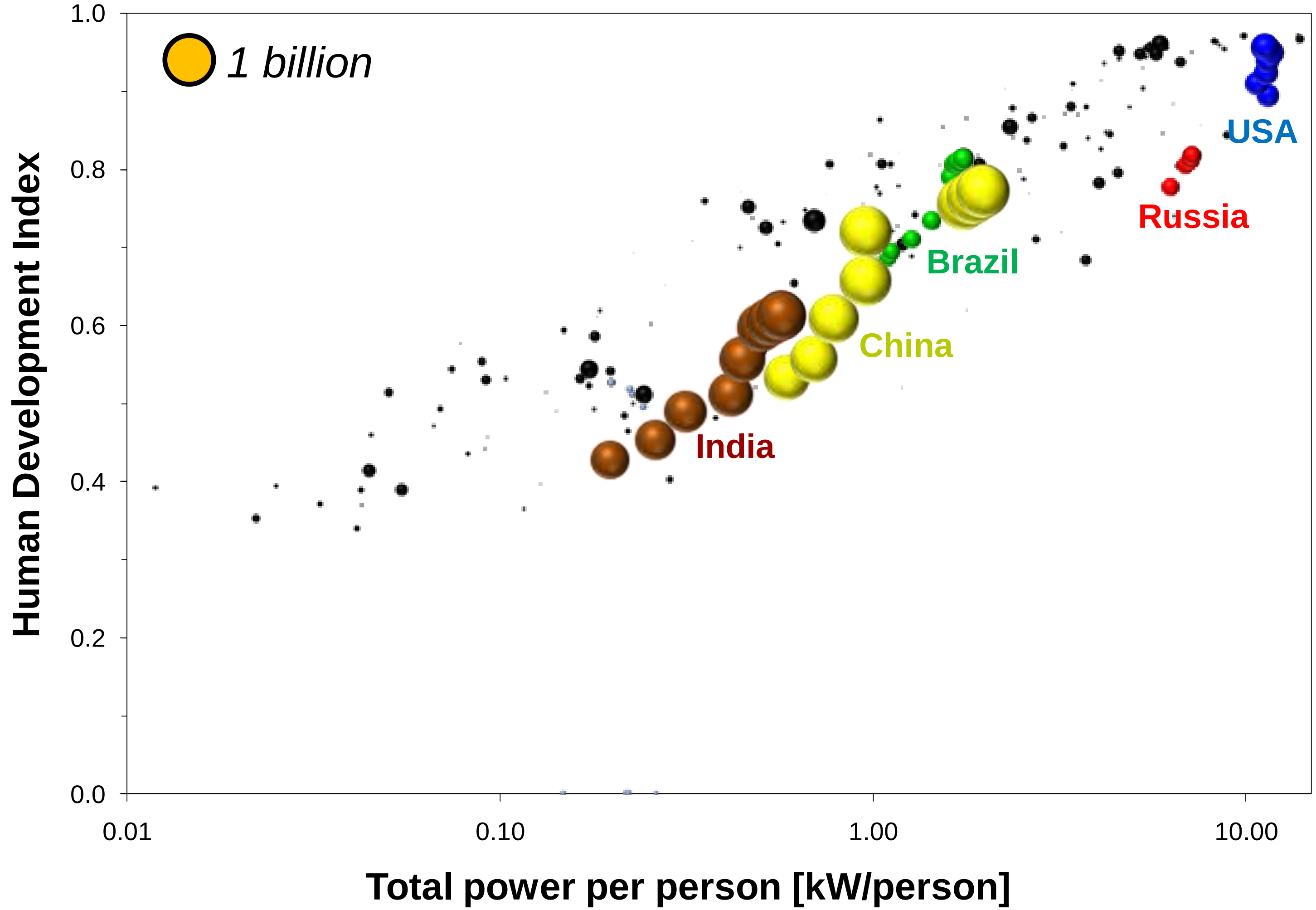
Energy Geotechnology

Energy and Life **(Global 2008)**



C. Pasten

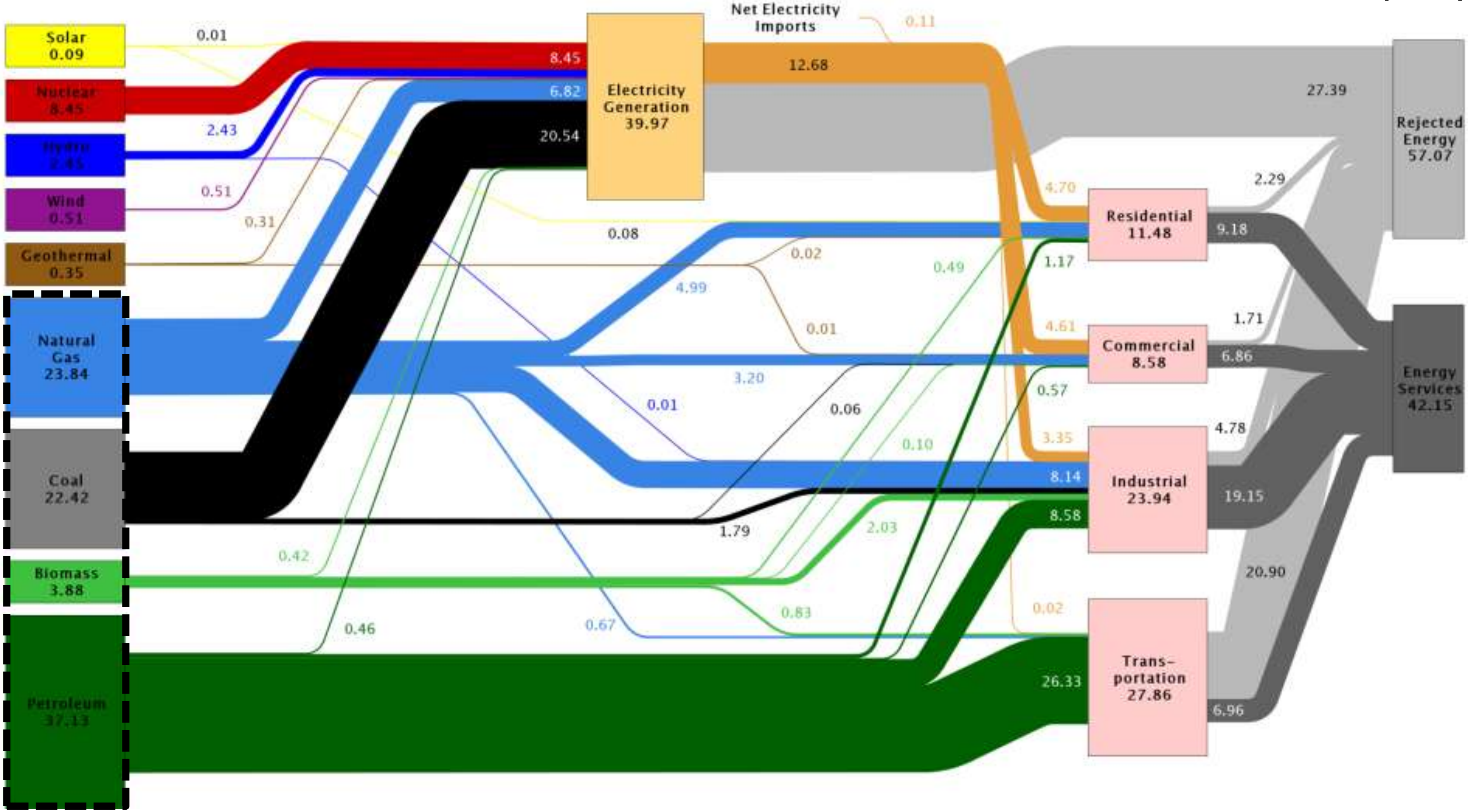
Energy and Life **(Global: 2008 – BRIC trends: 1980-2007)**



Countries following the same trend: P↑ ➔ HDI ↑

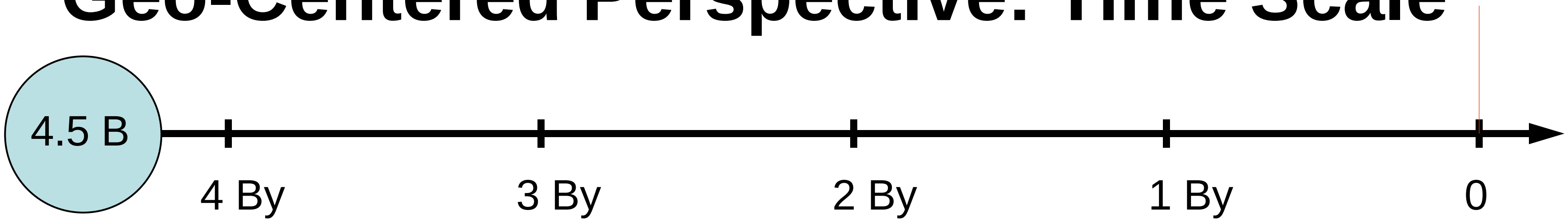
Sources – Case: USA

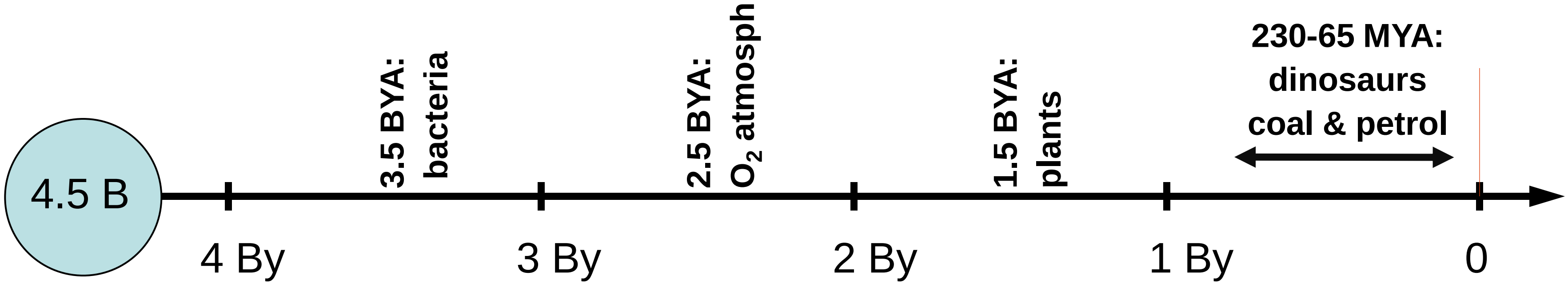
2008 LLNL – DOE
Units: [QUADS]

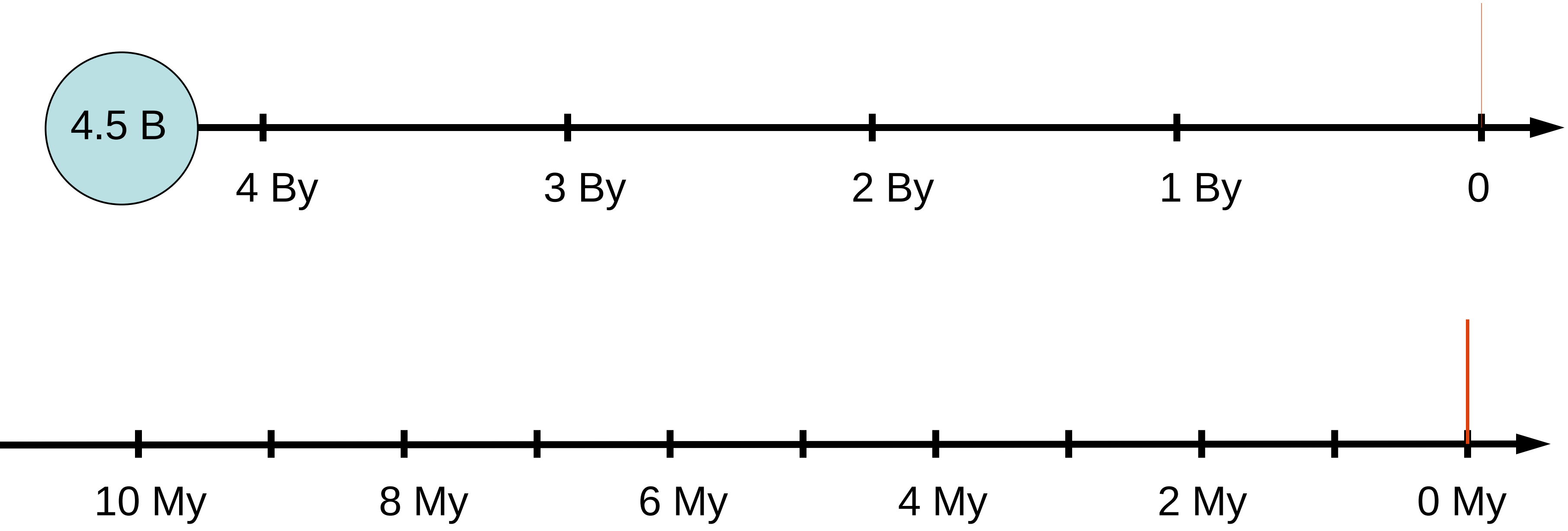


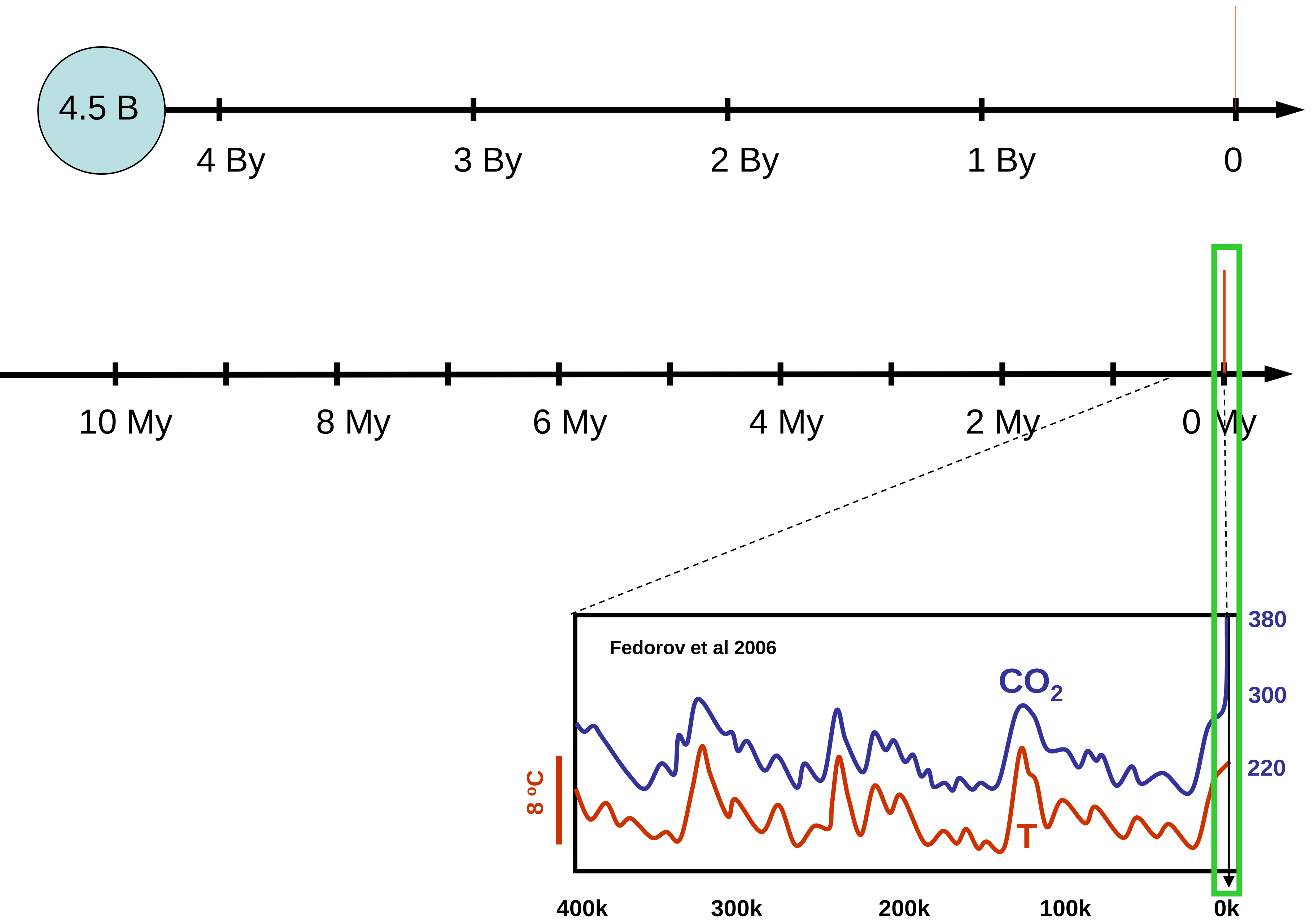
Efficiency in geotechnology? crushing<5% tunneling<< ants!

Geo-Centered Perspective: Time Scale

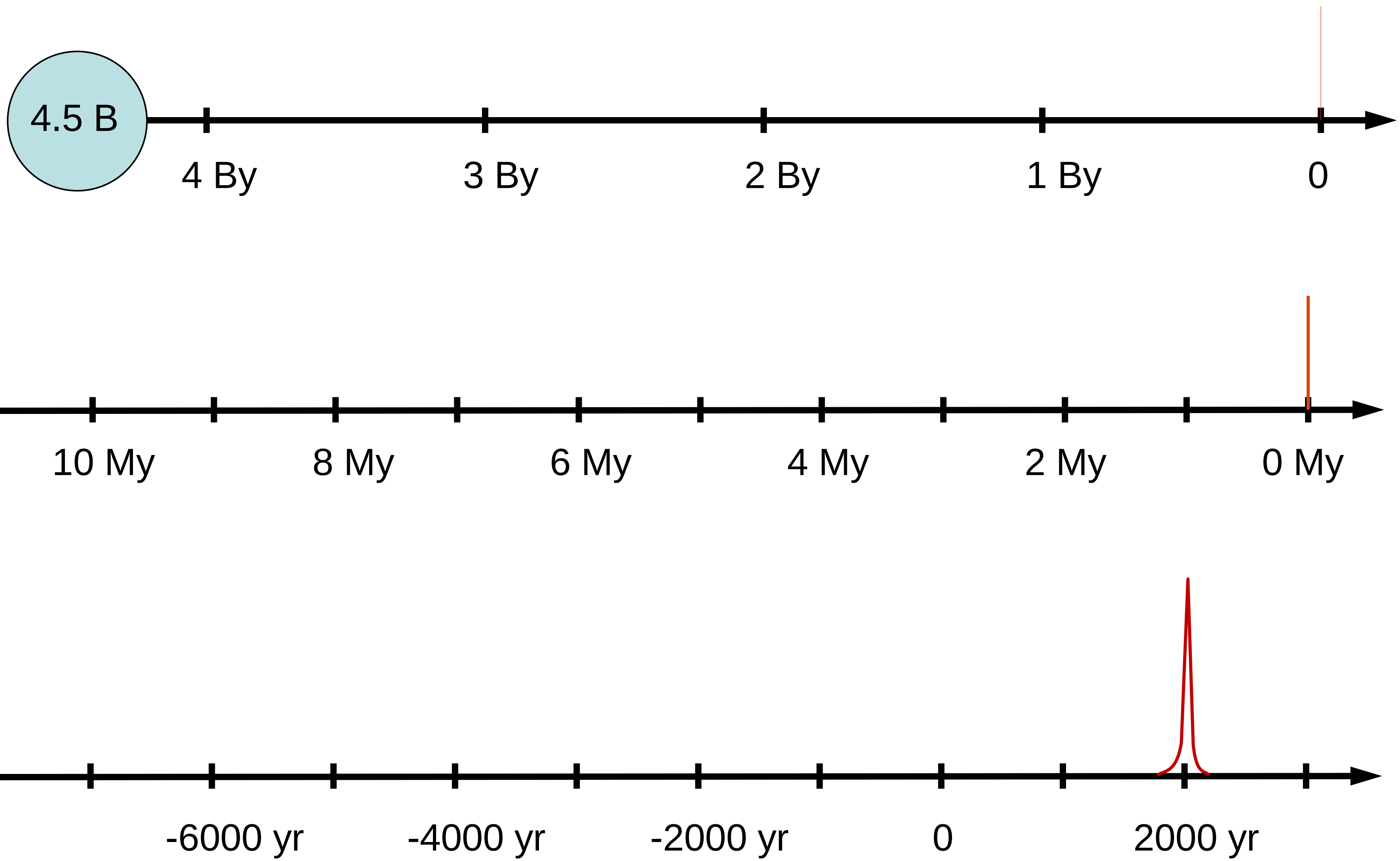



4.5 B
3.5 BYA:
bacteria
2.5 BYA:
O_2 atmosph
1.5 BYA:
plants
230-65 MYA:
dinosaurs
coal & petrol
4 By
3 By
2 By
1 By
0


4.5 B
4 By
3 By
2 By
1 By
0
10 My
8 My
6 My
4 My
2 My
0 My

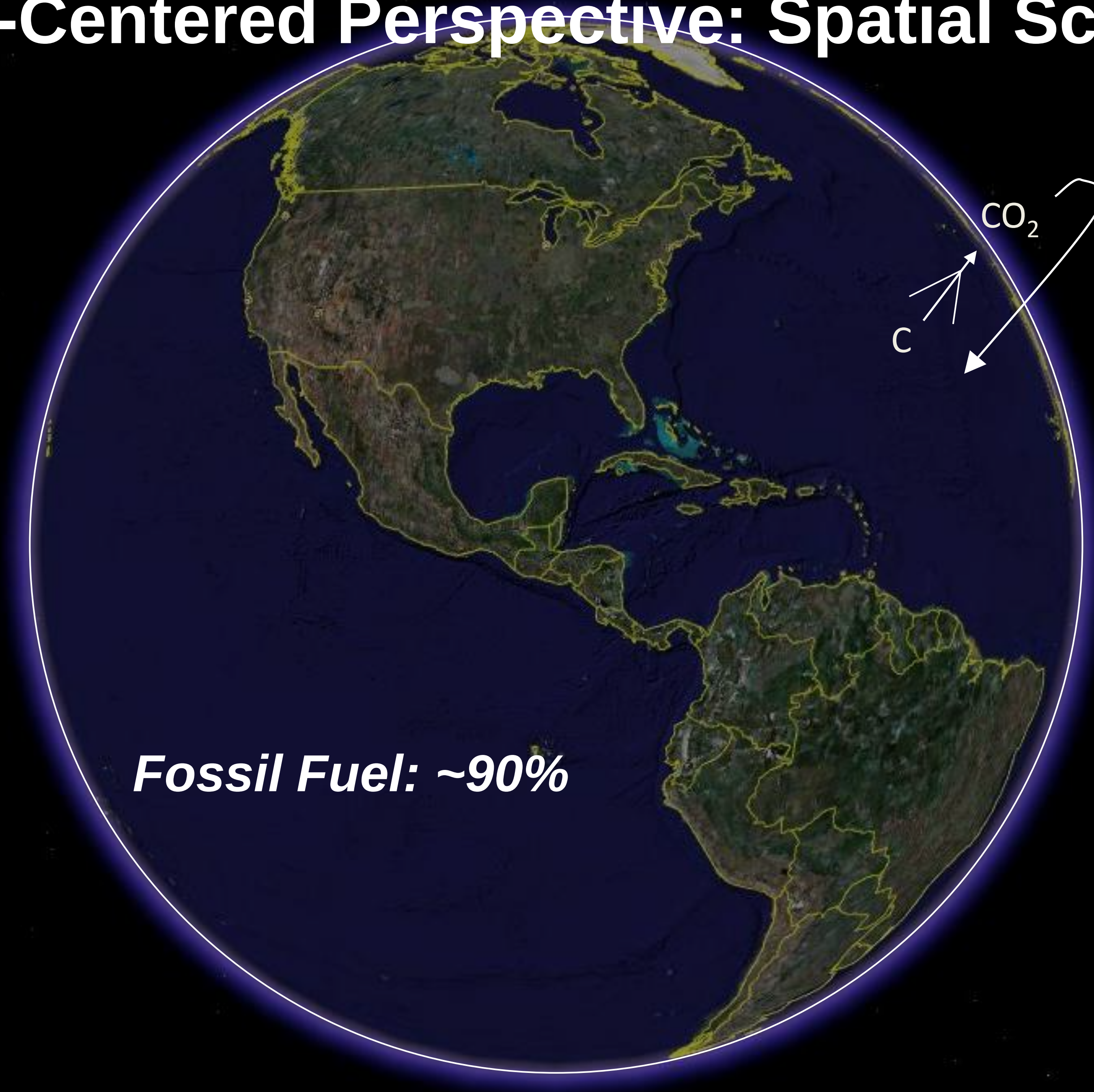


4.5 B
4 By
3 By
2 By
1 By
0
10 My
8 My
6 My
4 My
2 My
0 My
Fedorov et al 2006
CO2
T
8 °C
380
300
220
400k
300k
200k
100k
0k



History of fossil fuels: a δ-function

Geo-Centered Perspective: Spatial Scale



Energy Geotechnology

FOSSIL FUELS (C-BASED)			RENEWABLE	Nuclear
Petroleum	Gas	Coal	Wind Solar Biofuels Geo-T Tidal	
• fines & clogging •sand production • shale instability • EOR • heavy oil & tar sand	• gas hydrates • gas storage • low-T LNG found.	• characterization • optimal extraction • subsurface conv.	•periodic load • ratcheting	• engineered soils • decommission • leak detect • leak repair
• mixed fluid flow, percolation • contact angle & surface tension = $f(u_a)$				
GEOLOGICAL STORAGE				
CO_2 sequestration 10^4-10^5 yr BTHCM mineral dissolution ➔ shear faults, pipes			Energy Storage CAES, phase-change Cyclic HTCM	Waste storage 10^5 yr BTHCM
GEO-ENVIRONMENTAL REMEDIATION				
CONSERVATION				

• Hydro-electric: capacity almost saturated

Lessons Learned

Energy: critical for development

- High increase in demand in next decades
- Resources: C-economy
- Environmental implications

Geotechnology: Central Role

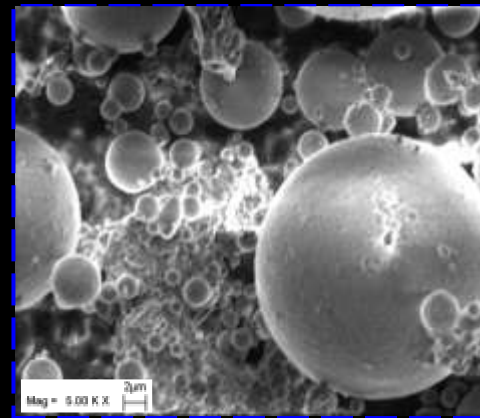
- Production, transport, conservation, waste
- Rich & complex phenomena - interwoven processes
- Urgency ….
- Fascinating !

Clays Fly Ash Sands

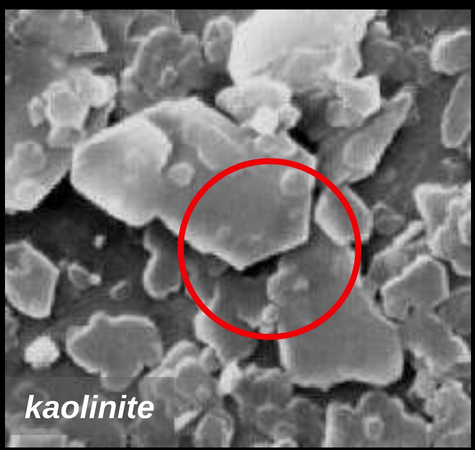
< 10 µm

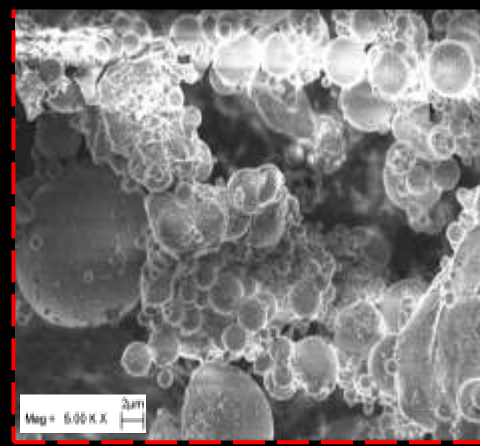
> 50 µm


illite
http://www.minersoc.org
c.V Spot Det WD 20 µm
.0 kV 4.0 SE 31.6 Platy illite

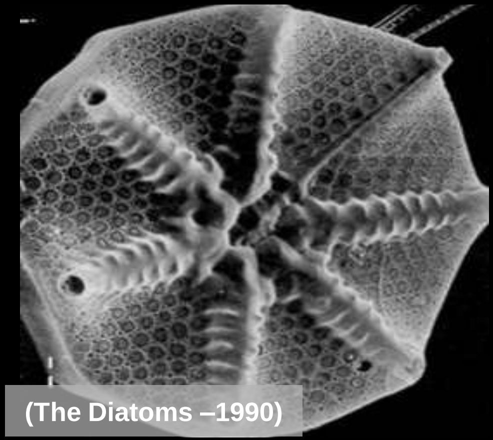

Mag = 5.00 K X
2µm

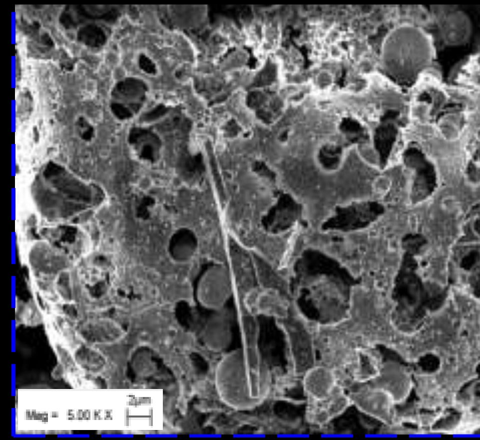

Ottawa sand


kaolinite


Mag = 5.00 K X
2µm


crushed granite

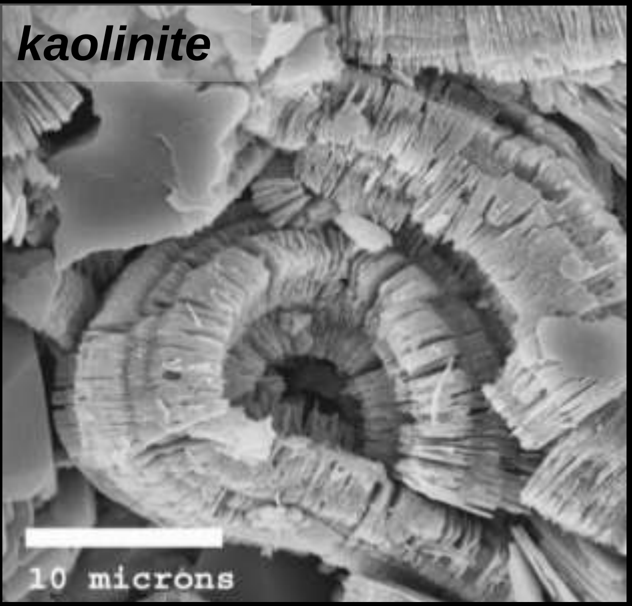

(The Diatoms –1990)

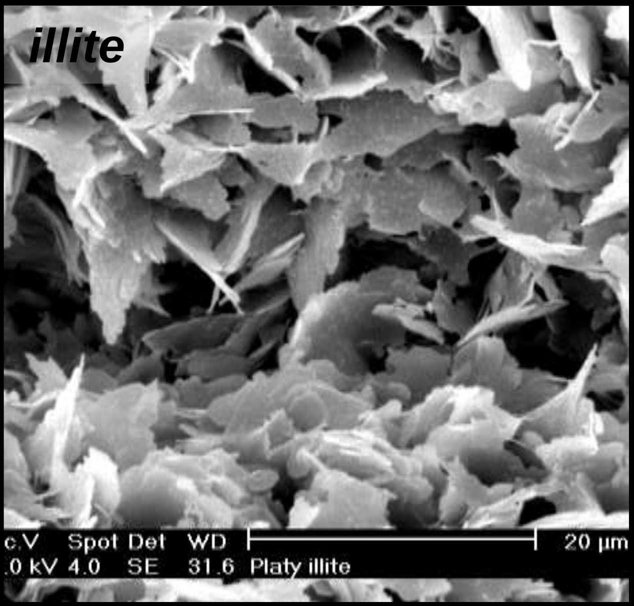

Mag = 5.00 K X
2µm

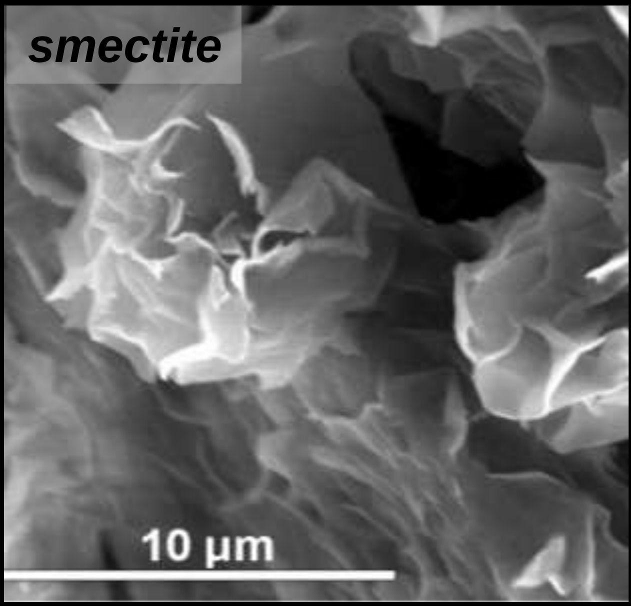

sintered lead

Clay Minerals: Very High Specific Surface

http://www.minersoc.org



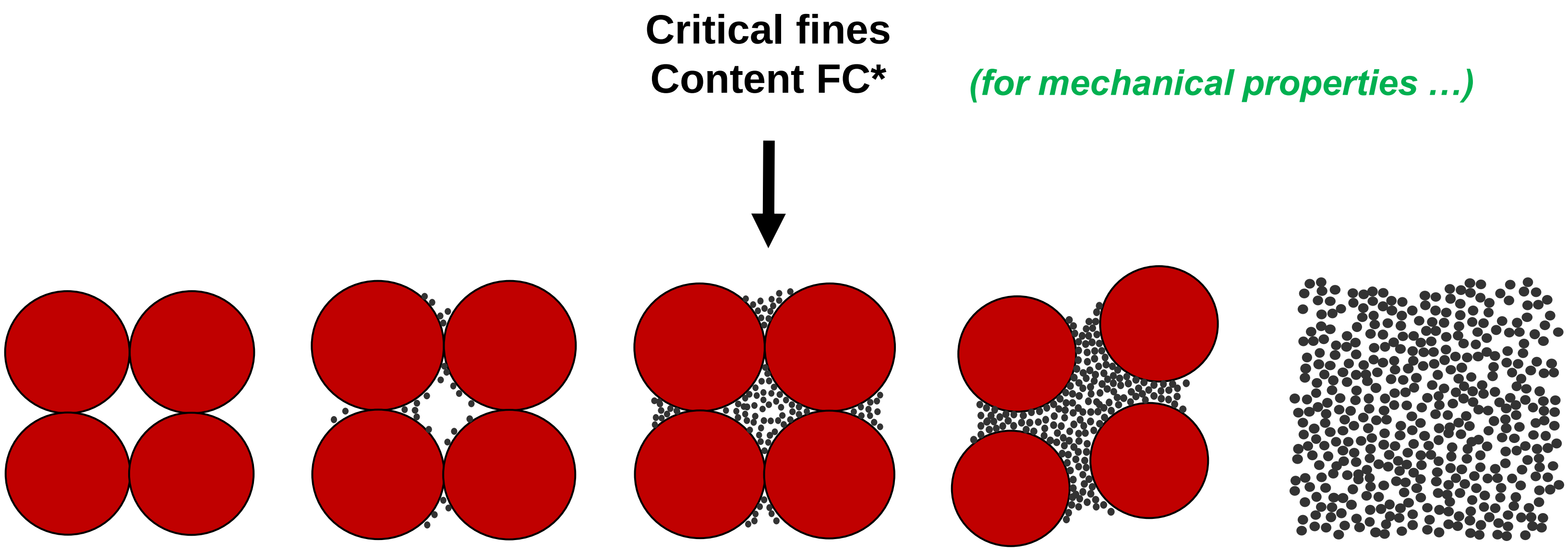




	kaolinite	illite	smectite
	S_s= 10 m^2/g	S_s= 50 m^2/g	S_s= 300 m^2/g
for n=0.2	d_{pore}=10 nm	d_{pore}=2 nm	d_{pore}=0.3 nm

Implications: (1) small pores; (2) very low k_{gas}; (3) adsorbed gas (clay); (4) high capillary entry; (5) low gas recovery; (6) low bioactivity

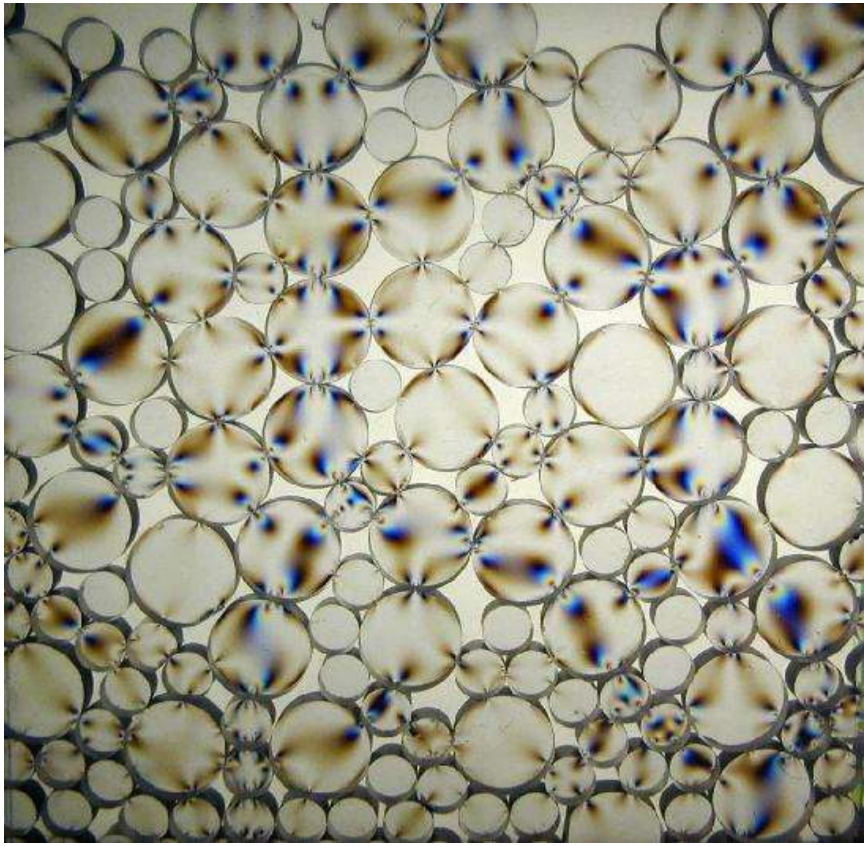
Grain Size Distribution: The Role of Fines



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

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

Particle Forces

Skeletal	
Weight	
Buoyant	
Hydrodynamic	
Capillary	
Electrical	
attraction	
repulsion	
Cementation	

Particle Forces

Skeletal

Weight

Buoyant

Hydrodynamic

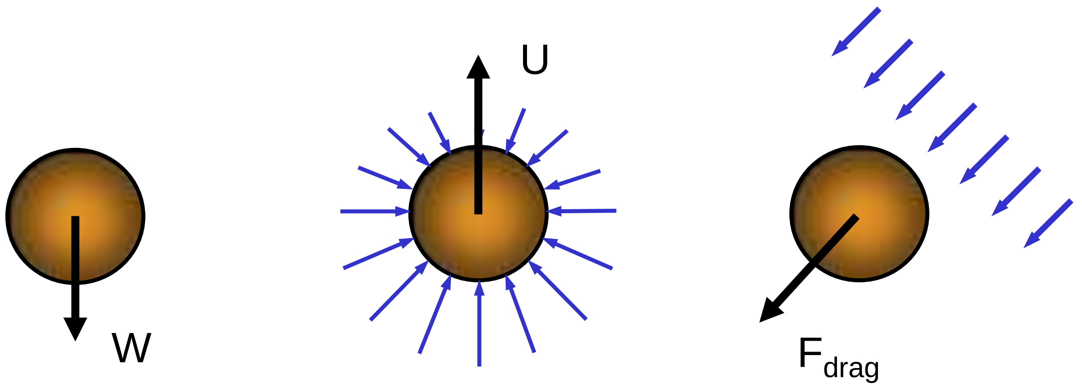
Capillary

Electrical

attraction

repulsion

Cementation



Particle Forces

Skeletal

Weight

Buoyant

Hydrodynamic

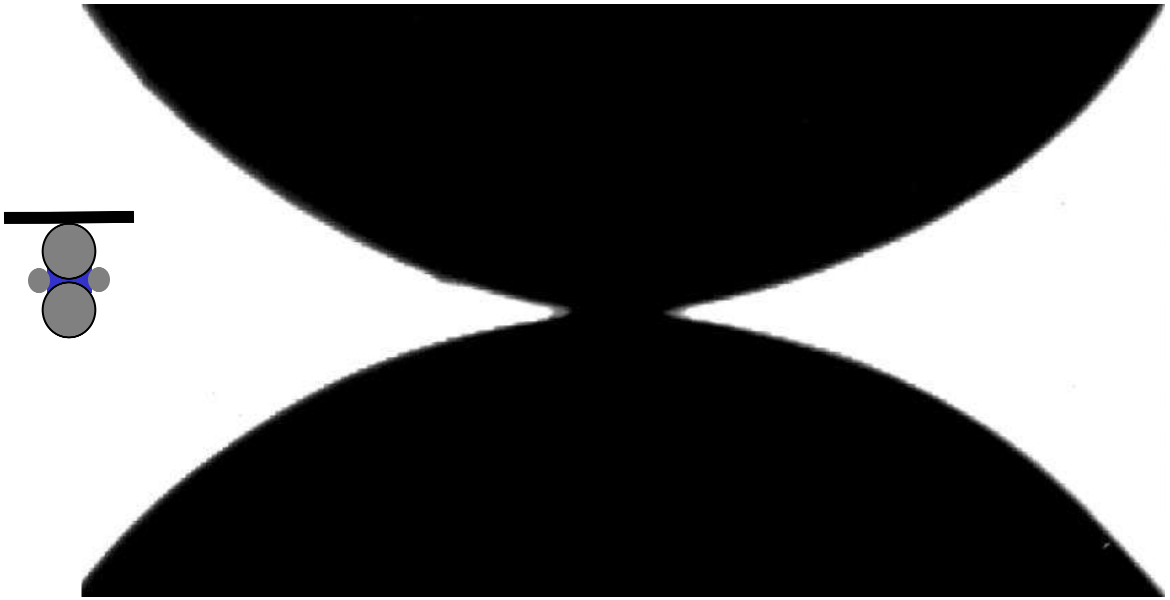
Capillary

Electrical

attraction

repulsion

Cementation



Particle Forces

Skeletal

Weight

Buoyant

Hydrodynamic

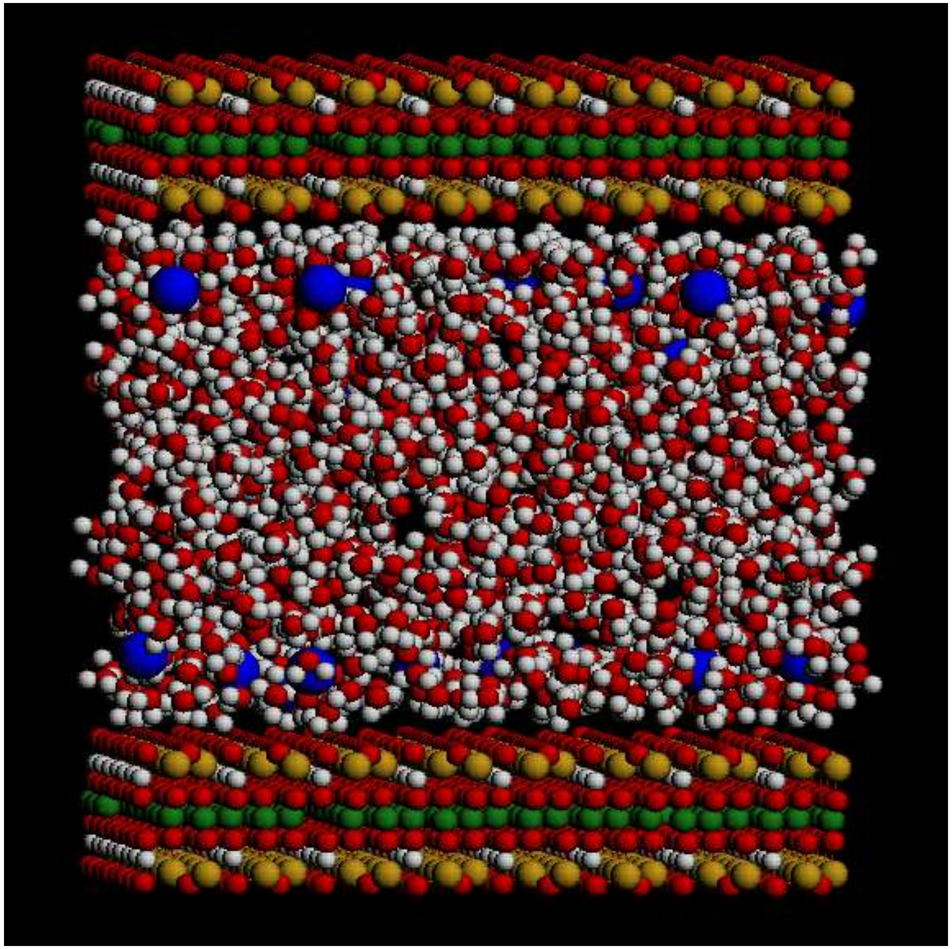
Capillary

Electrical

- attraction
- repulsion

Cementation

Laponite **1200 H_2O 24 Na^+**



(N. Skipper - UCL)

Particle Forces

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

Particle Forces

Skeletal

Weight

Buoyant

Hydrodynamic

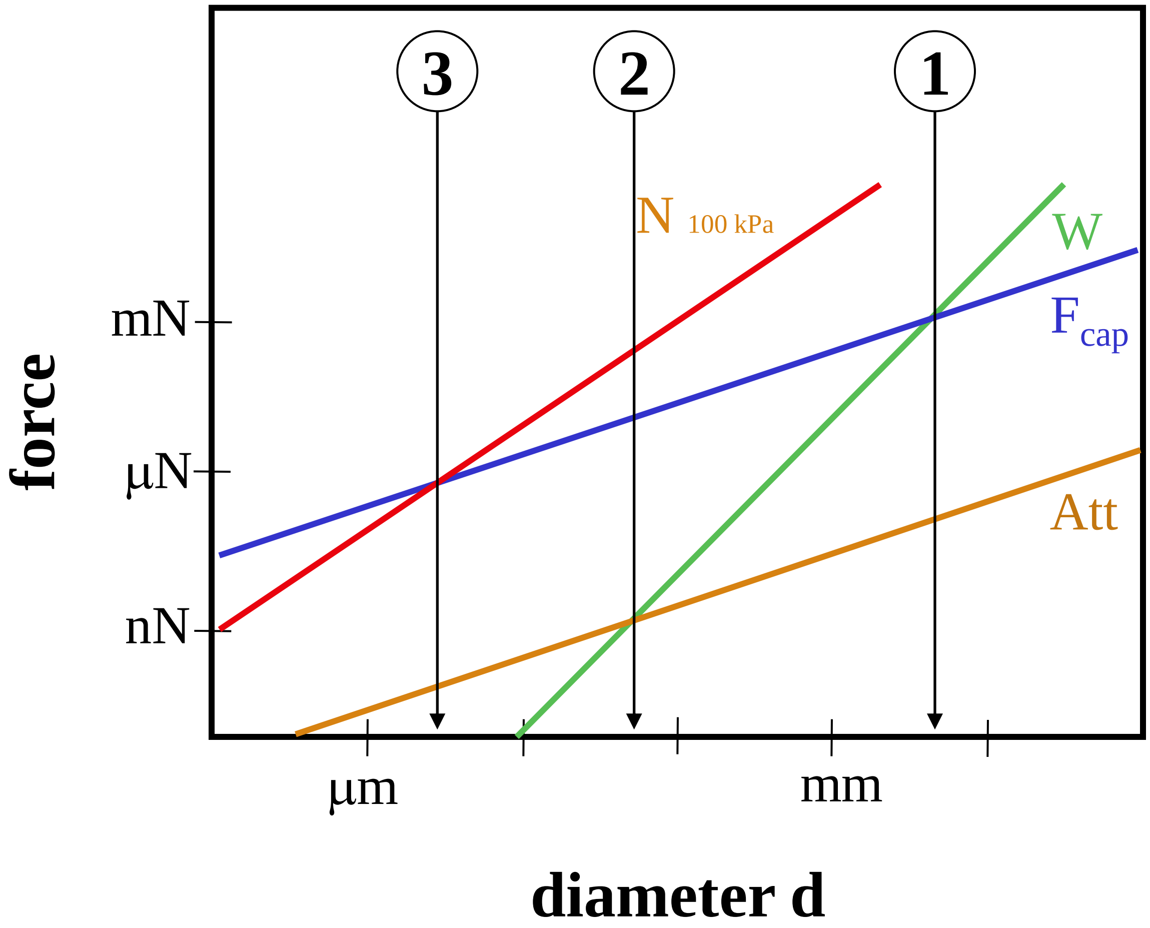
Capillary

Electrical

attraction

repulsion

Cementation



Kingston Fossil Plant – 22 December 2008

Lessons Learned

Soil Properties and Behavior

- Soils: particulate media
- Particle-level forces
- Transition: d ~10μm

Energy Geotechnology

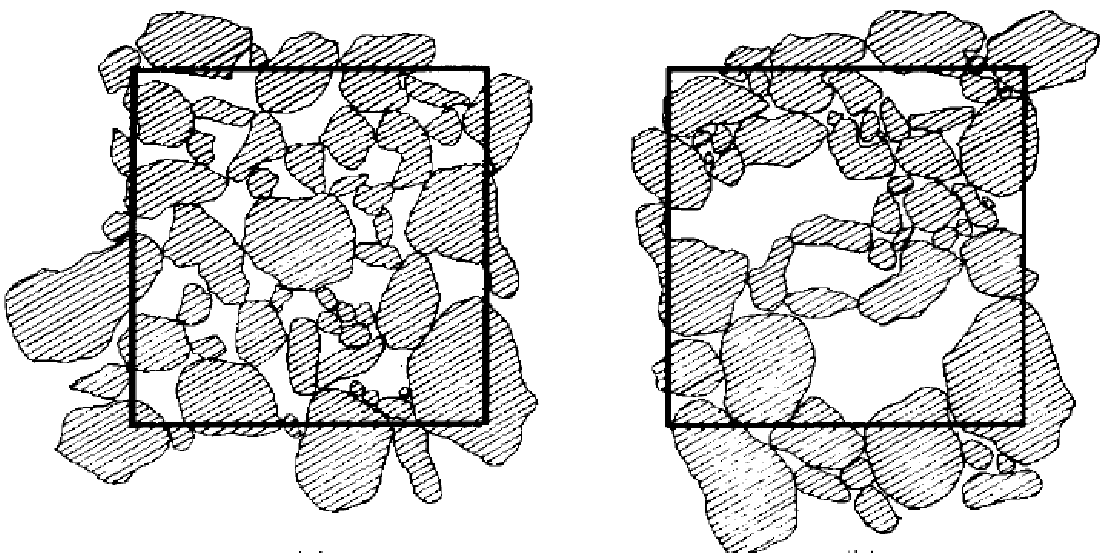
- Fly ash ponds
- Resource distribution
- Resource recovery
- Fines migration and formation damage
- Development of discontinuities – Fractures and lenses
- Mixed fluid conditions (oil-water; gas-water)
- Gas migration
- …

Hydraulic Conductivity
&
Fines Migration

Dynamic penetration resistance and the prediction of the compressibility of a fine-grained sand—a laboratory study

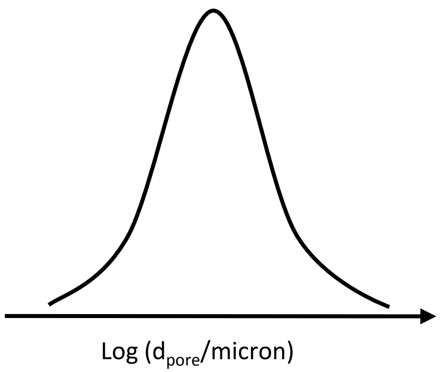
C. R. I. CLAYTON, M. B. HABABA and N. E. SIMONS (1985). *Géotechnique* **35**, No. 1, 19–31

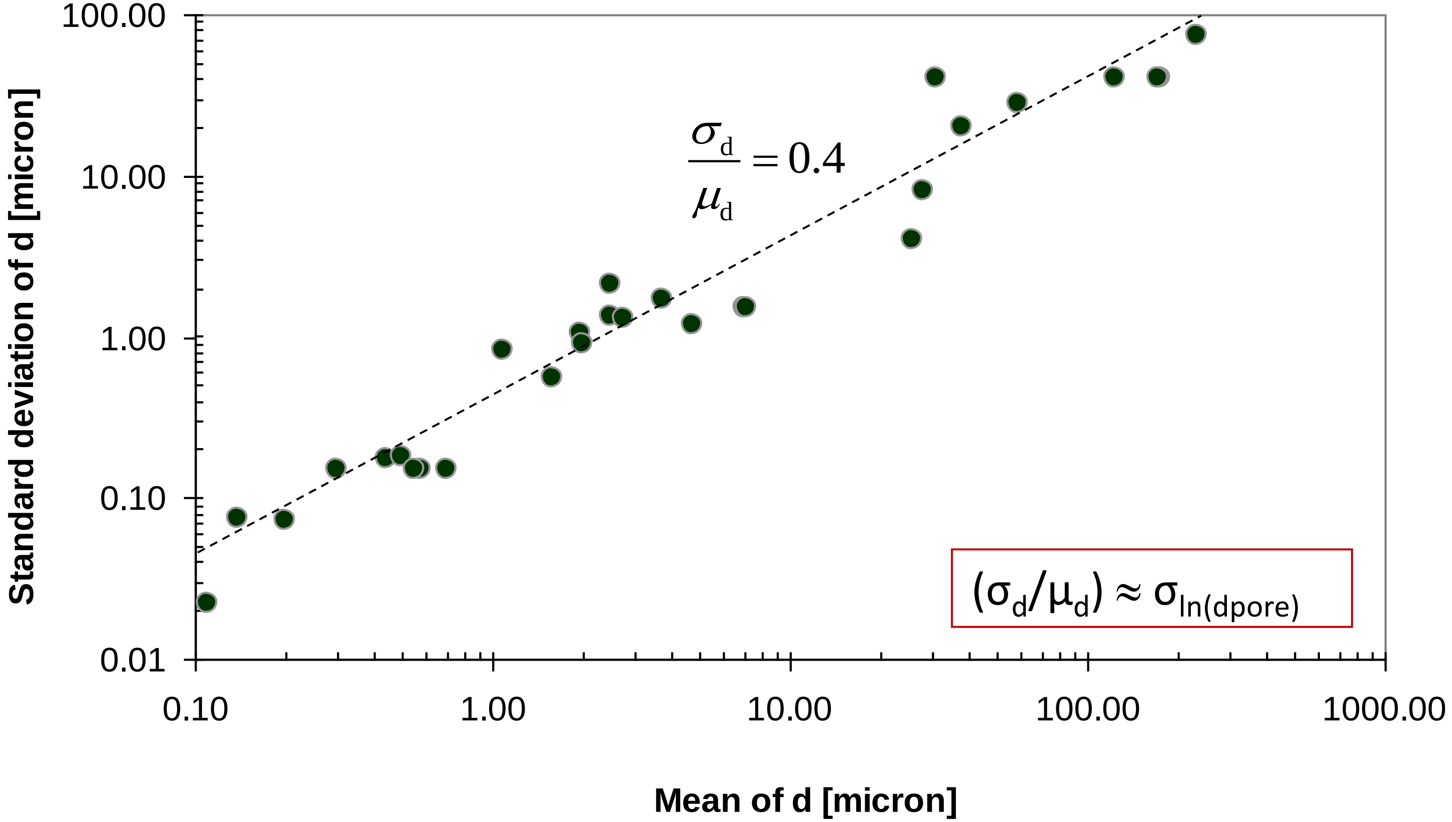
Professor G. A. Leonards, A. Alarcon, J. D. Frost, Y. E. Mohamedzein, J. C. Santamarina, S. Thevanayagam, J. E. Tomaz and J. L. Tyree, *Purdue University*



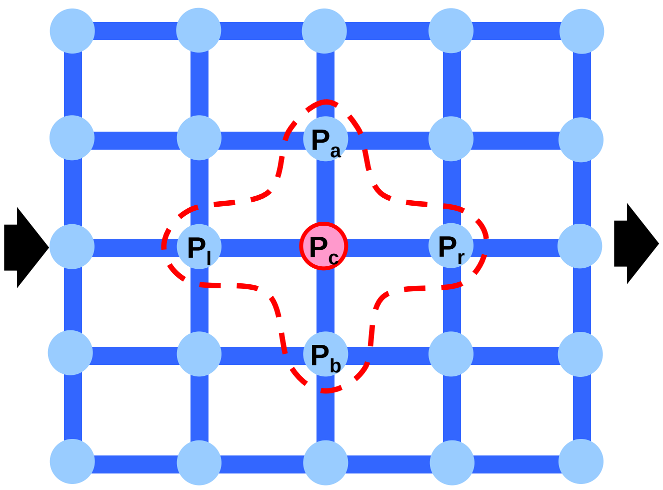
fabric *inherent and stress-induced anisotropy* *particle & pore-scale*

Pore Size Distribution





Network Models – Upscaling



Poiseuille's Eq. $$q = \frac{\pi R^4}{8\eta \Delta L} \Delta P \quad \left(\alpha = \frac{\pi R^4}{8\eta \Delta L} \right)$$

Mass Balance at Nodes

$$0 = \sum q_c$$

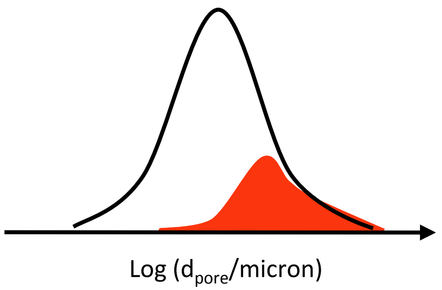
$$0 = \alpha_a \left(P_a - P_c \right) + \alpha_b \left(P_b - P_c \right) + \alpha_r \left(P_r - P_c \right) + \alpha_l \left(P_l - P_c \right)$$

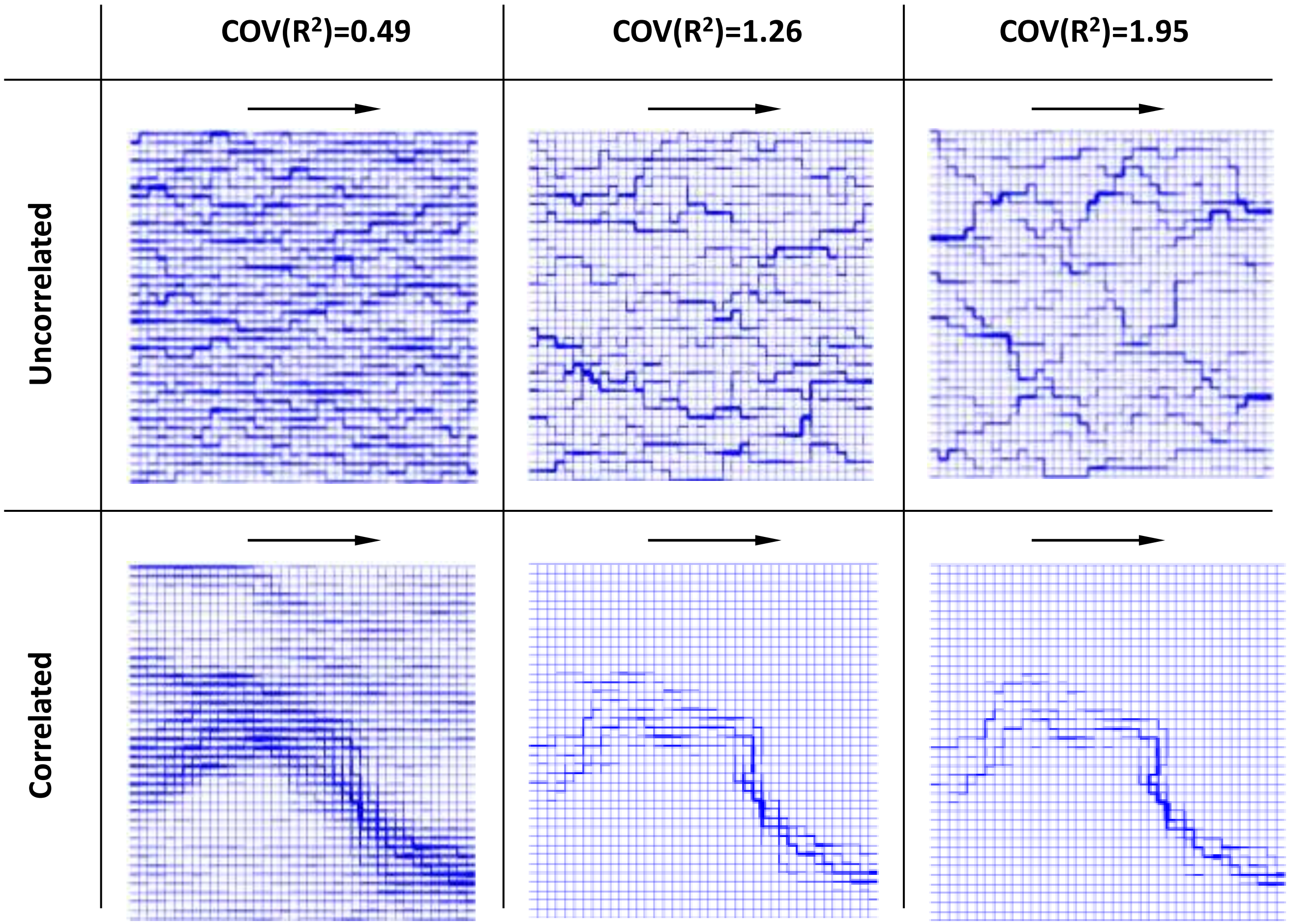
$$P_c = \frac{\alpha_a P_a + \alpha_b P_b + \alpha_r P_r + \alpha_l P_l}{\left(\alpha_a + \alpha_b + \alpha_r + \alpha_l \right)}$$

System of Equations

$$\underline{B} = \underline{\underline{A}}\, \underline{P} \quad \text{then} \quad \underline{P} = \underline{\underline{A}}^{-1} \underline{B}$$

Spatially Correlated Porosity





J. Jang

Particle Forces

Skeletal

Weight

Buoyant

Hydrodynamic

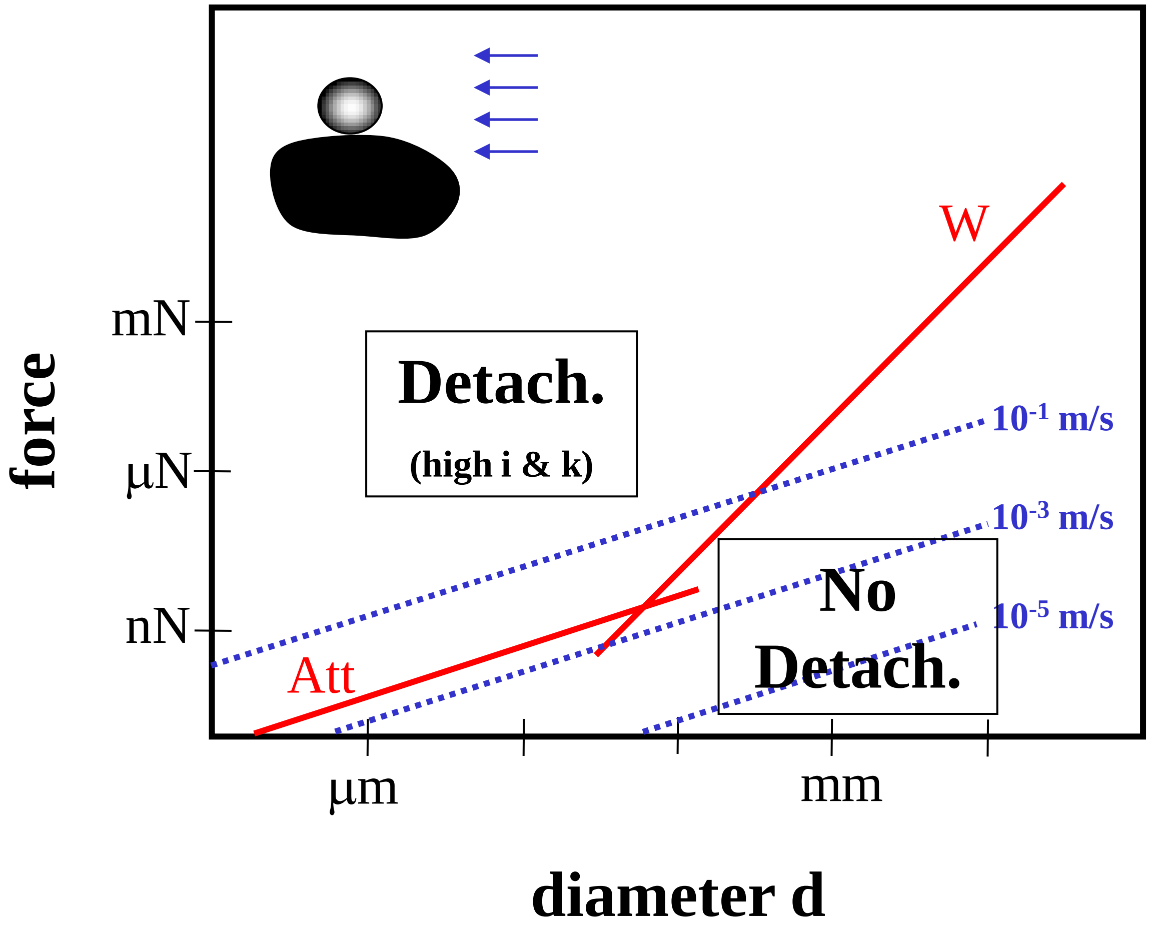
Capillary

Electrical

attraction

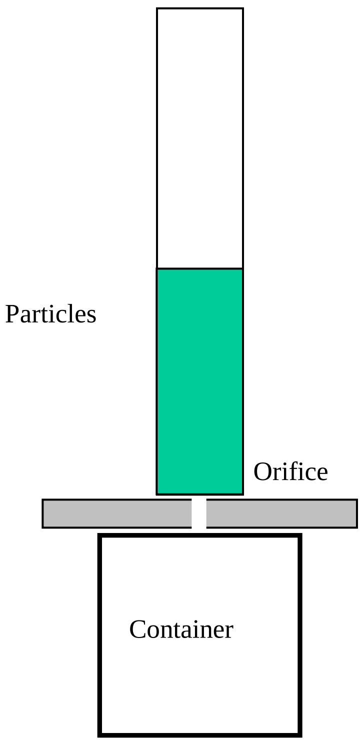
repulsion

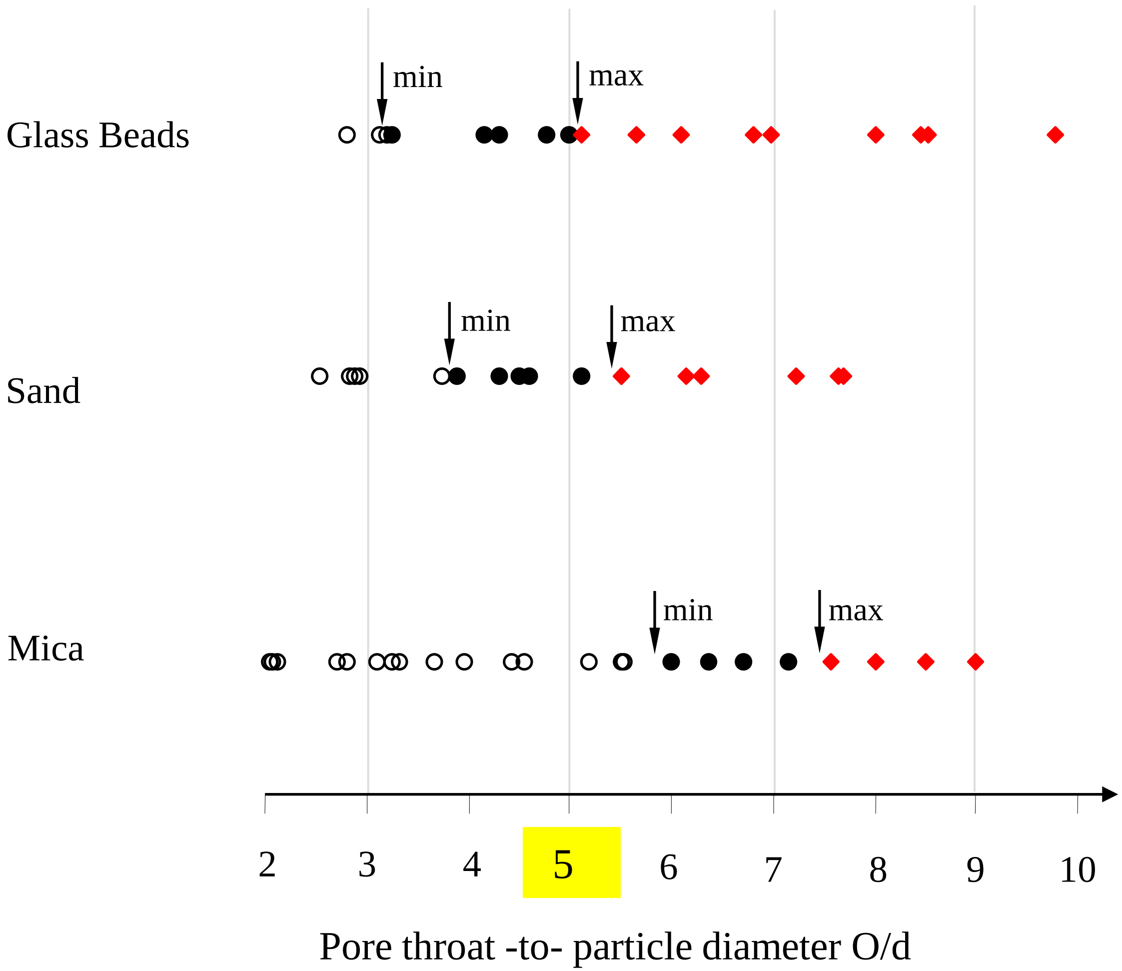
Cementation



Bridging

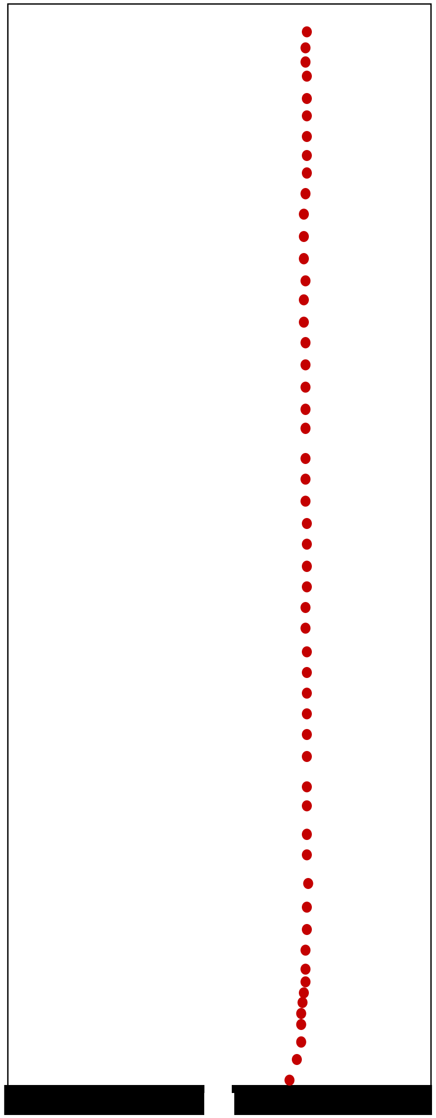
Bridging Conditions



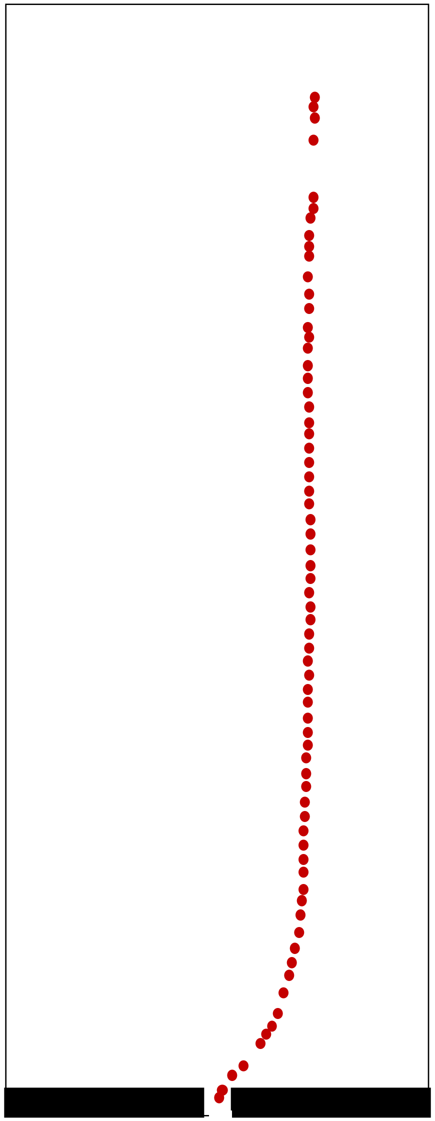


J. Valdes

Grain-Fluid paths



$\rho_s / \rho_f = 3.2$



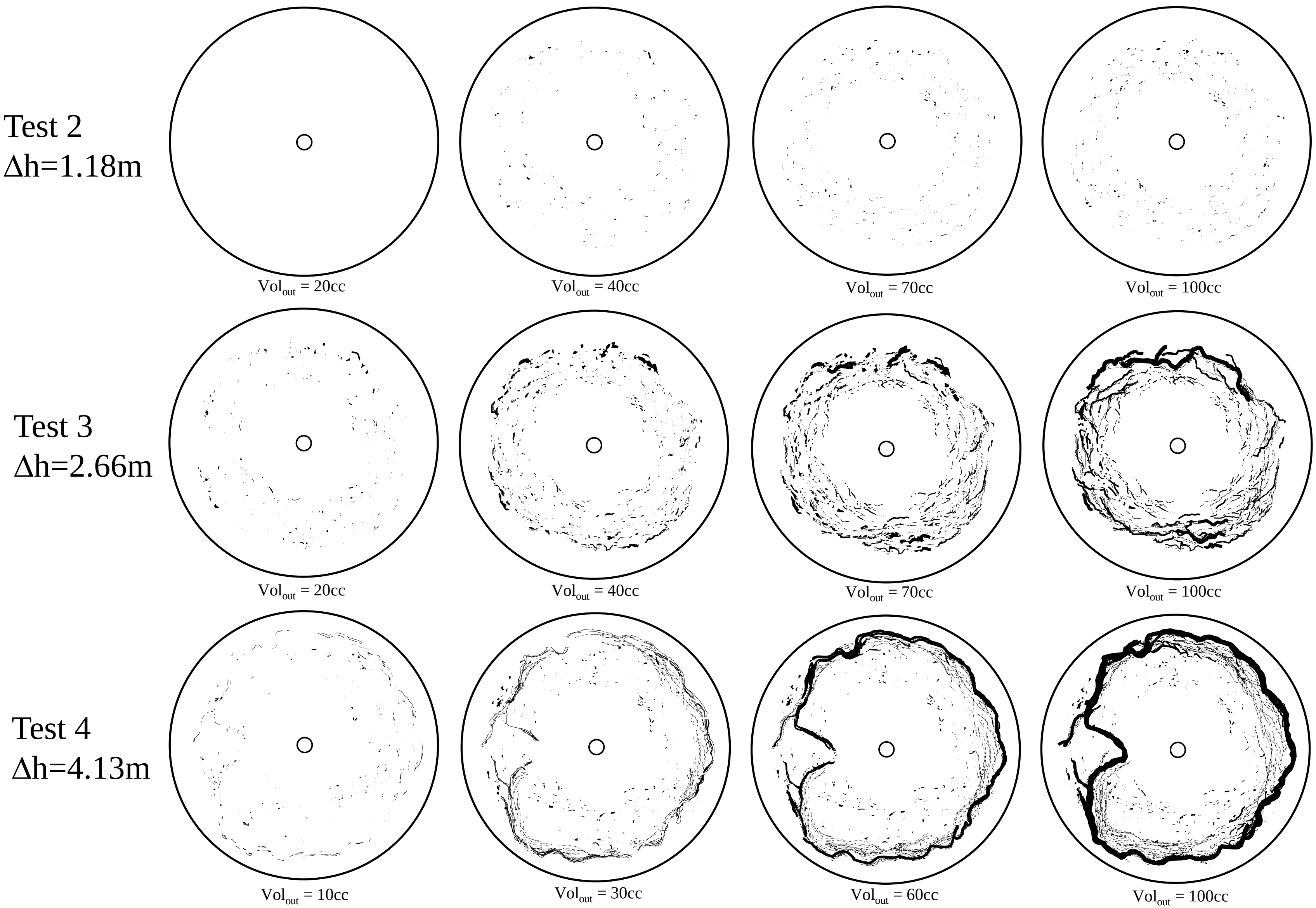
$\rho_s / \rho_f = 1.3$

Deviation enhanced:

$\boldsymbol{\rho_s / \rho_f} \uparrow$

ec $\uparrow$

Clogging in radial flow



Lessons Learned

Soil Properties and Behavior

Inherent: pore size distribution

Emergent: fluid flow localization ➔ reactive fluid transport ?

Fines migration ➔ retardation ➔ bridging

Emergent: clogging ring at characteristic length scale

Energy Geotechnology

Oil and gas recovery

Geothermal

CO_2 injection (….but different)

Discontinuities

GAL *Cracks*
Weak seams

3460 March, 1963 SM 2

Journal of the

SOIL MECHANICS AND FOUNDATIONS DIVISION

Proceedings of the American Society of Civil Engineers

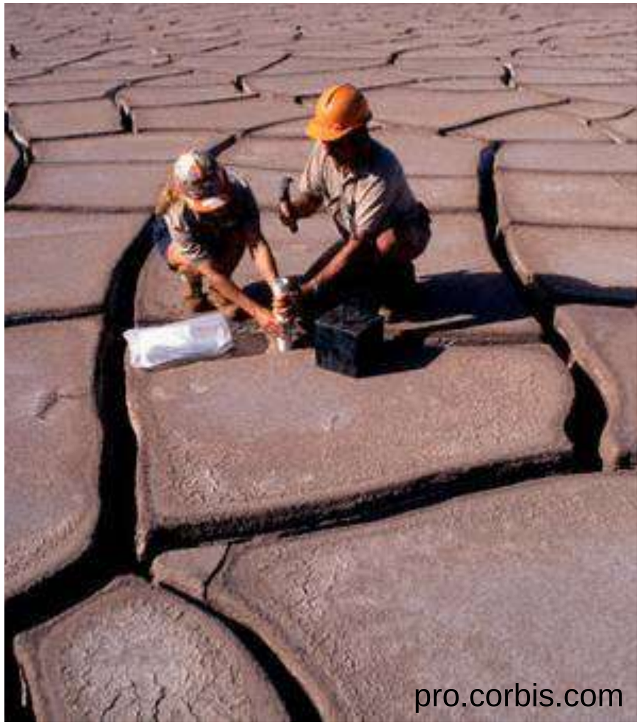
FLEXIBILITY OF CLAY AND CRACKING OF EARTH DAMS

By G. A. Leonards,[1] F. ASCE, and J. Narain,[2] M. ASCE

1965 ASCE Norman Medal

Desiccation Cracks

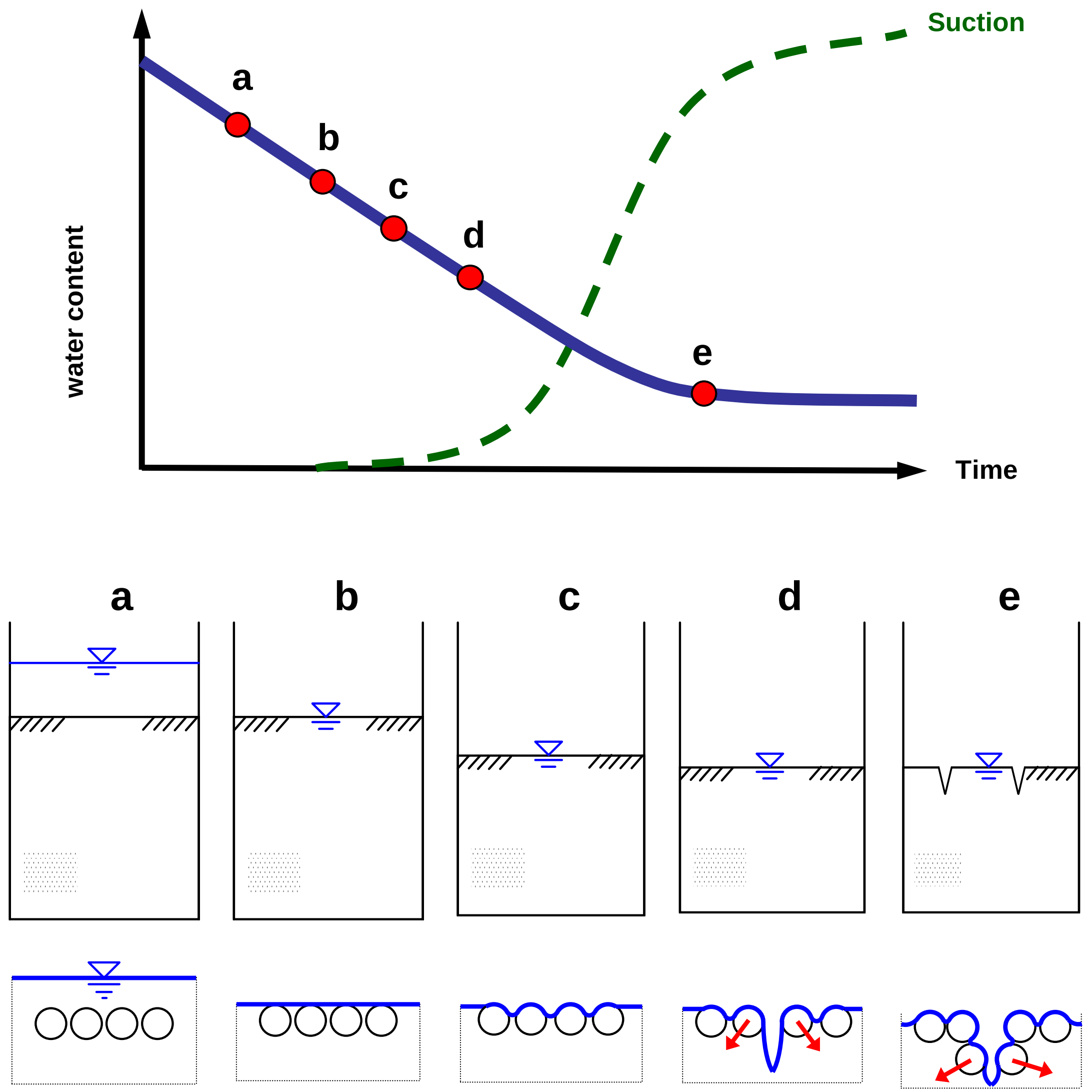
cm



Surface Tension

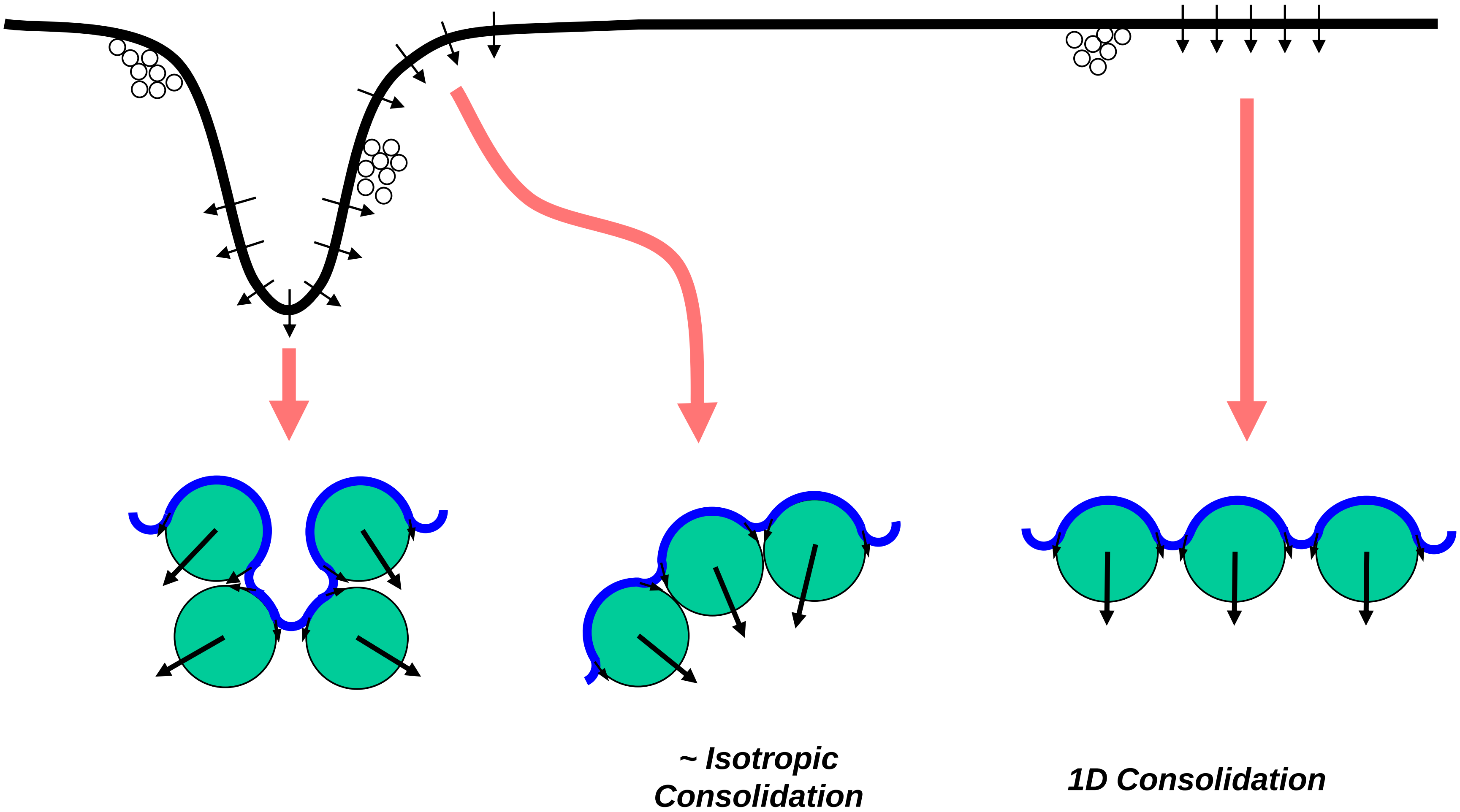
BBC News In pictures Visions of Science.jpg

Desiccation Cracks - Evolution



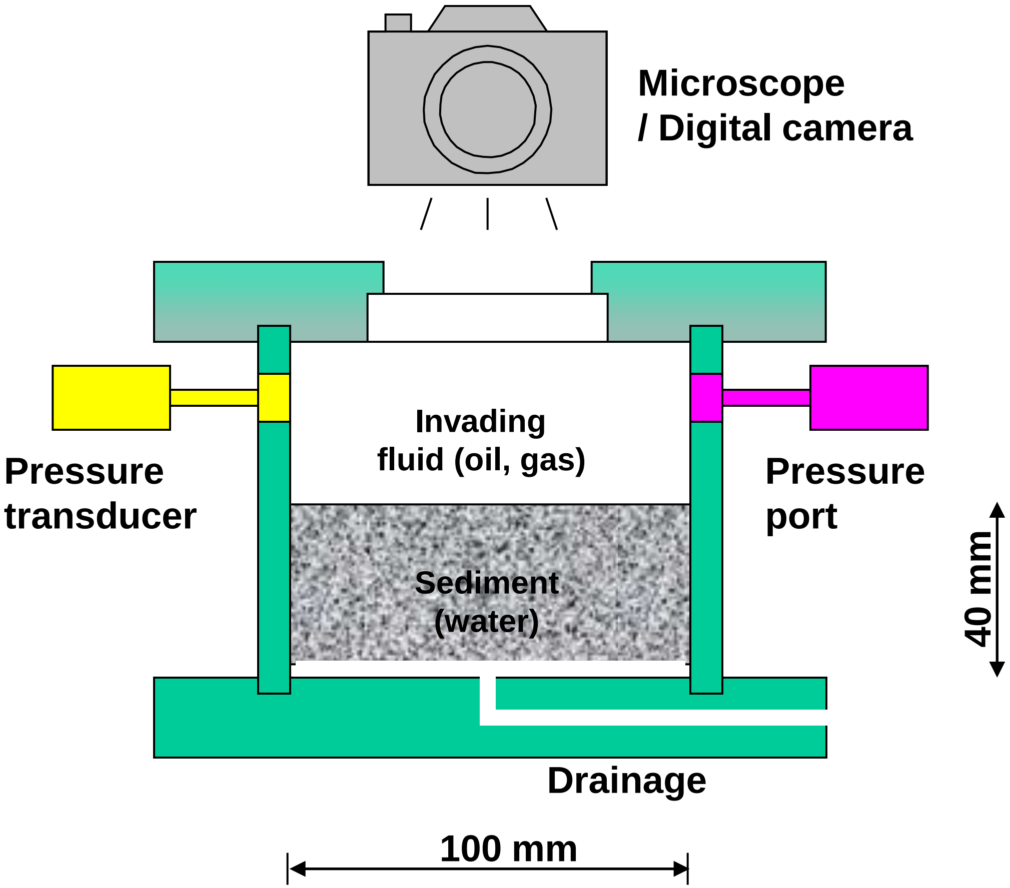
Desiccation Cracks

Desiccation Crack: Capillary Forces

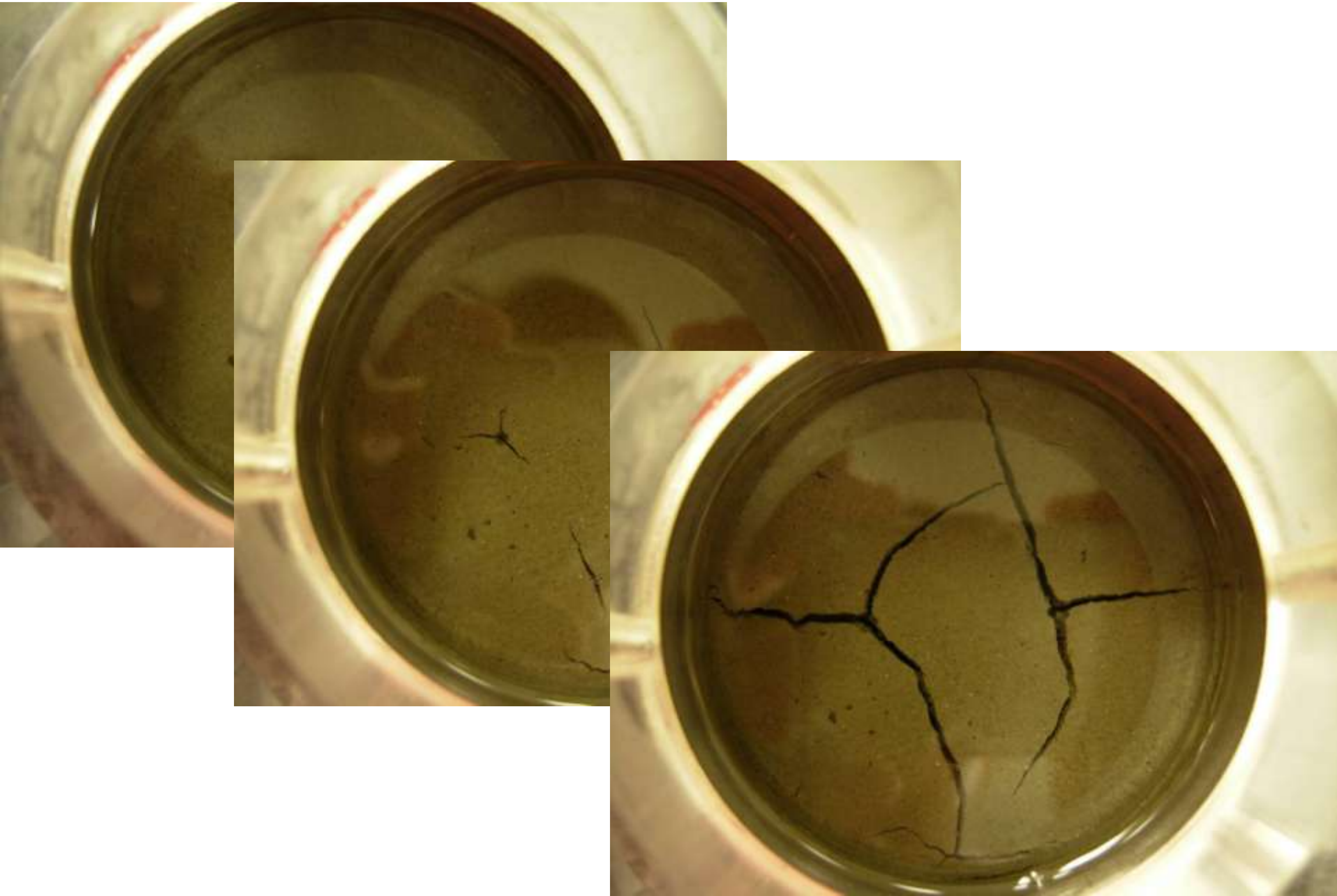


Soil is in compression EVERYwhere

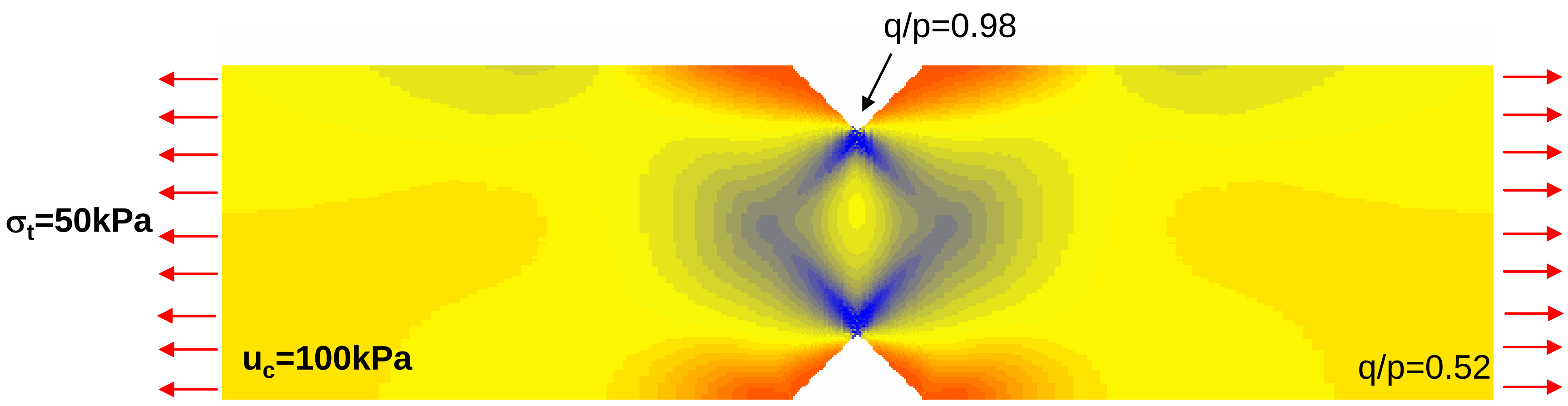
Forced Invasion of Immiscible Fluid

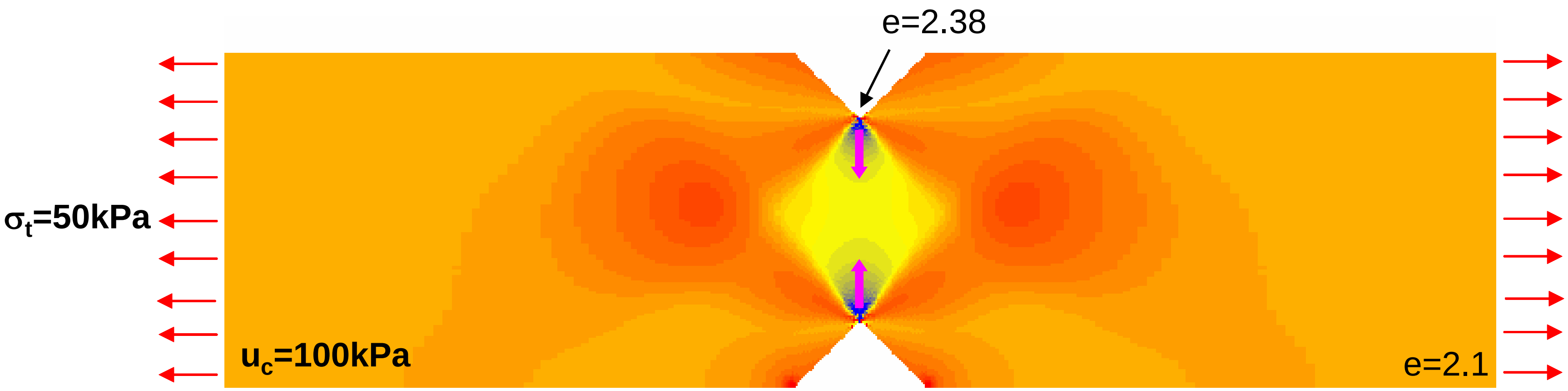


Forced Fluid: Oil



Apparent Tensile Strength





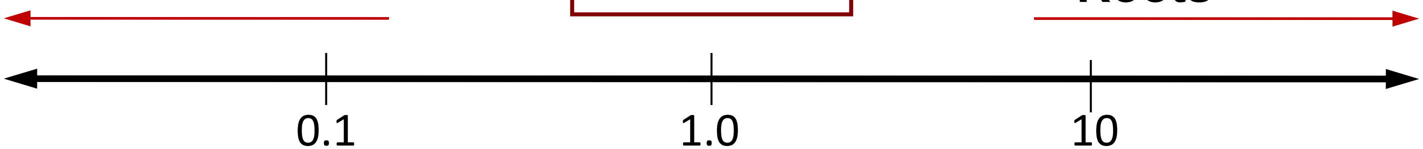
$$\sigma_T \leq u_0 \frac{2\sin(\phi')}{1+\sin(\phi')}$$

Invasion vs. Open-mode Discontinuities

Invasion
Fluid invasion
Crystal growth in pores

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

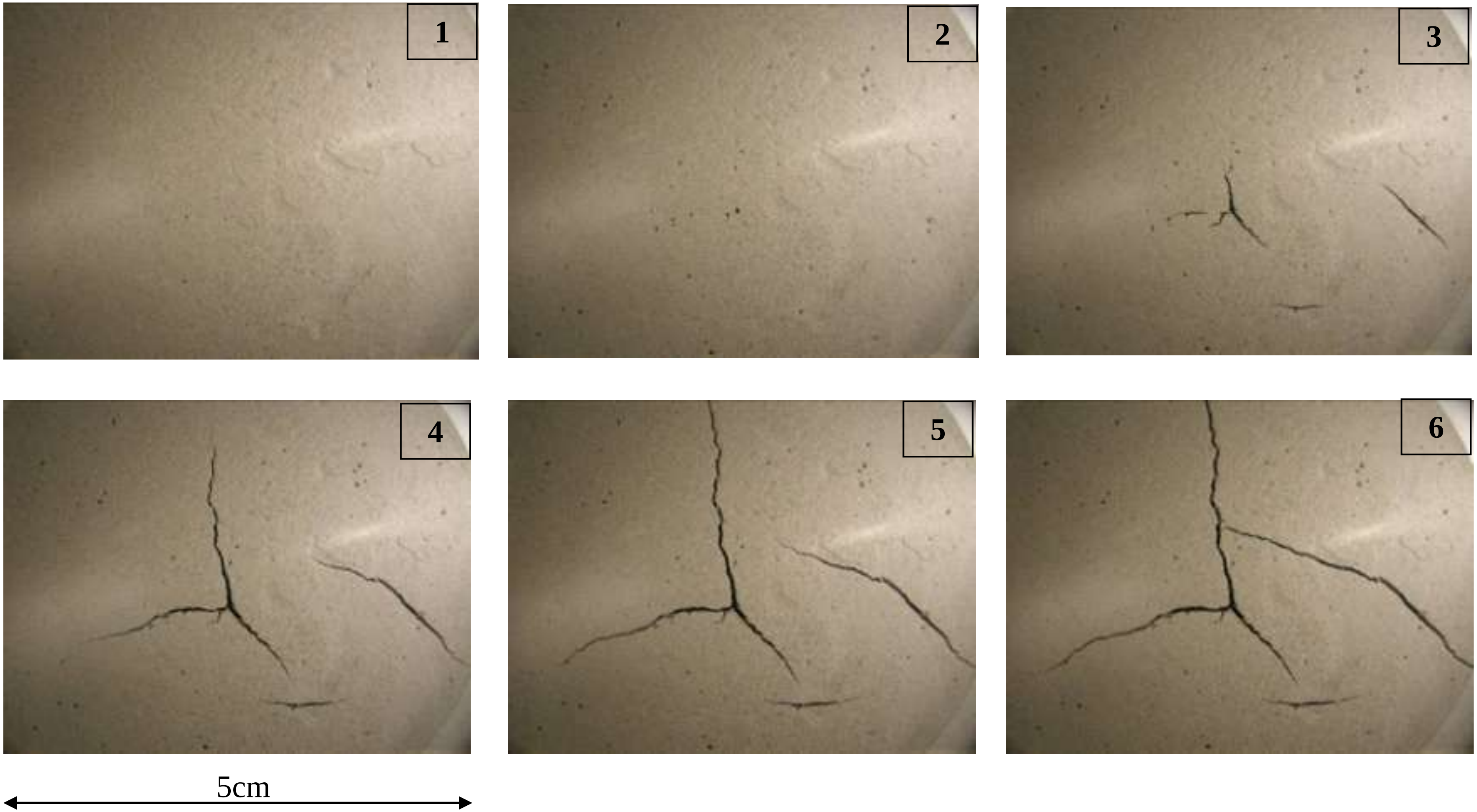
DISCONTINUITIES
Lenses
Fractures
Roots



coarse grained soils
high effective stress

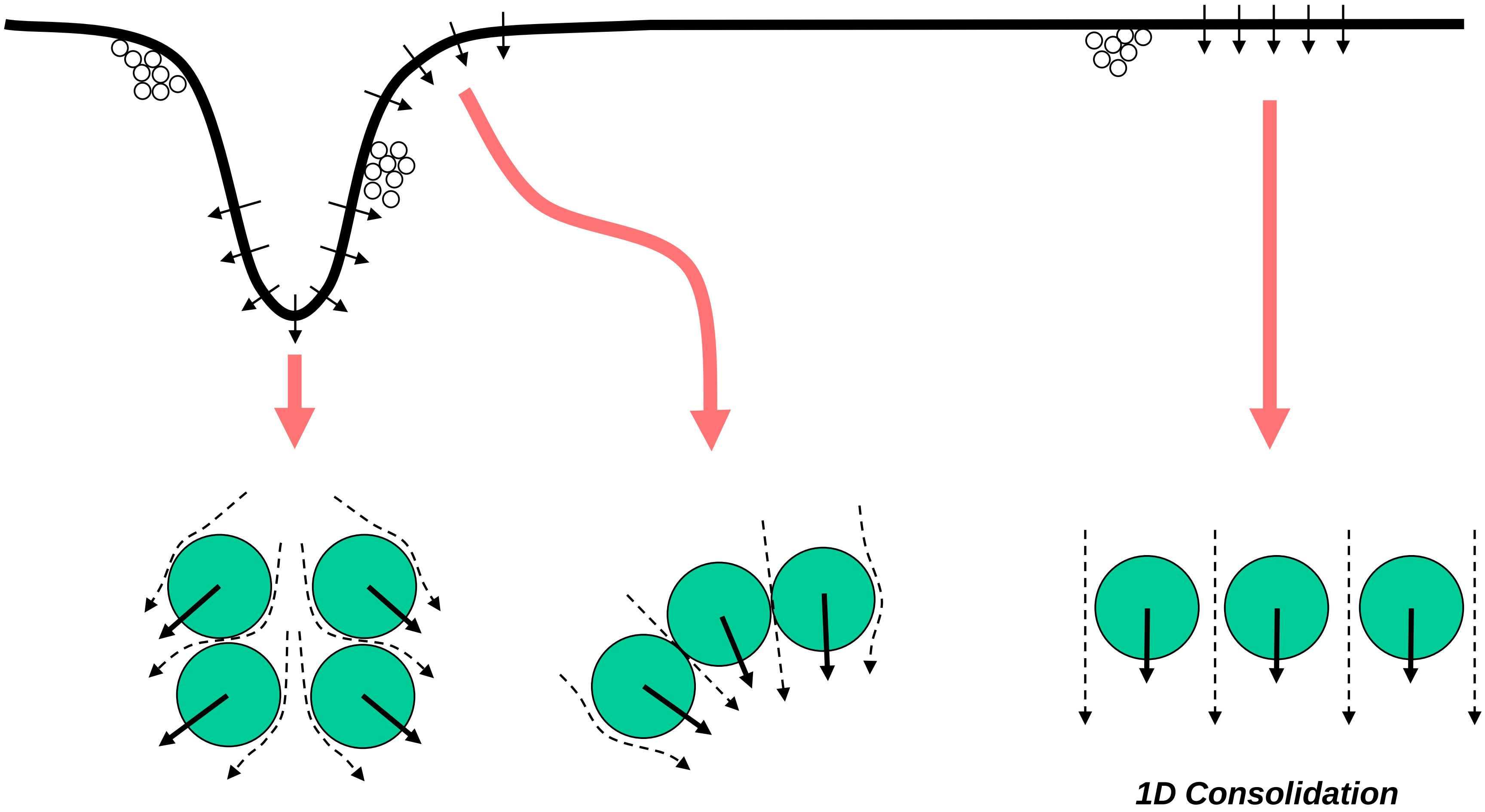
fine grained soils
low effective stress

Forced Miscible Fluid: Hydraulic Fracture



Hosung Shin

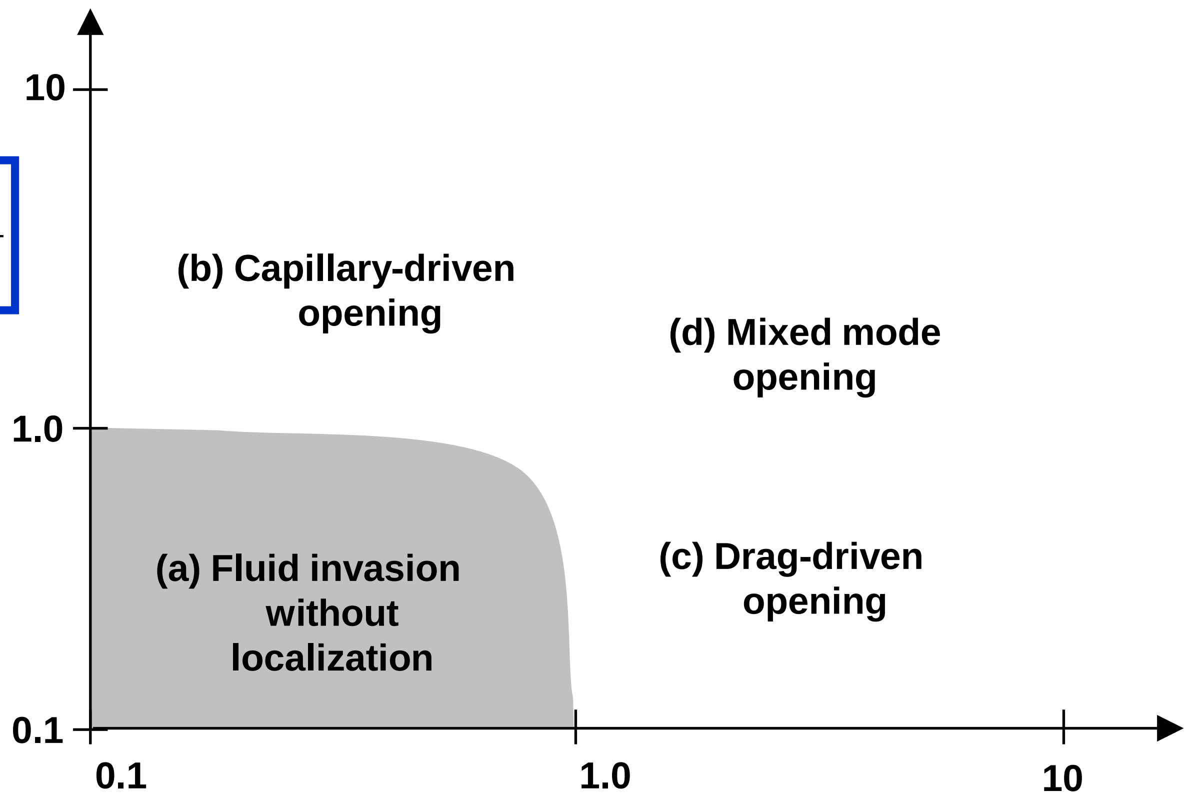
Hydraulic Fracture: Seepage Drag Forces



Soil is in compression EVERYwhere

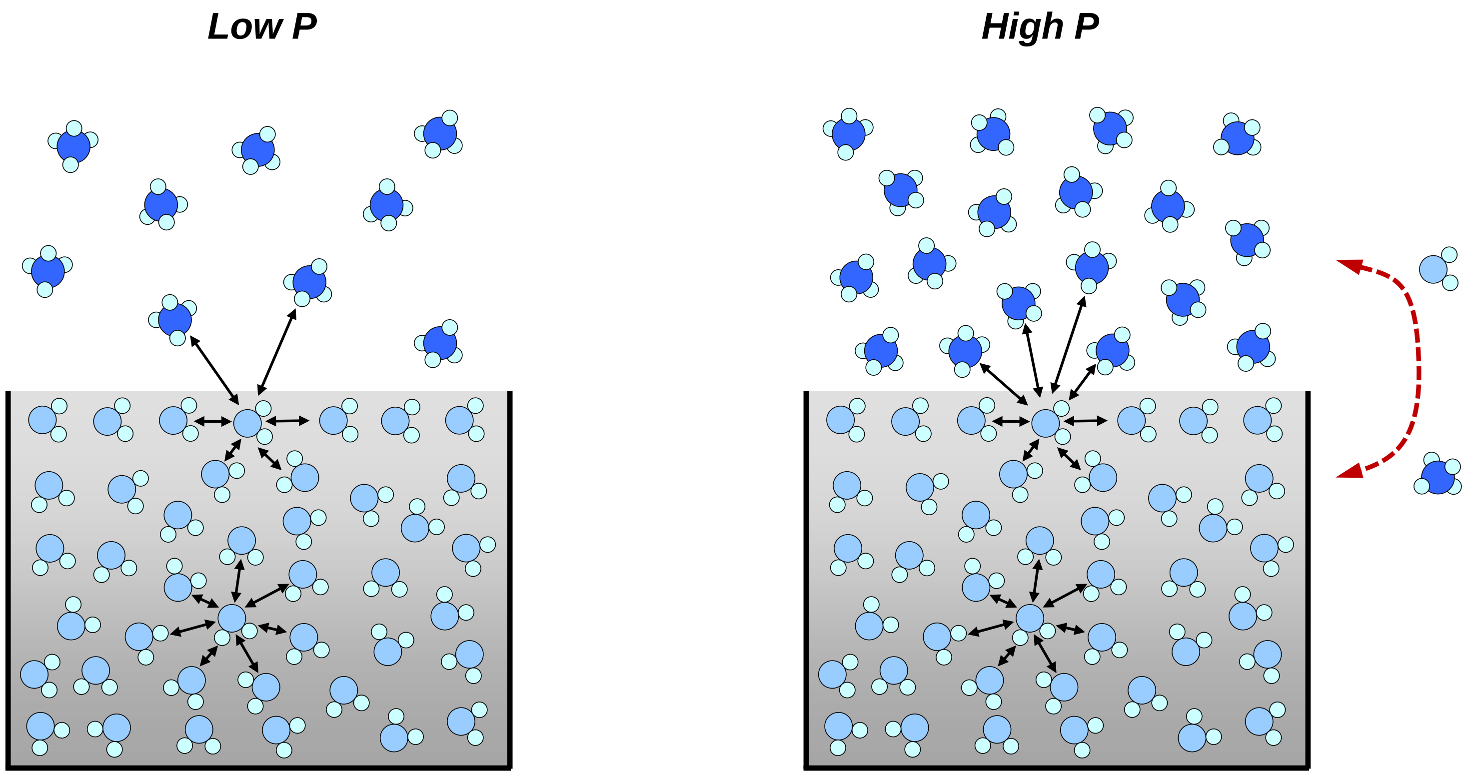
Miscible and/or Immiscible Fluid Invasion

$$\frac{F_{cap}}{N} = 2\pi \frac{T_{LV}}{\sigma' d}$$

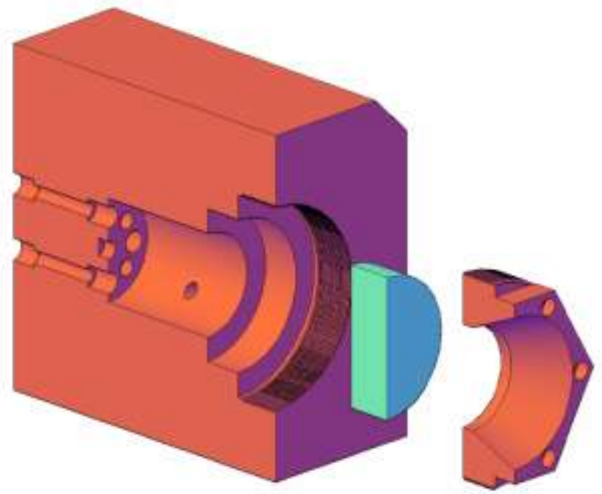


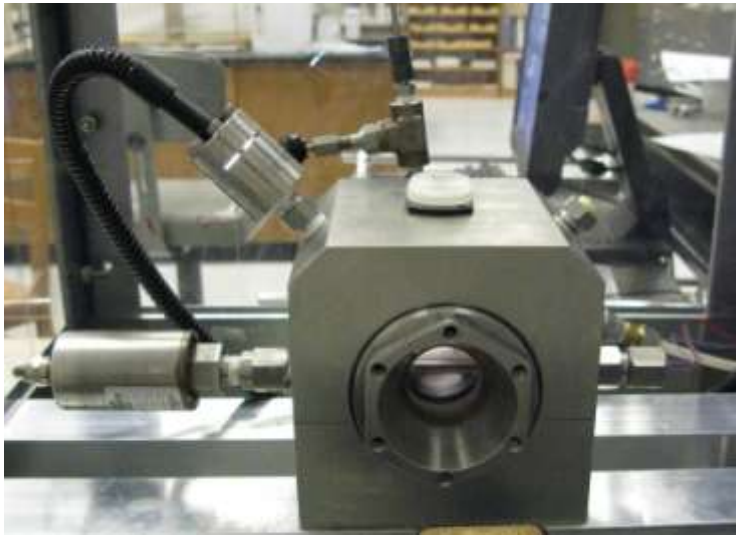
$$\frac{F_{drag}}{N} = 3\pi \frac{\mu v}{\sigma' d}$$

CO_2-H_2O Interfacial Interaction ?



Surface Tension and Contact Angle

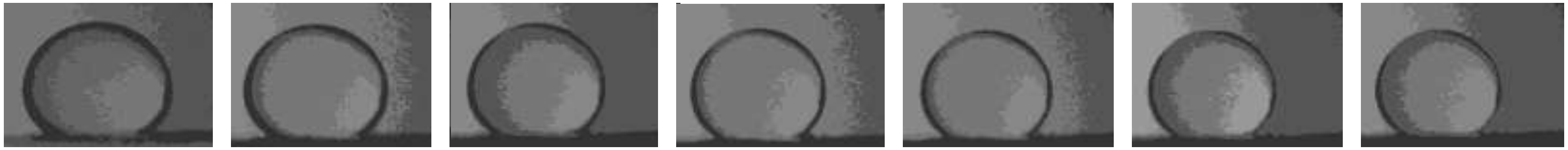




Water droplet in

CO_2 gas

CO_2 liquid



N. Espinoza

Lessons Learned

Soil Properties and Behavior

Effective stress analysis: NO tension anywhere

Particle-level forces:

skeletal-capillary

skeletal-drag

Energy Geotechnology

Resource recovery: oil, shale gas, hydrates, coalbed CH_4, geoT

Development of discontinuities – Fractures and lenses

Unsaturated soil behavior: GREAT (but adapt)

Common: Mixed fluid conditions: oil-H_2O; CH_4-H_2O; CO_2-H_2O

Lateral Earth Pressure

Lateral Earth Pressure

Jacky 1944

Brooker and Ireland 1965

Schmidt 1966

Andrawesand El-Sohby 1973

Abdelhamid and Krizek 1976

Mayne and Kulhawy 1982

Feda 1984

Kavazanjian and Mitchell (1984)

Leonards 1985

Mesri and Hayat 1993

Michalowski 2005

Castellanza and Nova 2004

…. among others….

For all soils [NC and OC], K_o should asymptotically approach unity

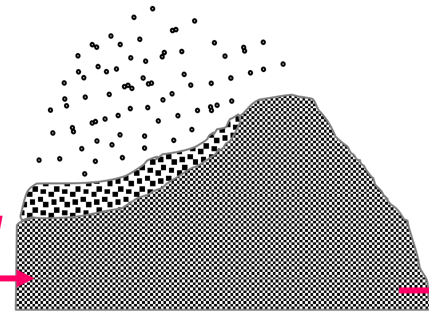
Mount St. Helens – May 18, 1980

Mount St. Helens – May 18, 1980

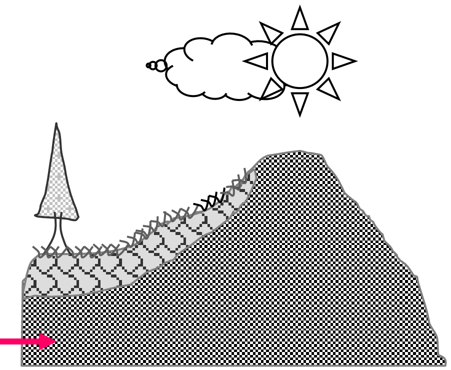
Mount St. Helens – May 18, 1980

Volcanic Ash Soils: Formation

wind



time



$e = 0.8\text{-}1.5$

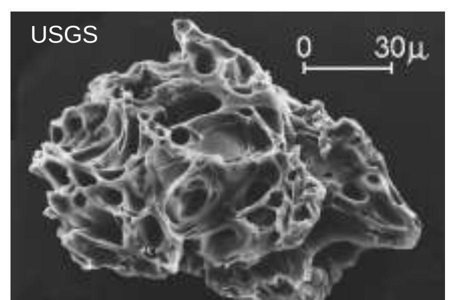
$S_s \sim 0.1\text{-}1\ m^2/g$

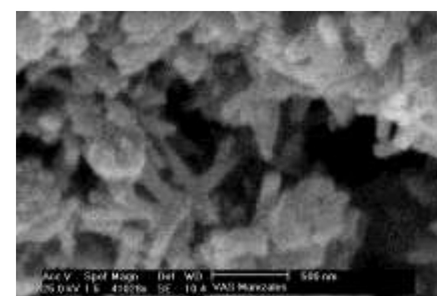
volcanic glass

$e = 2.0\text{-}7.0$

$S_s = 50\text{-to-}200\ m^2/g$

hallosite
imogolite
alophane

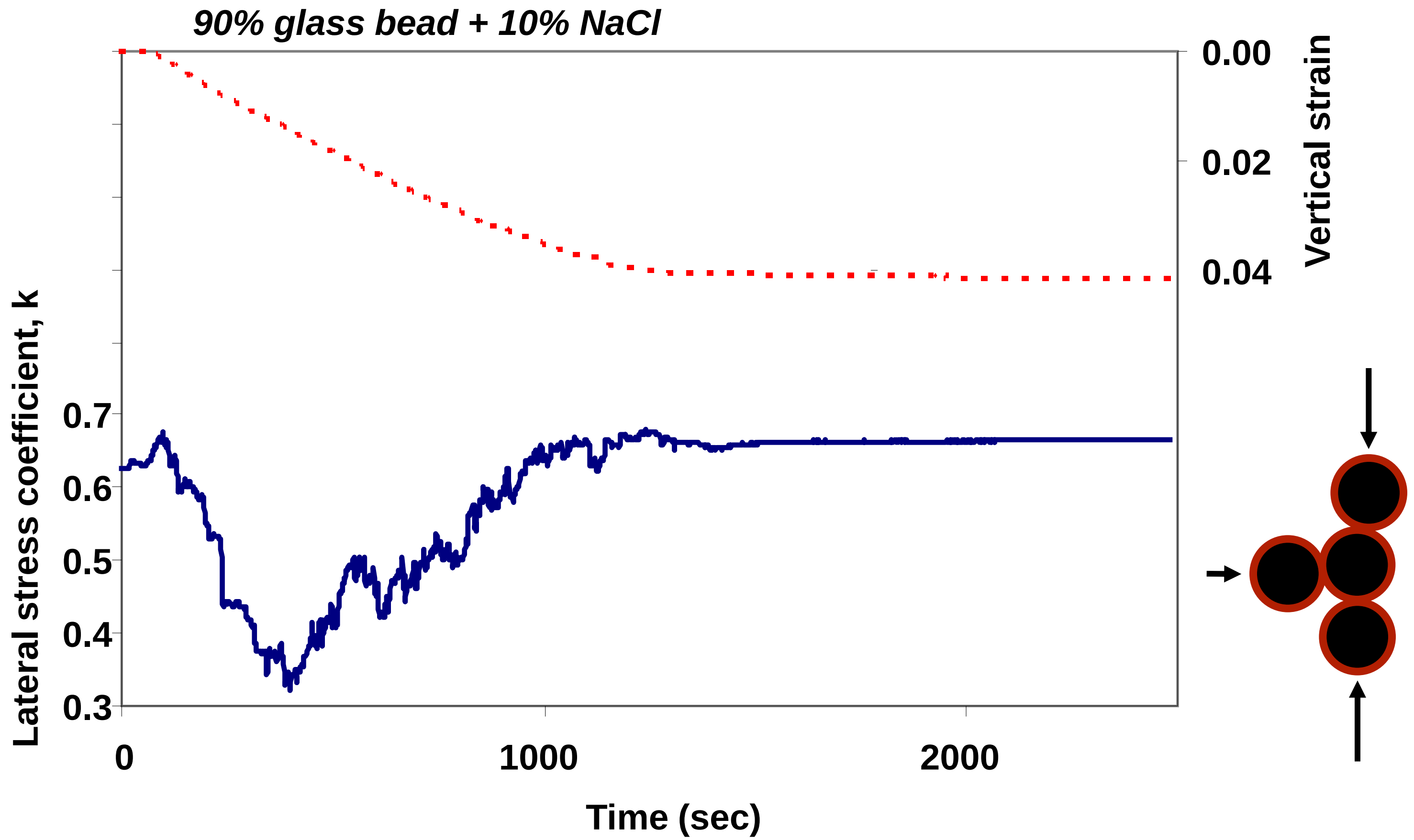




$k_o = 1 - \sin\varphi$

$k_o =$??

k_o: Experimental Results



Hosung Shin

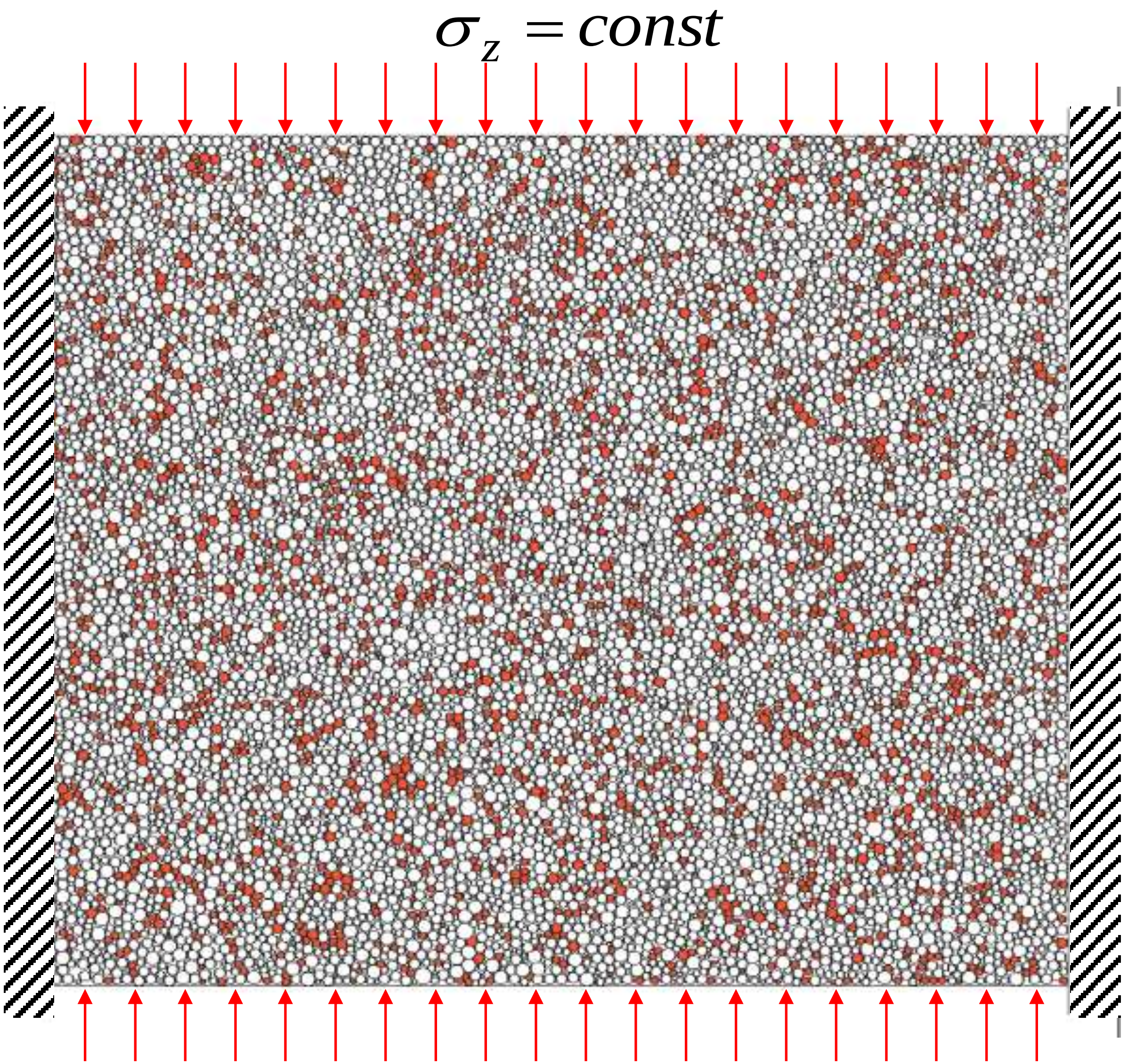
k_o: DEM Simulation

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

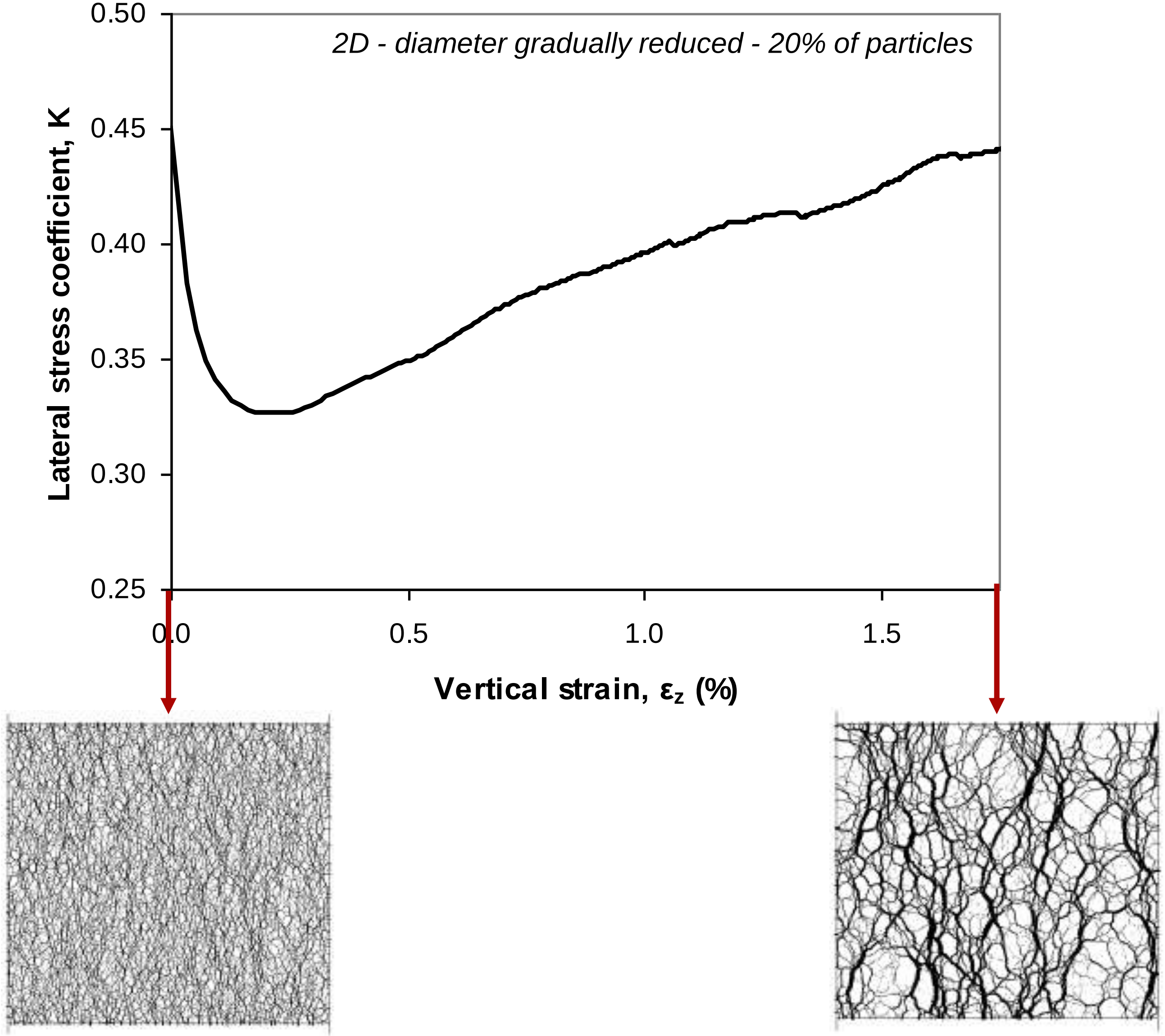
cov particle diameter: 0.25

Interparticle friction: 0.5

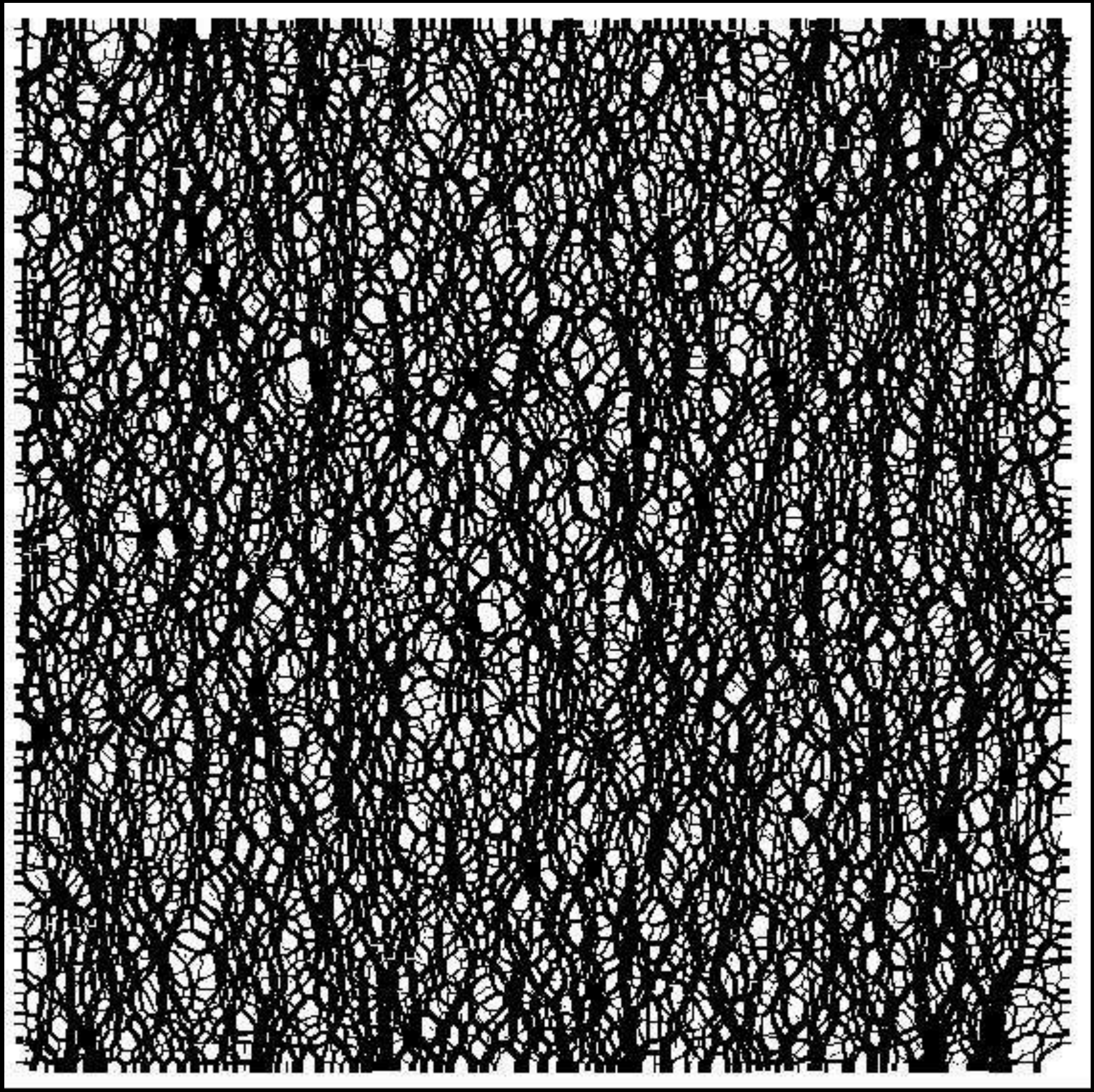
Simulation: reduce D or G



k_o: DEM Simulation

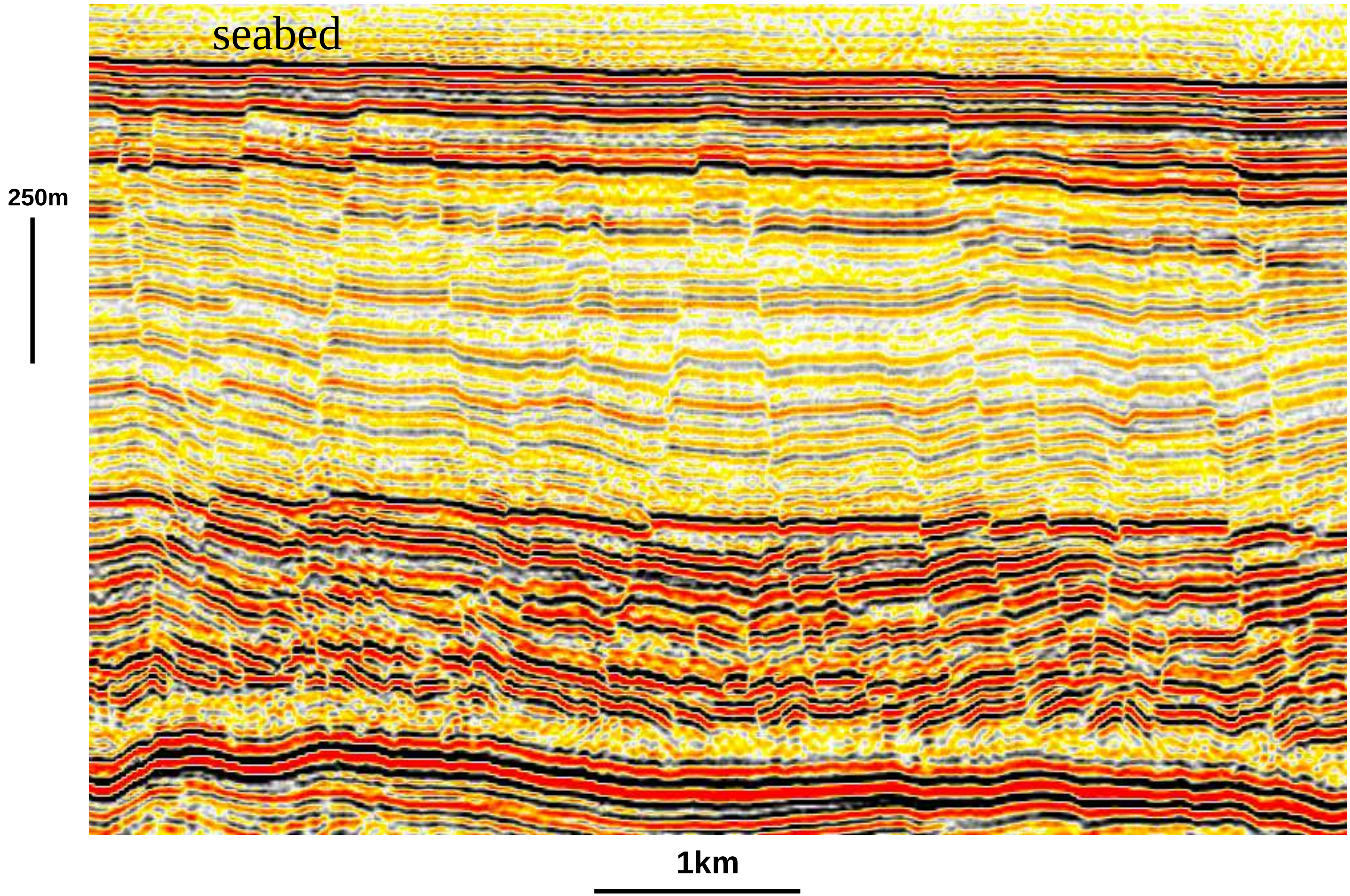


k_o: DEM Simulation – Pressure Solution



Minsu Cha

Polygonal Fault Systems



Cartwright (2005)

Lessons Learned

Soil Properties and Behavior

Discussion by G. A. Leonards[7]

The existing state of stress in the ground is needed to predict ground deformations due to construction operations; to assess the potential for hydraulic fracturing; for reconsolidating clay samples to in-situ conditions, to measure strength and deformation properties; to assess the long-term lateral earth pressure against restrained retaining walls, and so on.

Dissolution and diagenesis: affect k_o

Emergent phenomena: shear localization

Complex geo-plumbing

Energy Geotechnology

Resource accumulation (oil, gas)

Gas recovery from hydrate bearing sediments

Leakage (C-sequestration)

Frozen Ground

GAL: Pavements
Teton Dam

United States Patent Office

3,250,188
Patented May 10, 1966

3,250,188
PAVEMENT CONSTRUCTION
Gerald A. Leonards, West Lafayette, Ind., assignor to The Dow Chemical Company, Midland, Mich., a corporation of Delaware
Filed Mar. 4, 1963, Ser. No. 262,550
15 Claims. (Cl. 94—7)

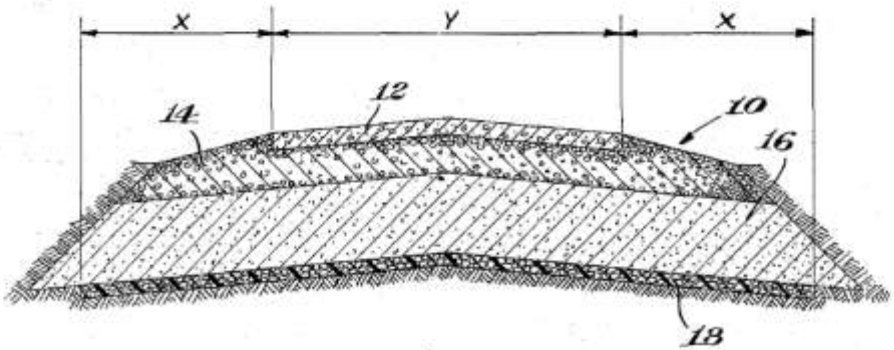


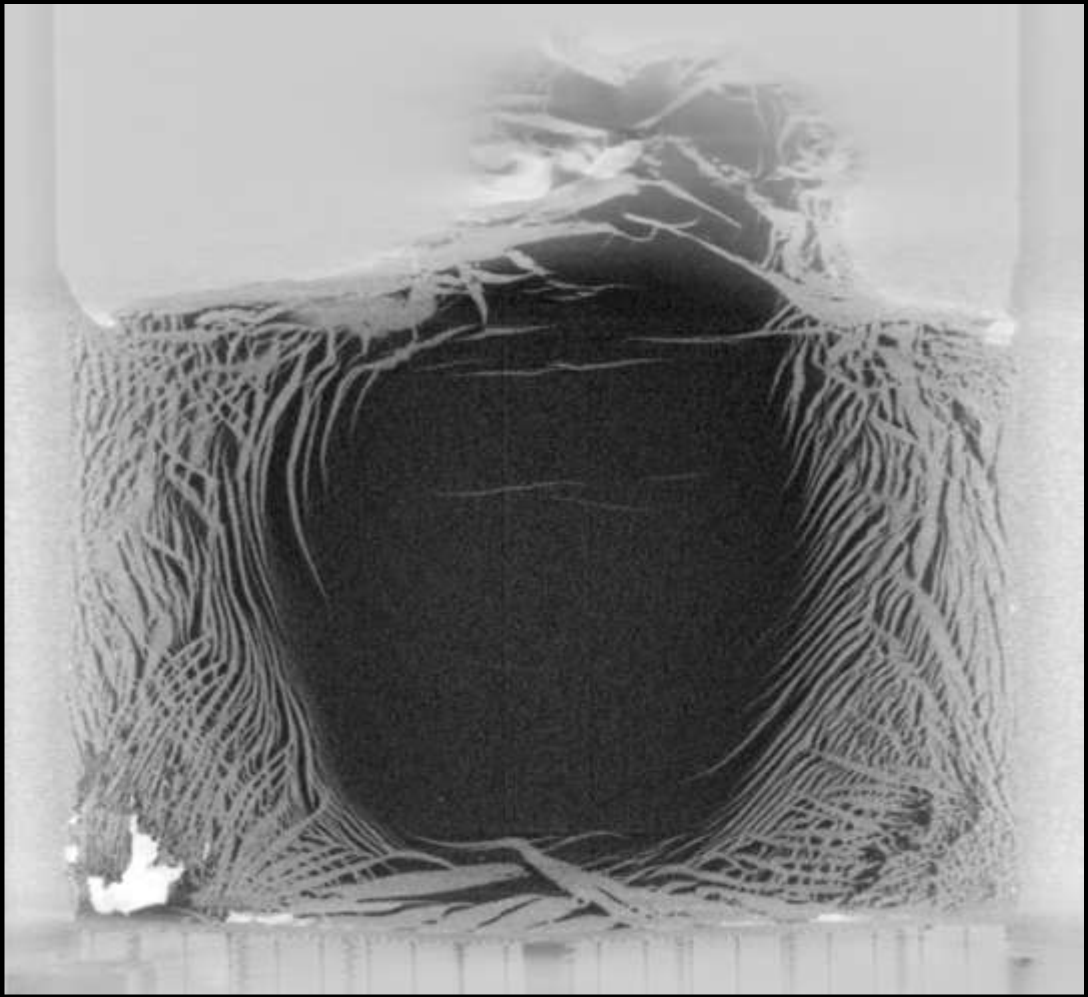
Fig. 1

Briefly, the present invention comprises the employment of a high insulating layer in between the layer of a non-frost susceptible material and the frost susceptible material, which substantially reduces the depth of freezing to the point where a given depth of insulating material can be substituted for an equivalent of several times this depth of gravel. It is necessary that this insulating layer have certain qualities of insulation, heat capacity, imperviousness to vapor transport, compressibility, strength and thermal conductivity to prevent detrimental effects. The type and location of these layers are factors determined by the principles of this invention.

Accordingly, prior limiting assumptions not included in the approach of the present invention, are as follows: (1) Specific heat and thermal conductivity of the soil are independent of temperature, (2) the heat capacity of the soil can be neglected, (3) the temperature at which water first freezes in the soil pores is independent on time and space, and (4) at the freezing front, when nucleation first occurs, all of the water in the soil pores freezes instantaneously. Layered systems are treated only by crude approximations in the prior approaches.

1965 Highway Research Board "Best Paper Award"

Ice Lenses



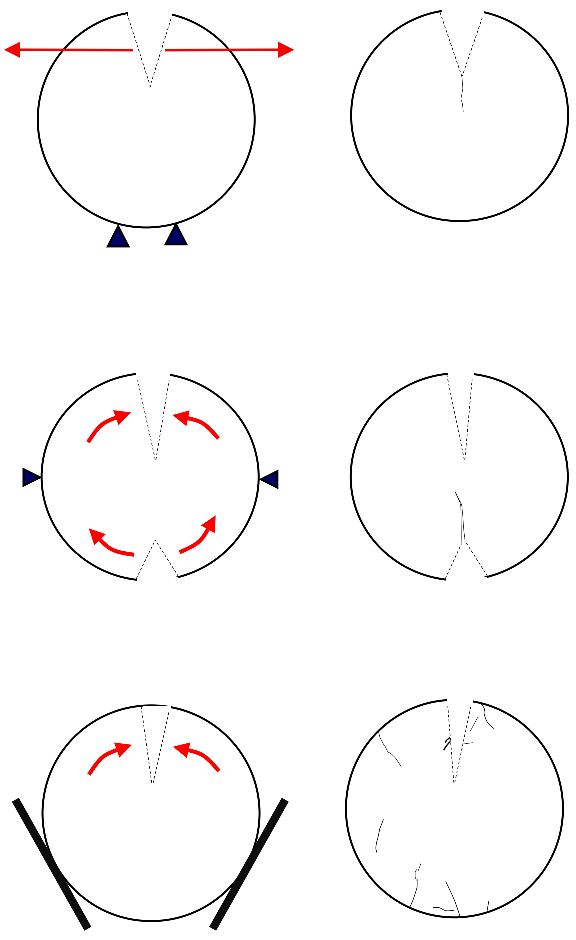
Kaolin

Ice Lens Formation Under Stress Boundary

Tension

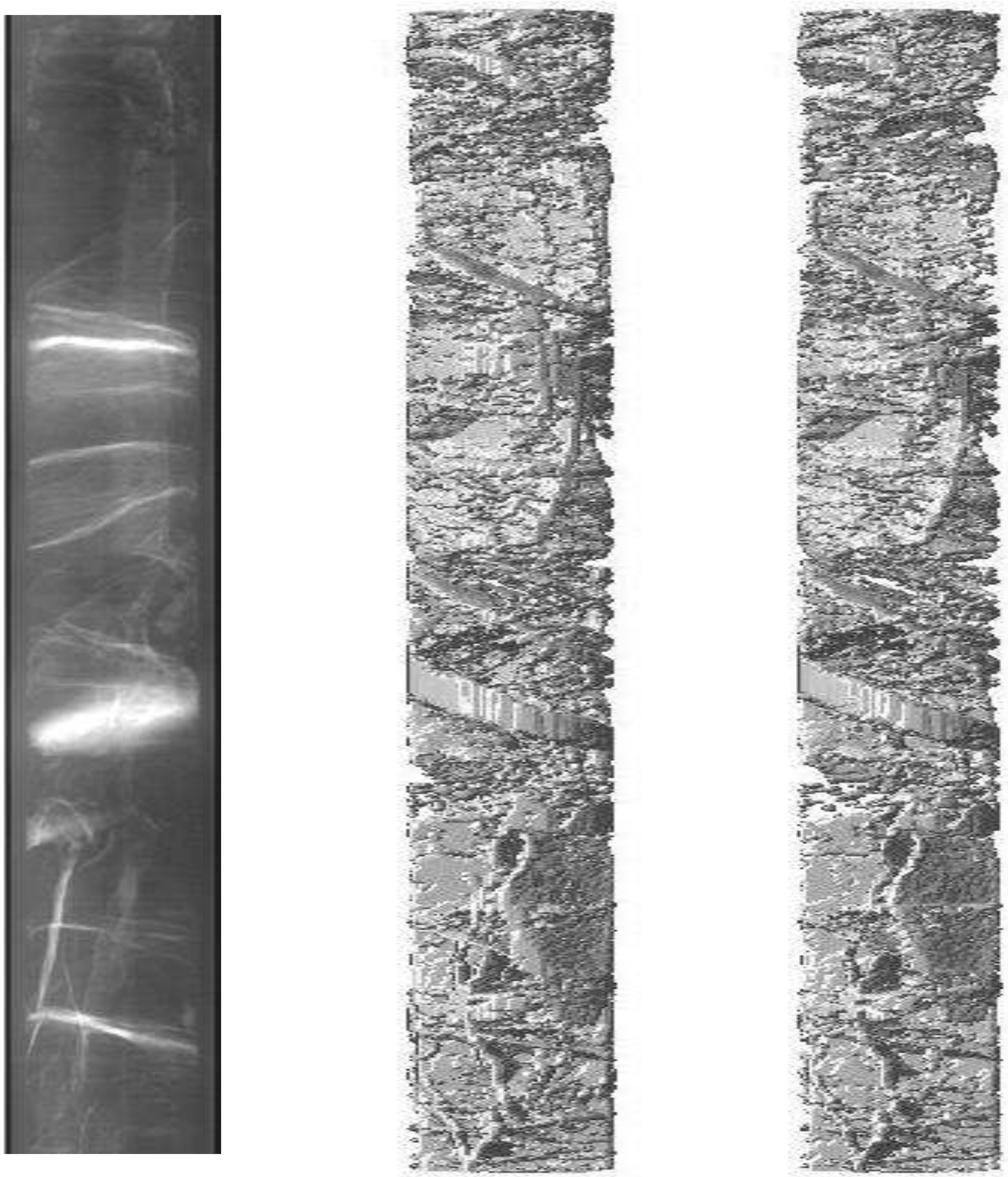
Tension / compression

Compression



Taesup Yun

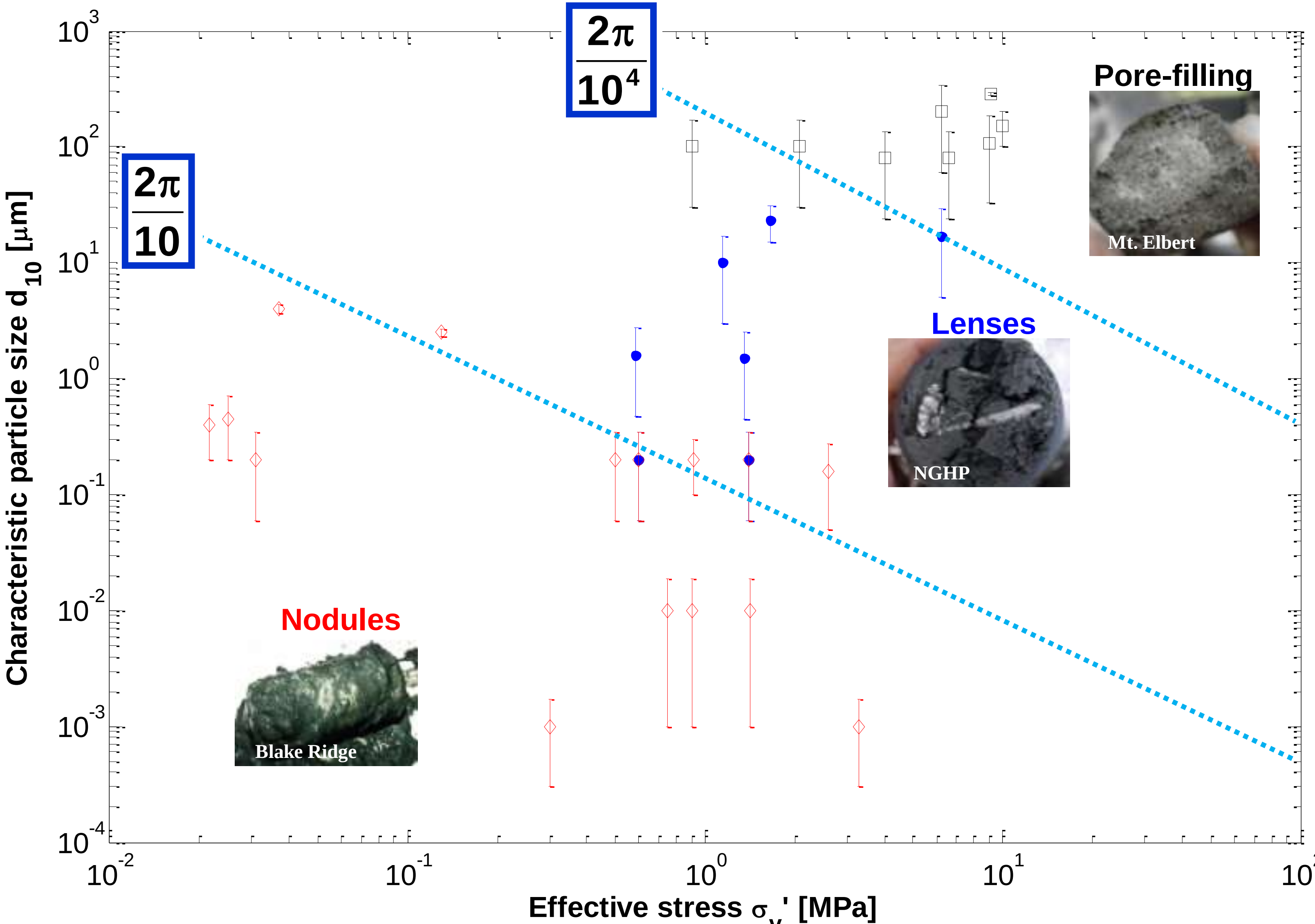
Hydrate lenses – Pressure cores



Percussion Core - KUB

Hydrate Bearing Sediments

$$\frac{F_{cap}}{N} = \frac{2\pi T_{WH}}{\sigma' d_{10}}$$



Sheng Dai

Lessons Learned

Soil Properties and Behavior

FIELD: lens formation = Normal to thermal front

MORE GENERAL: also affected by effective stress

Energy Geotechnology

Frozen ground engineering

GREAT

but… generalize

Hydrate distribution

Friction
&
Repetitive Loading

<3500 BC	Mesopotamia	The wheel
~2750 BC	Egyptians	Sliding on sand and on wet silt
1452-1519	L. da Vinci	T ≠ (apparent contact area)
1663-1705	G. Amontons	Re-discovered da Vinci's
1736-1806	C.A. Coulomb	Referred to Amontons observations

EXPERIMENTAL STUDY OF STATIC AND DYNAMIC FRICTION BETWEEN SOIL AND TYPICAL CONSTRUCTION MATERIALS

G. A. Leonards
Purdue University
School of Civil Engineering
Lafayette, Indiana

TECHNICAL REPORT NO. AFWL-TR-65-161

December 1965

AIR FORCE WEAPONS LABORATORY
Research and Technology Division
Air Force Systems Command
Kirtland Air Force Base
New Mexico

Strength and Repeated Loads
Larew & Leonards (1962)

Subsidence and Vibration
Brumund & Leonards (1972)

Friction and Vibration
Brumund & Leonards (1973)

Dynamic Compaction
Leonards, Cutter & Holtz (1980)

Undrained Monotonic And Cyclic Strength
Alarcon , Leonards & Chameau (1988)

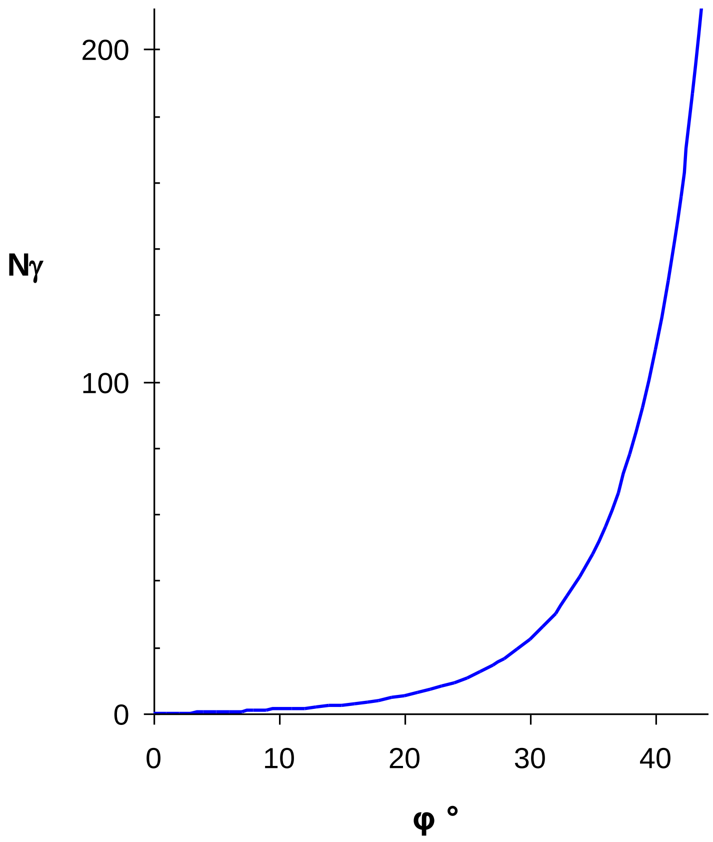

www.dot.ca.gov

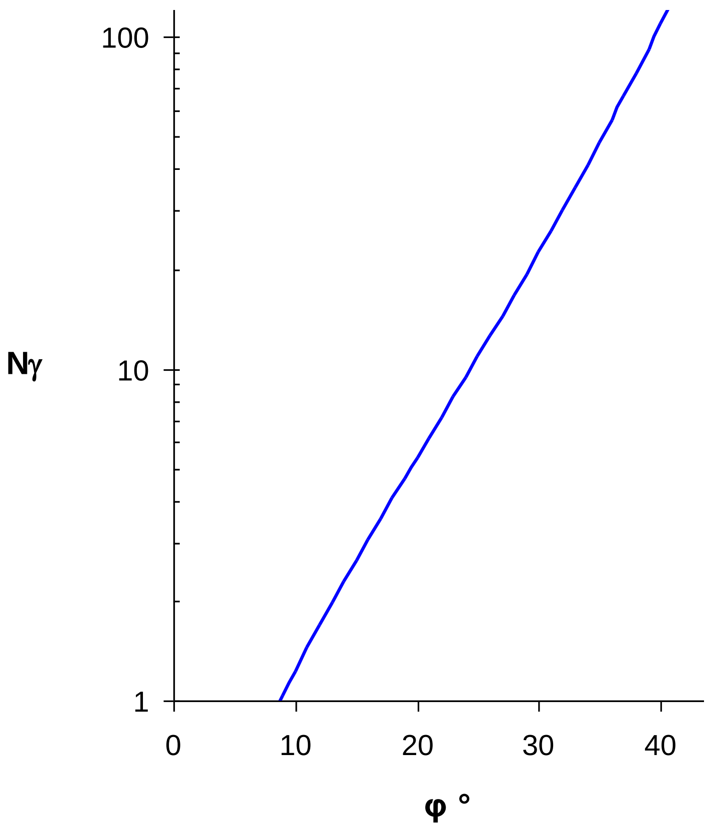

irc.nrc-cnrc.gc.ca


coal mine – Australia – guardian.co.uk

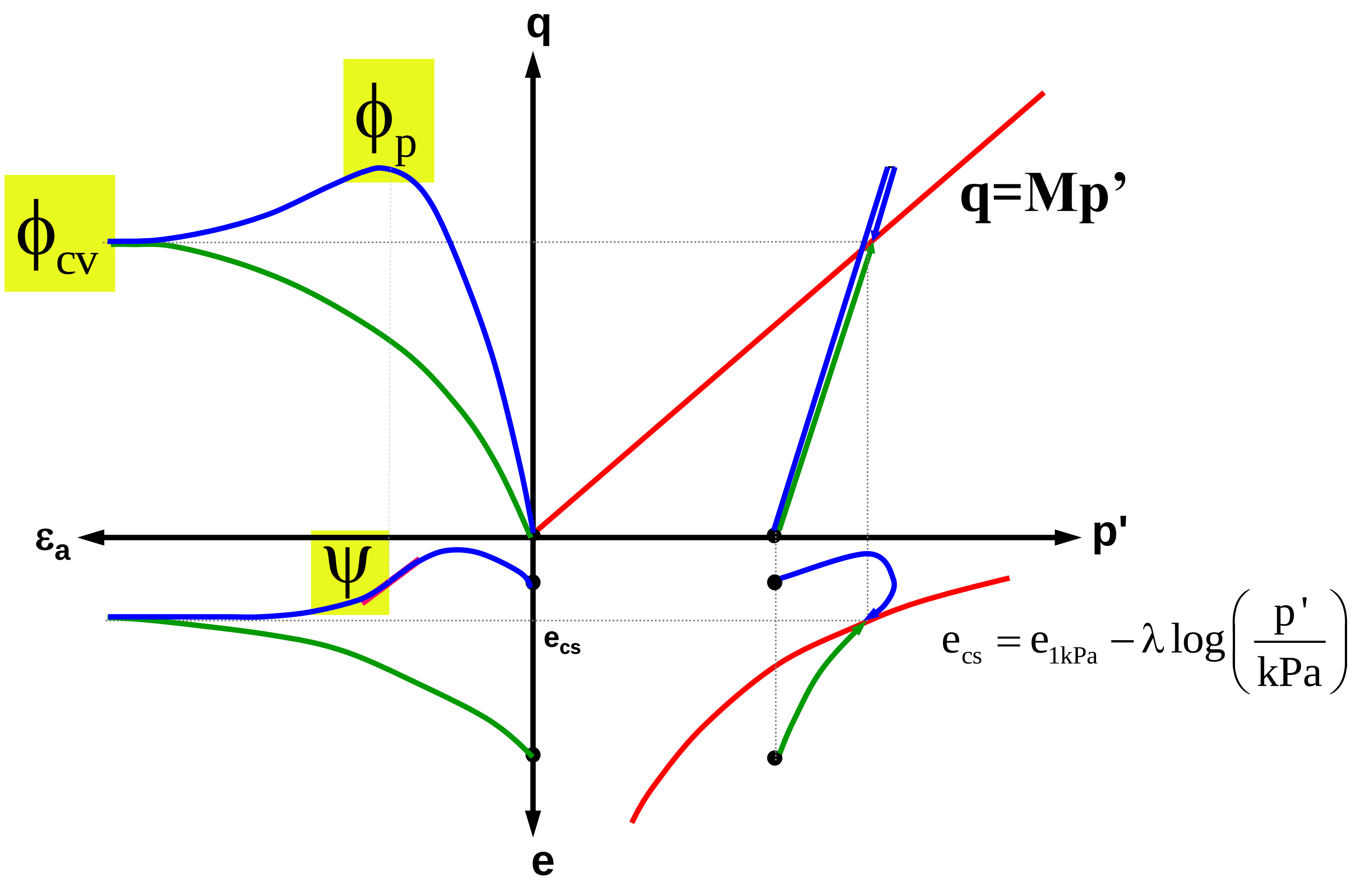

Reinforced Earth

Bearing Capacity – N_g factor

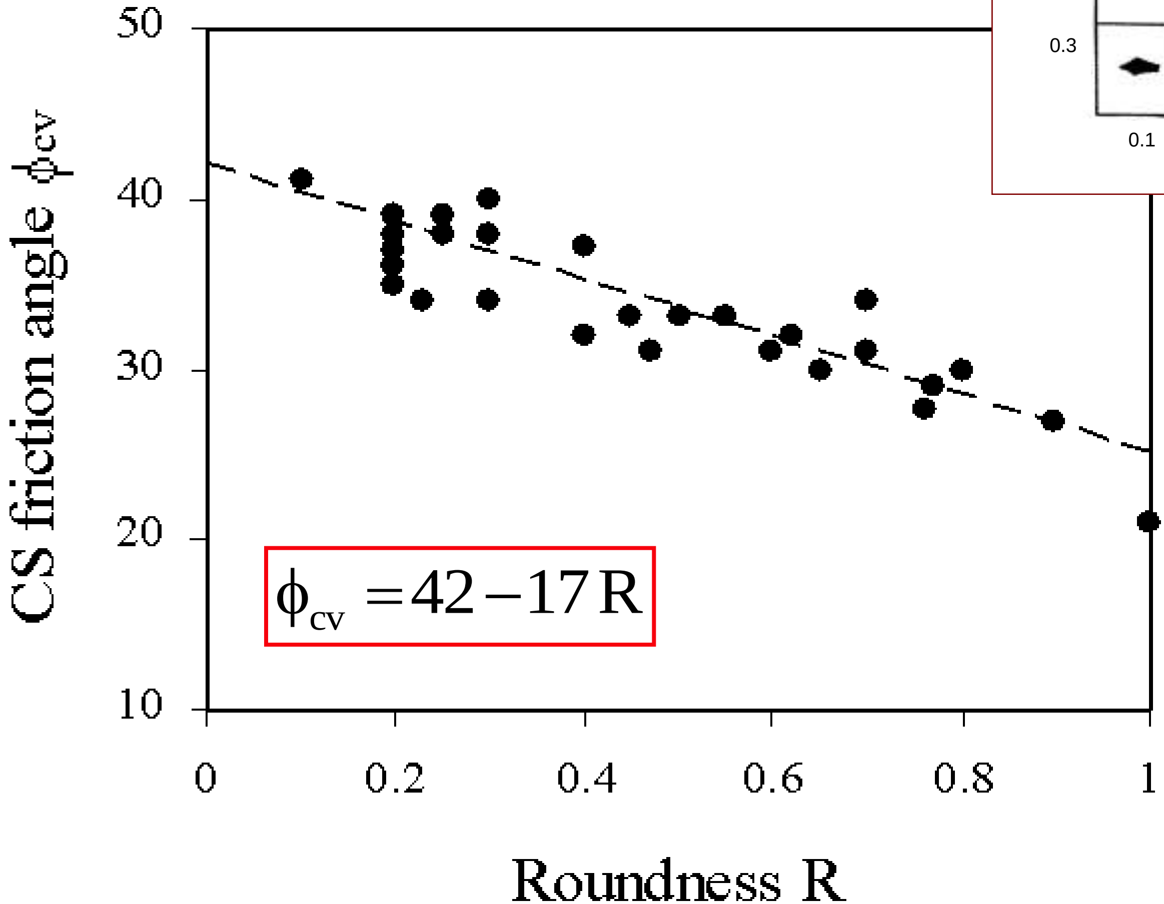


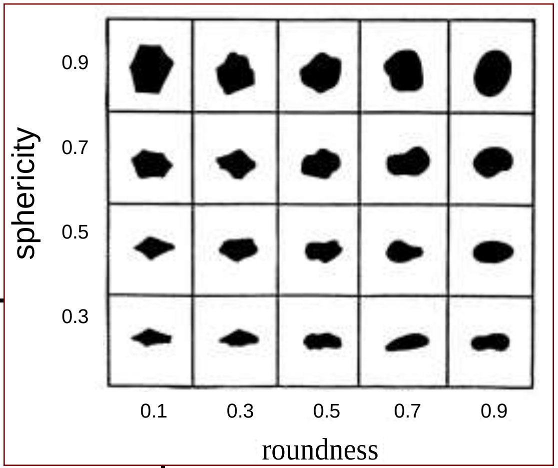


Macroscale Response in q, p’, e, ε



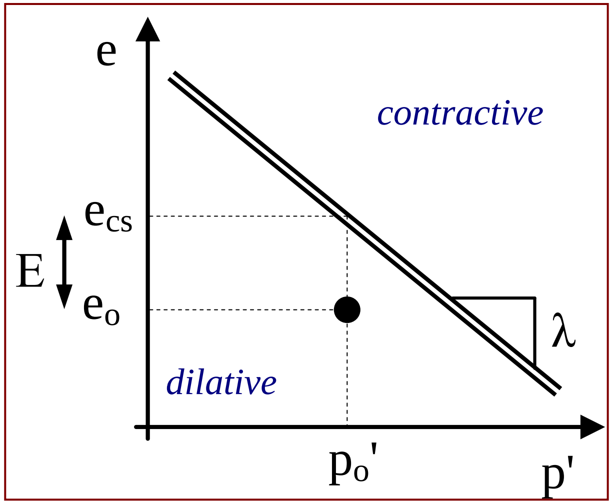
Constant Volume Shear ϕ_{cv}

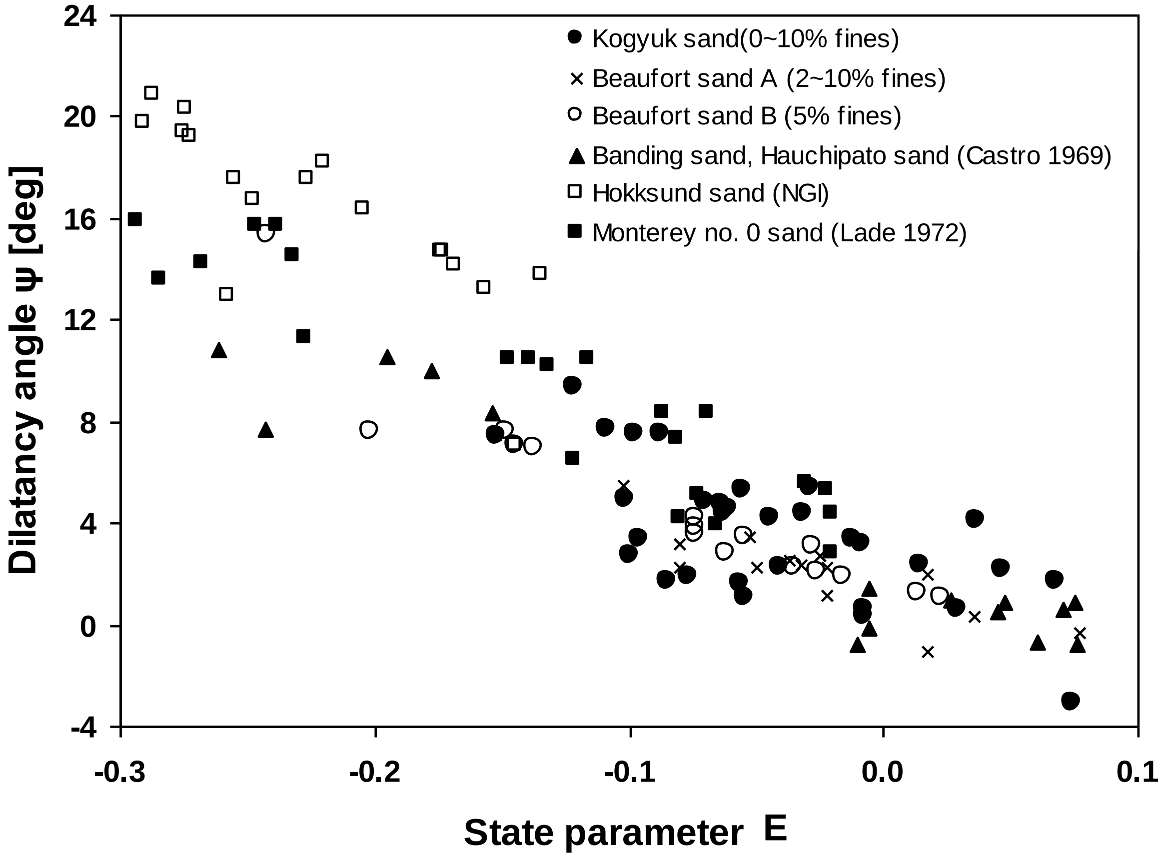




Gye-Chun Cho

Dilatency Angle ψ



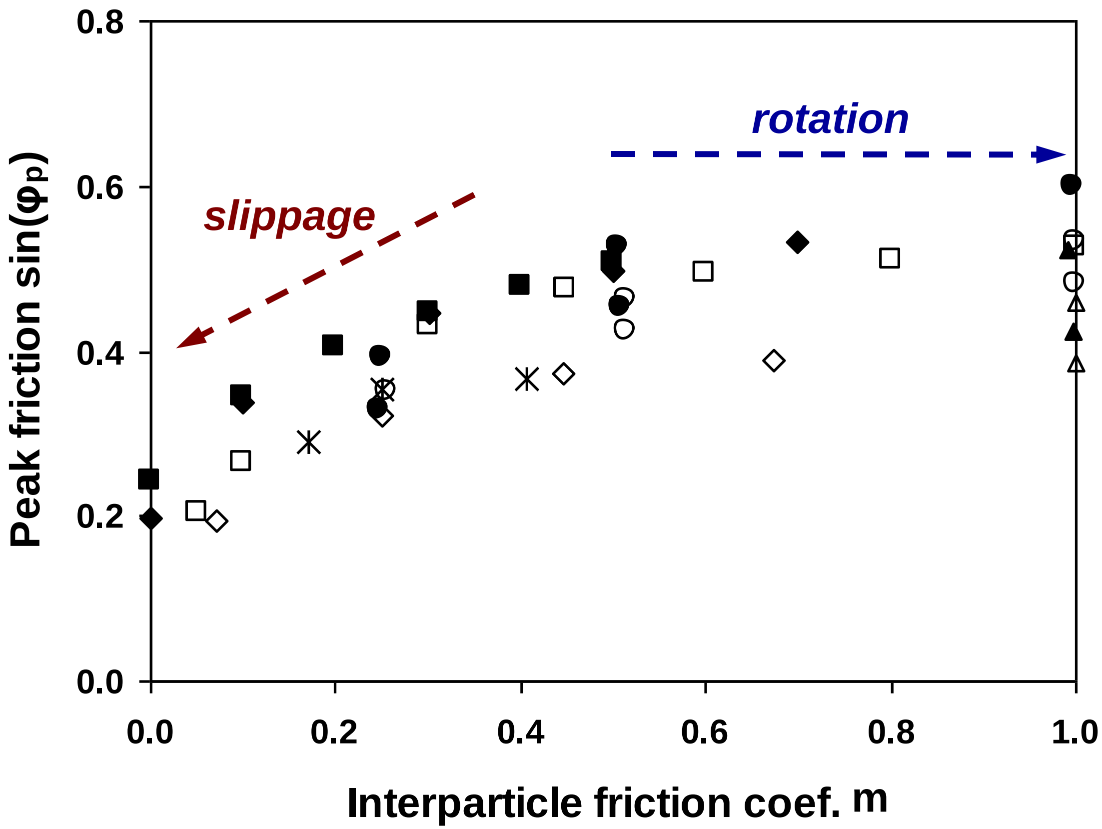


(Been and Jefferies 1985)

Peak Friction Angle ϕ_p

Taylor 1948: $\tan\phi_p = \tan\phi_{cv} + \tan\psi$

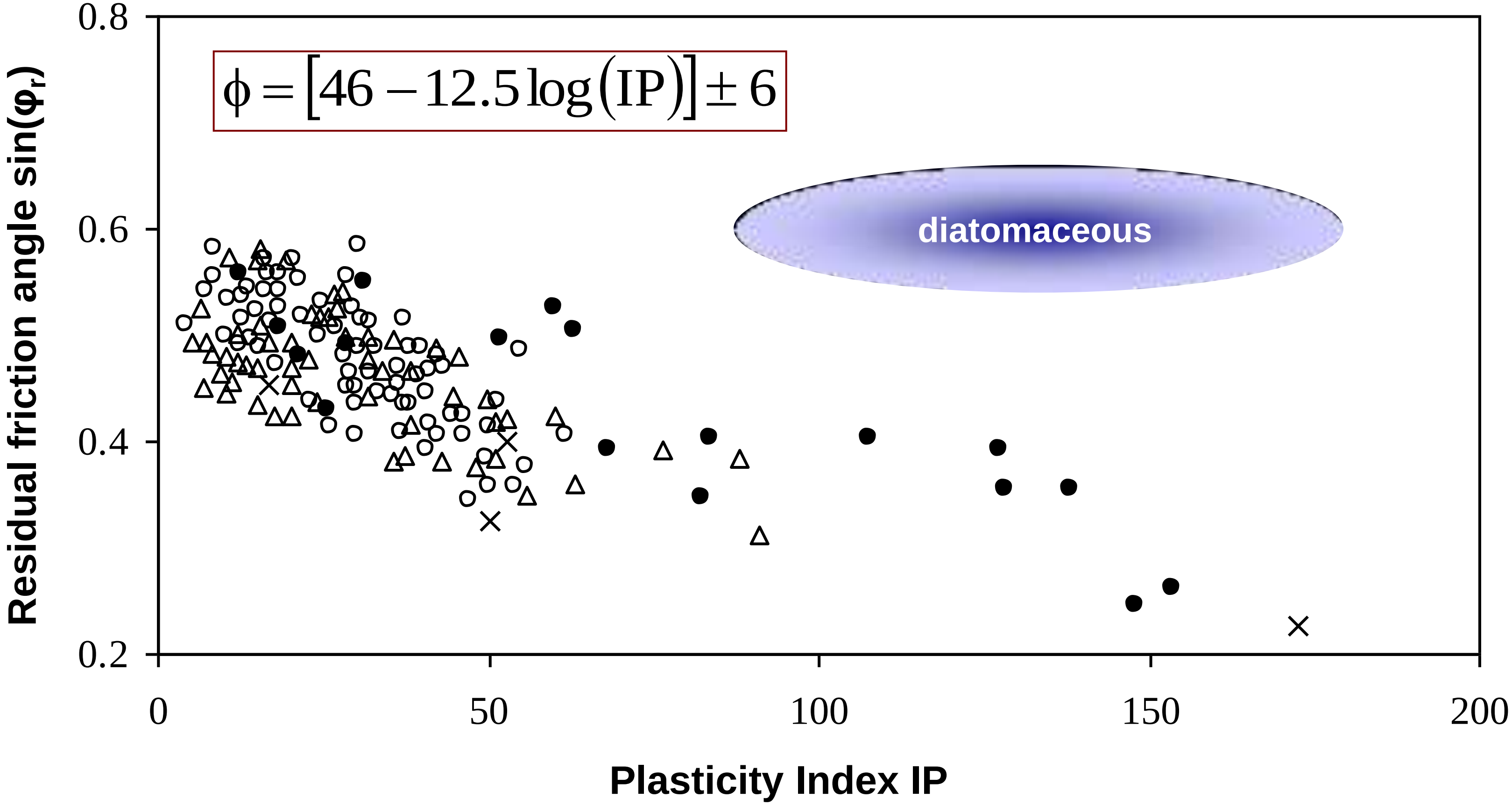
Bolton 1986: $\phi_p = \phi_{cv} + 0.8\psi$



□ (DEM 3D from Thornton 2000), ■ (DEM 2D from Kruyt and Rothenberg 2006), Drained TC(△), Undrained TC(▲), Drained TE(™), Undrained TE(˜) (DEM-3D from Yimsiri 2001), ∗ (experiments) and ◇ (DEM 3D from Suiker and Fleck 2004), ◆ by the authors.

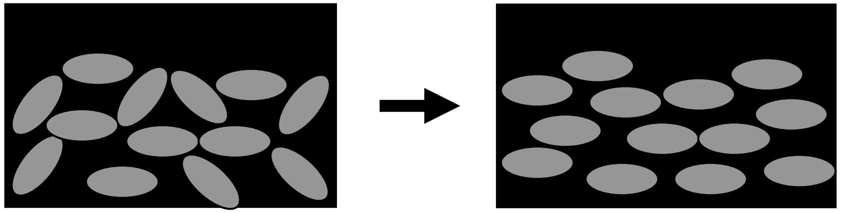
Residual Friction Angle ϕ_r

Note: clay fraction must exceed ~20%

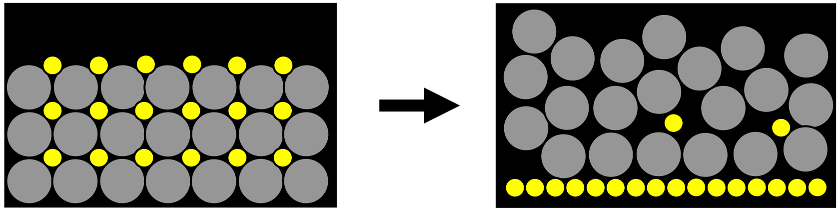


Very large strains $\phi_r < \phi_{cv}$

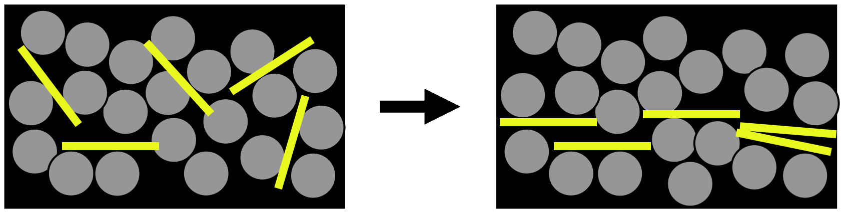
particle alignment



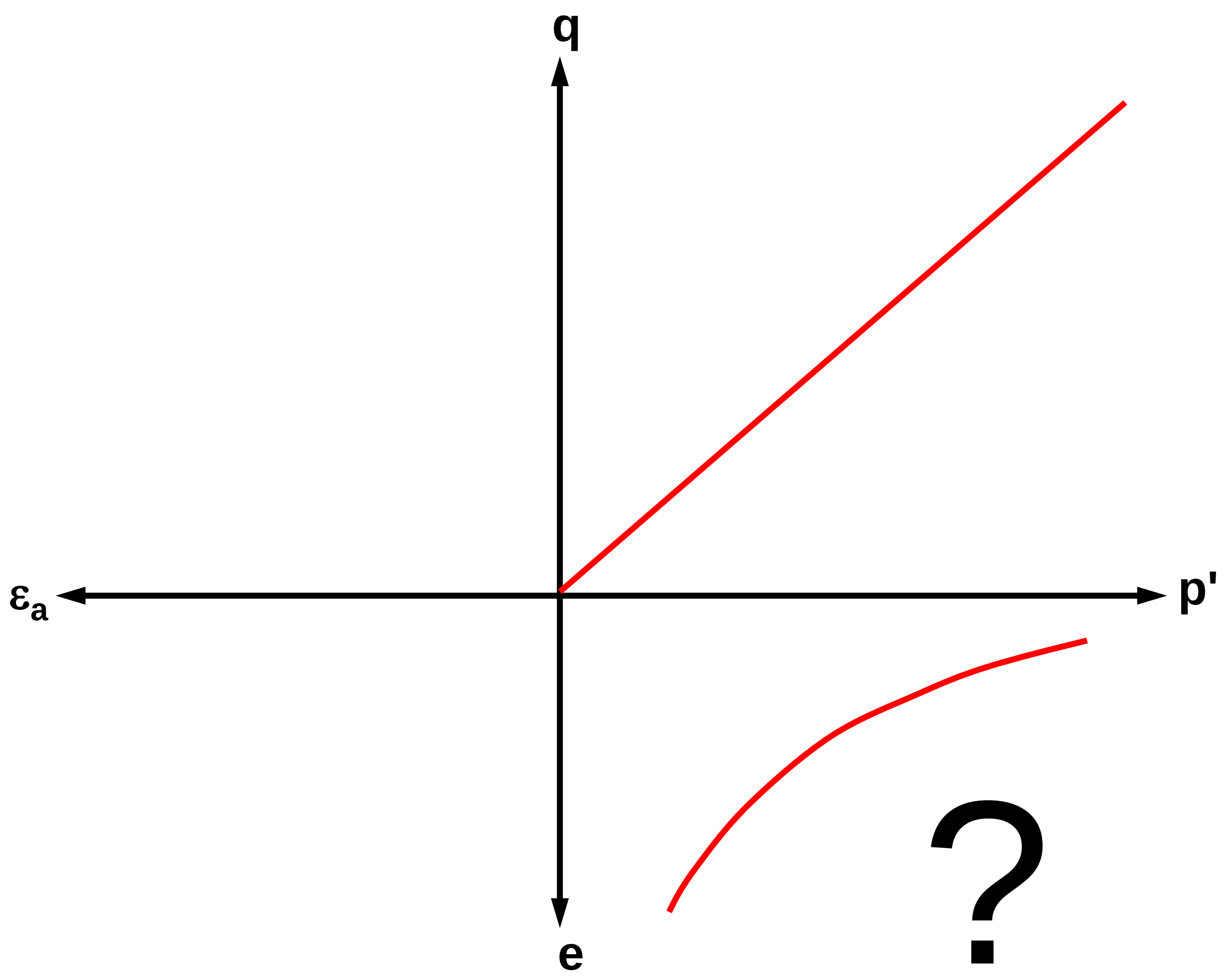
size segregation



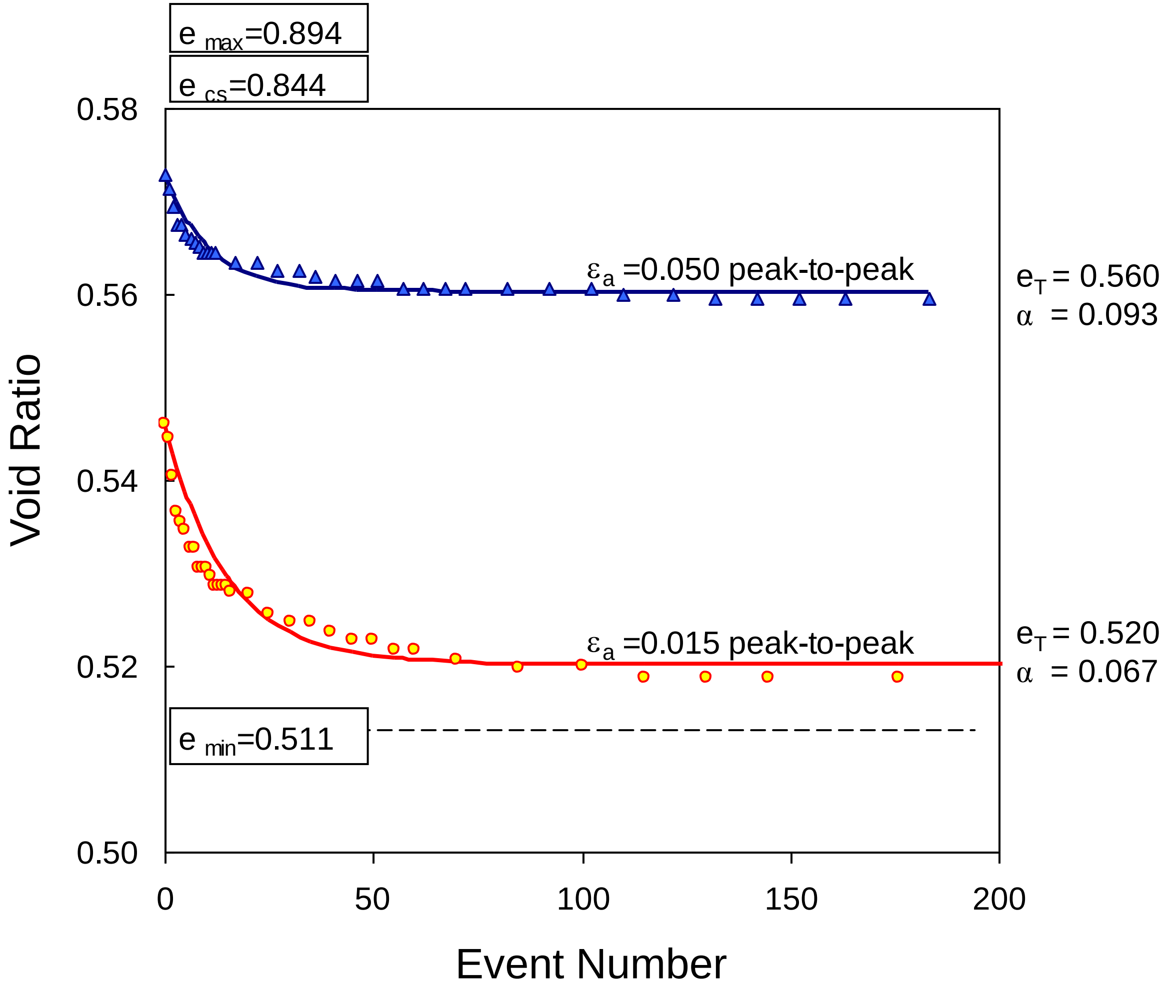
shape segregation



Macroscale Response in q, p’, e, ε



Repetitive Loading – Terminal Density



Guillermo Narsilio

Lessons Learned

Soil Properties and Behavior

Friction: complex parameter !

ϕ_{cv} particle shape

ψ packing density (OC), shape, cementation

$\phi_p = \phi_{cv} + 0.8\,\psi$

ϕ_r clay(PI) or mica >~20% … also segregation

Repetitive loading: further work needed

Energy Geotechnology

Vibration and repetitive loading: common !

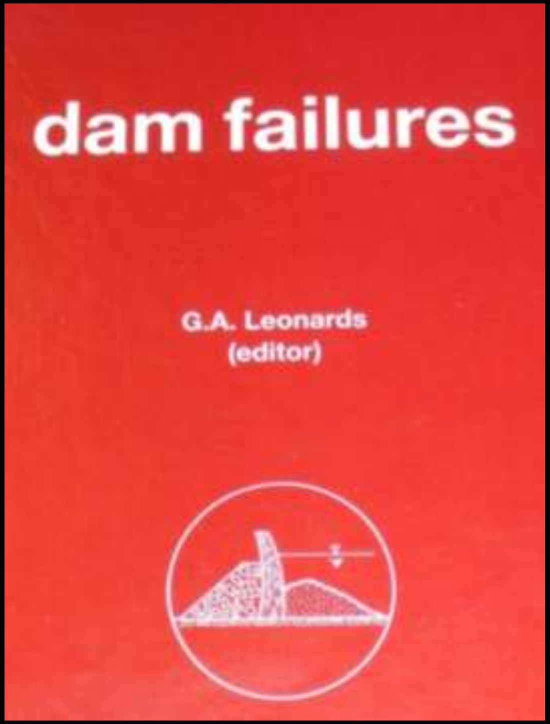
stress: e.g., foundations

temperature: energy piles

miscible/immiscible fluid fronts: e.g., geo-storage

Slopes Instability
&
Dam Failures

GAL's analysis of failures:	**Multiple working hypotheses + Falsification**
GAL's life:	**either PASSIONATE or SKEPTICAL**



Pre-session meal ➔ "harmony"

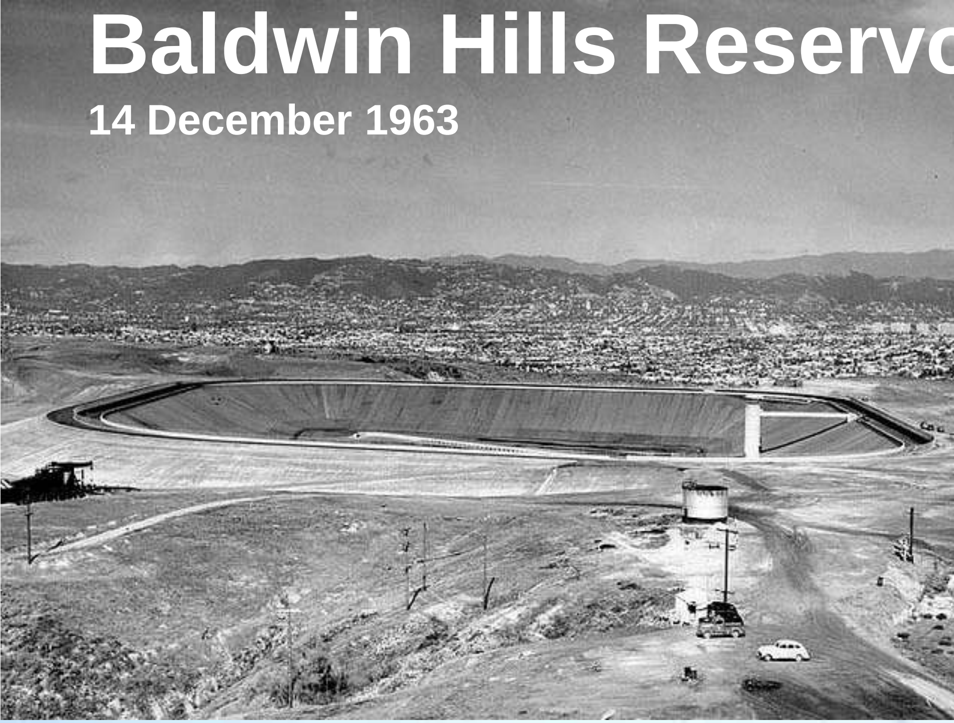
Vajont Landslide

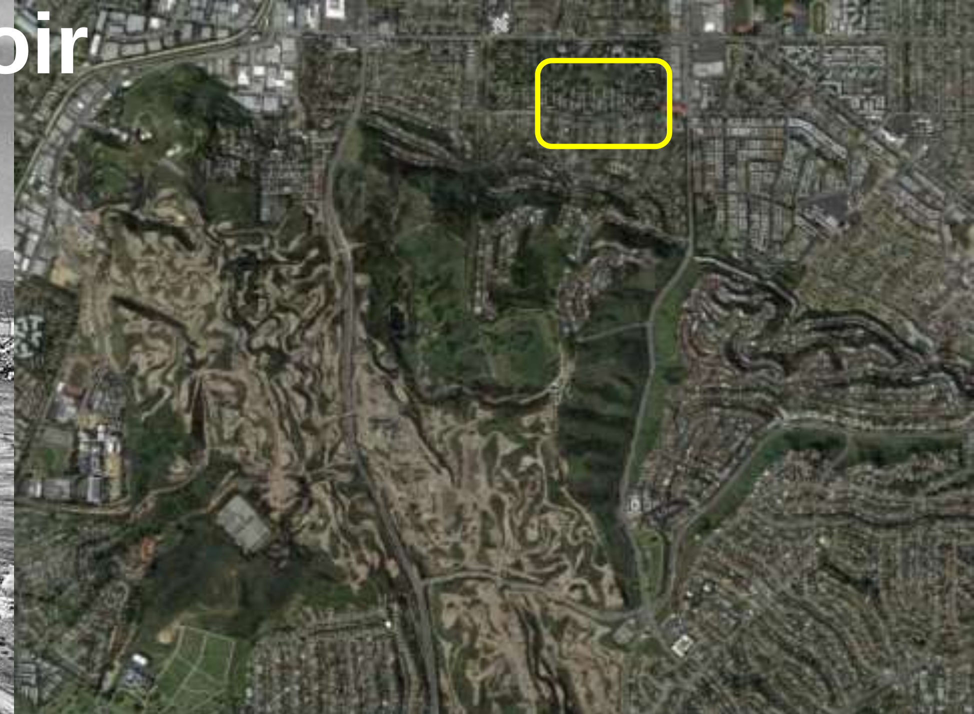
9 October 1963

L. Muller
L. G. Belloni
J. Hendron
F.D. Patton

Baldwin Hills Reservoir

14 December 1963

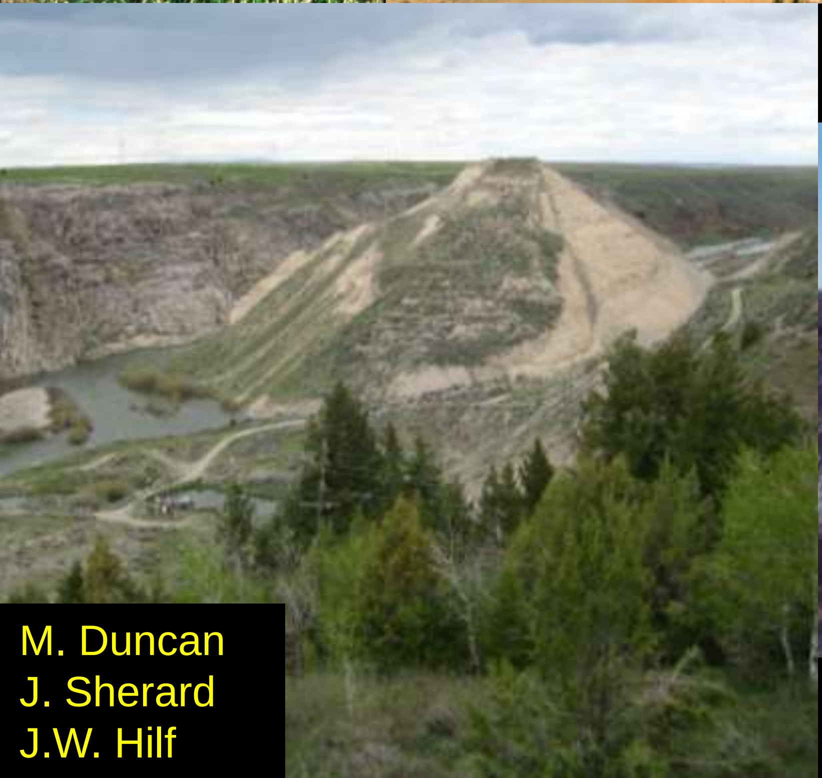




R.F. Scott

http://www3.gendisasters.com

Teton Dam June 5, 1976



M. Duncan
J. Sherard
J.W. Hilf

Malpasset Dam

December 2, 1959

P. Londe
J. L. Serafin
W. Wittke

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

Conclusions

G.A. Leonards: (1) deepest clear-thinker (2) passion

Emphasized: Understanding

Historical geology

Discontinuities – Weak seams

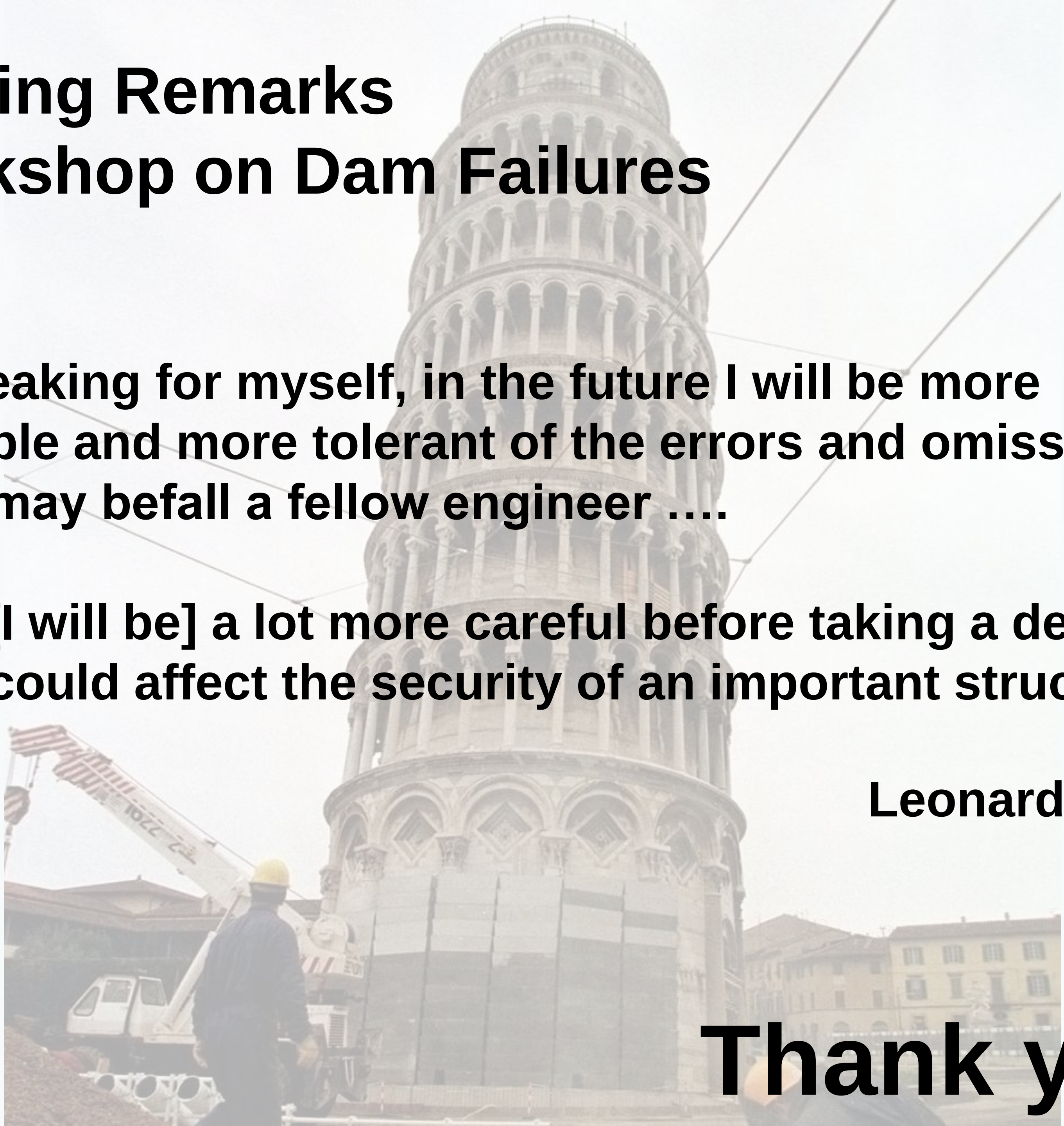
Multiple working hypotheses + Falsification

Contributions: soils, geo-processes, engineering

Renewed relevance in the context of energy geotechnology

Fascinating field !!

Closing Remarks
Workshop on Dam Failures



" Speaking for myself, in the future I will be more humble and more tolerant of the errors and omissions that may befall a fellow engineer ….

and [I will be] a lot more careful before taking a decision that could affect the security of an important structure"

Leonards 1985

Thank you !