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

Understanding

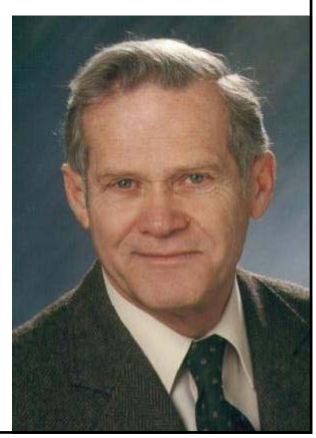
Soil Properties and Behavior - Recent Developments -

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?



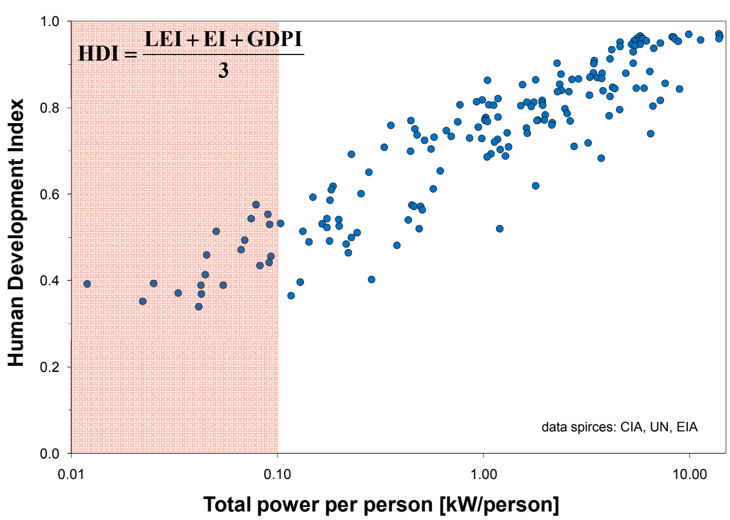
1921 Born (April 29, Montreal)	
1943 BSc (McGill University) 1944 Army @ McGill 44-45 Canadian Mines & Resources 1945 Married 45-46 Canadian DoT 1948 MSc (Purdue)	Frozen ground Pavements
1952 PhD (Purdue): Compacted clay 1952 Assistant Professor 1955 Associate Professor 1958 Full Professor	Clays: σ-history
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)	
1943 BSc (McGill University) 1944 Army @ McGill 44-45 Canadian Mines & Resources 1945 Married 45-46 Canadian DoT 1948 MSc (Purdue)	Clays Sands Fly Ash Frozen ground Discontinuities - Weak seams Friction Hydraulic conductivity Piping, erosion Pavements - Culverts Shallow and Deep Foundations Slopes and dams Lateral Earth Pressure Failures *Energy Geotechnology*
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)	

Energy Geotechnology

GAL Historical Geology (Homework #1)

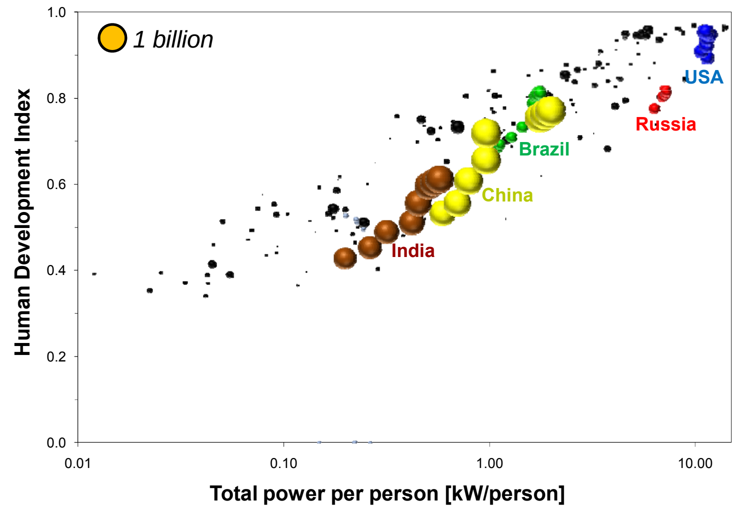
Energy and Life (Global 2008)



C. Pasten

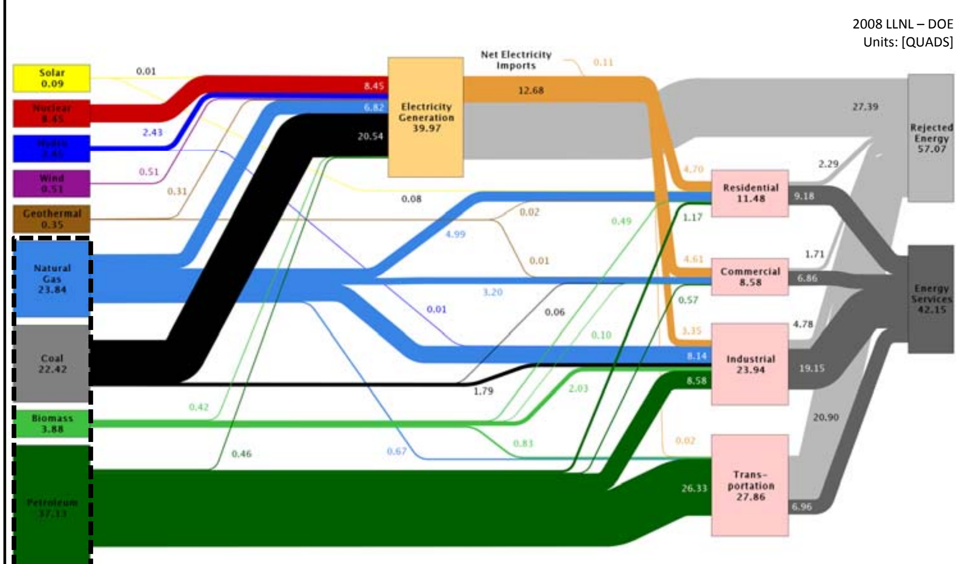
Energy and Life

(Global: 2008 – BRIC trends: 1980-2007)



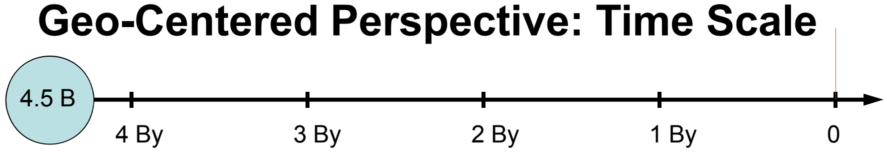
Countries following the same trend: P↑ ➔ HDI ↑

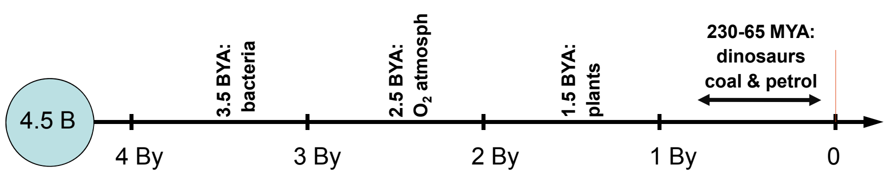
Sources – Case: USA

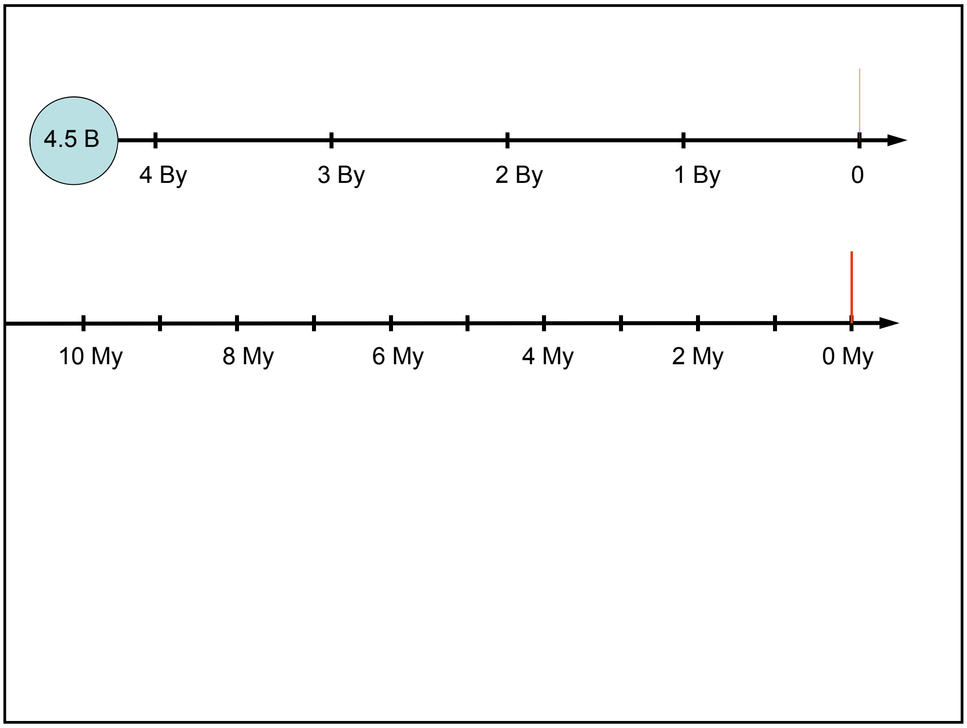


Efficiency in geotechnology? crushing<5% tunneling<< ants!

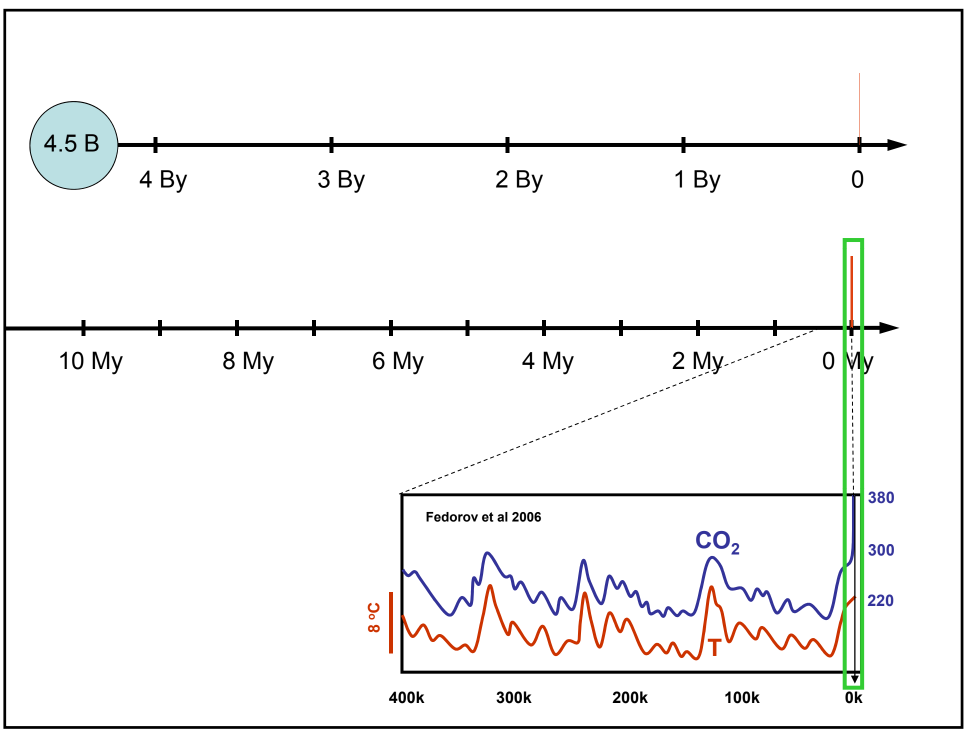
Geo-Centered Perspective: Time Scale







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
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10 My
8 My
6 My
4 My
2 My
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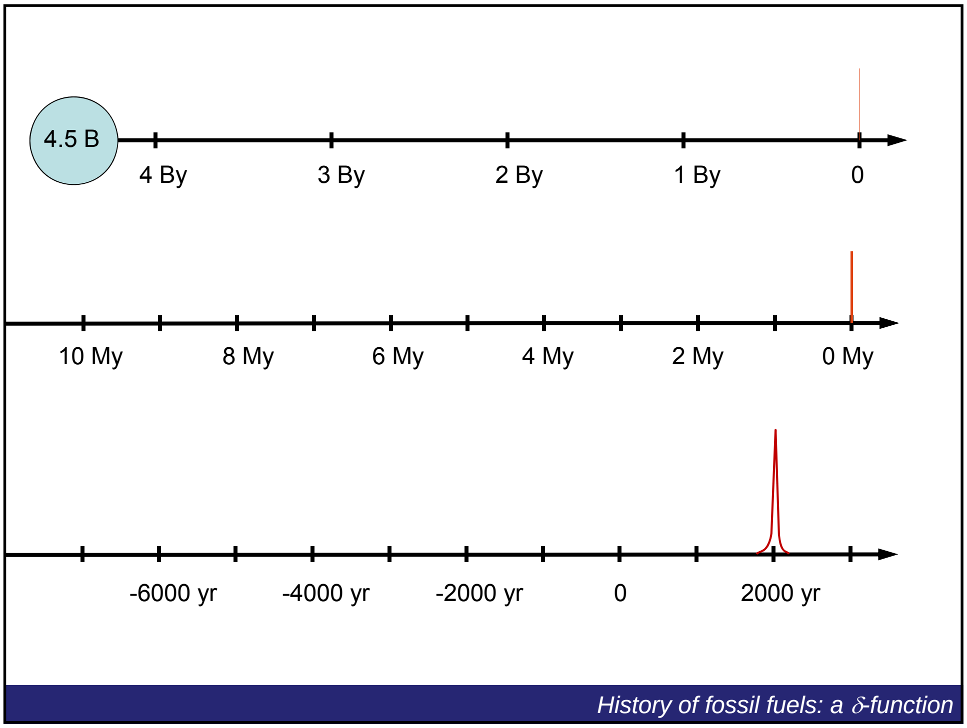
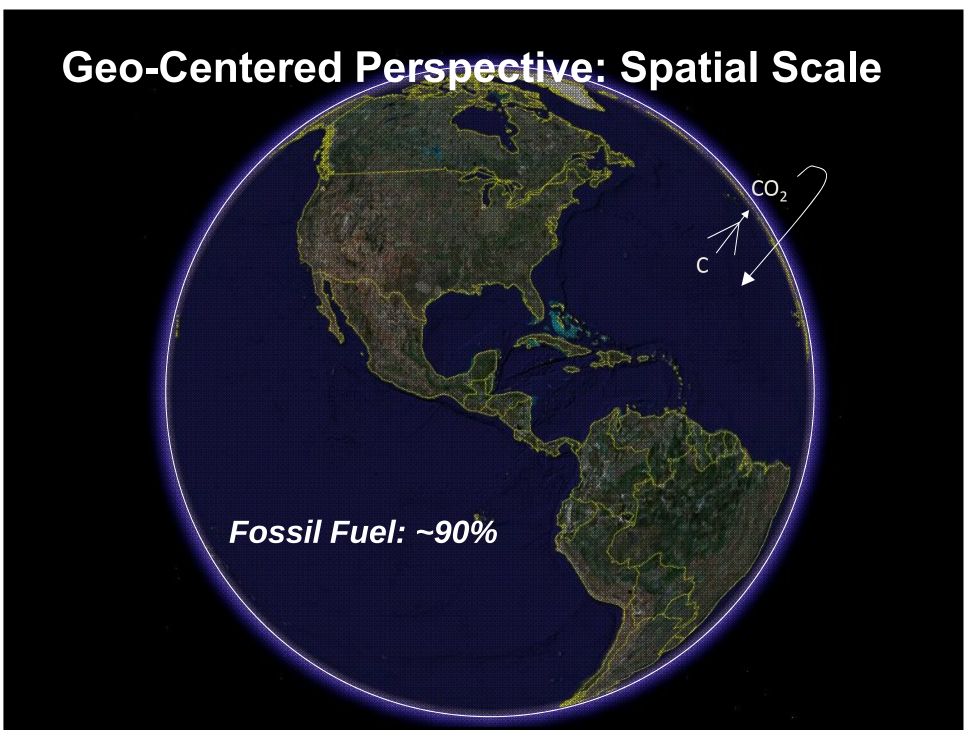
Fedorov et al 2006
CO_2
T
8 °C
380
300
220
400k
300k
200k
100k
0k


4.5 B
4 By
3 By
2 By
1 By
0
10 My
8 My
6 My
4 My
2 My
0 My
-6000 yr
-4000 yr
-2000 yr
0
2000 yr
History of fossil fuels: a δ-function


Geo-Centered Perspective: Spatial Scale
CO2
C
Fossil Fuel: ~90%

Energy Geotechnology

FOSSIL FUELS (C-BASED)			RENEWABLE	
Petroleum	Gas	Coal	Wind Solar Biofuels Geo-T Tidal	Nuclear
• 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

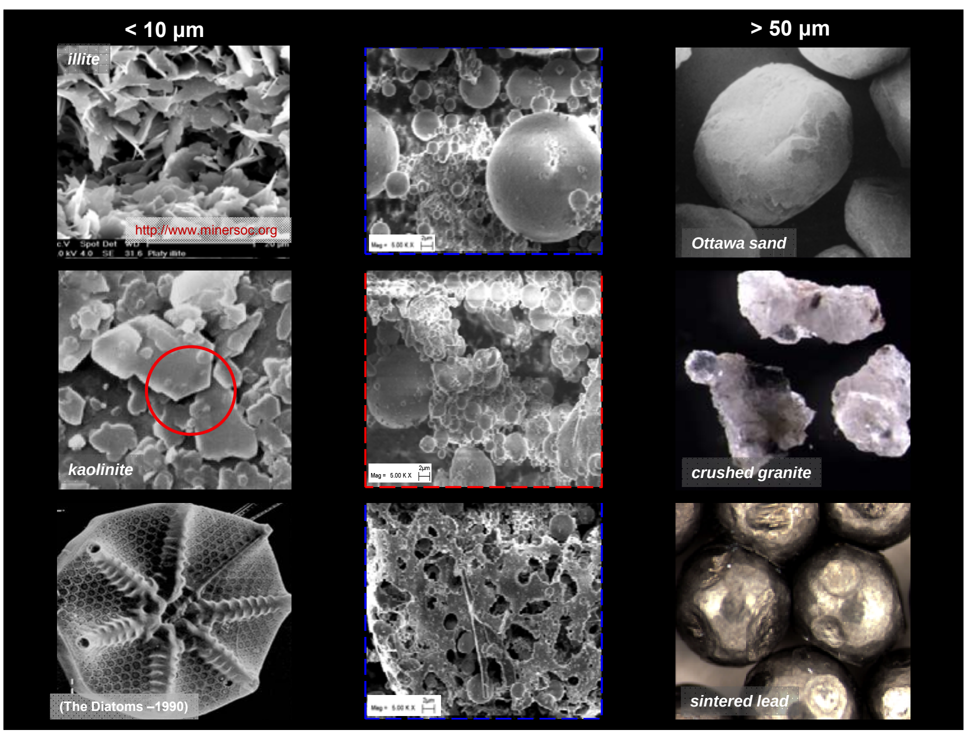
Production, transport, conservation, waste

Rich & complex phenomena - interwoven processes

Urgency ….

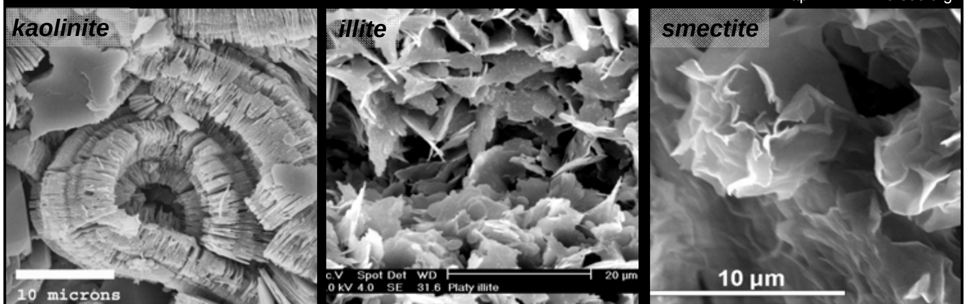
Fascinating !

Clays Fly Ash Sands



Clay Minerals: Very High Specific Surface

http://www.minersoc.org

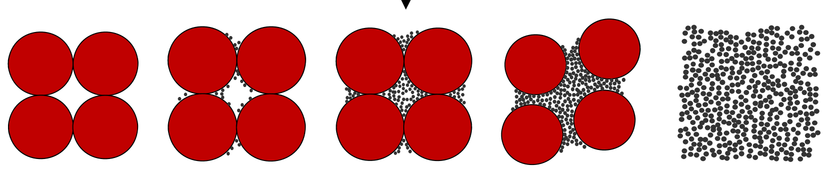


	kaolinite	illite	smectite
	S_s= 10 m²/g	S_s= 50 m²/g	S_s= 300 m²/g
for n=0.2	d_{pore}=10 nm	d_{pore}=2 nm	d_{pore}=0.3 nm

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

Critical fines Content FC* *(for mechanical properties …)*



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

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

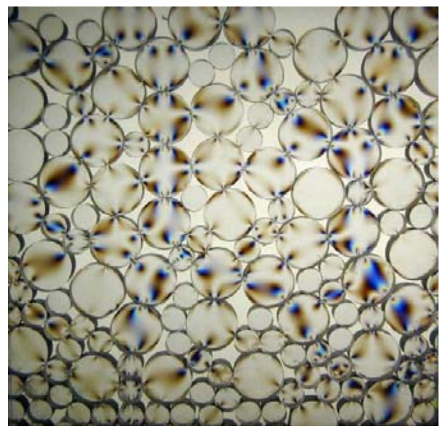
Capillary

Electrical

attraction

repulsion

Cementation



Particle Forces

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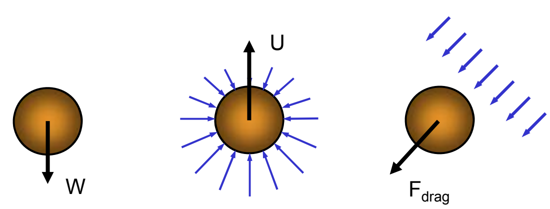


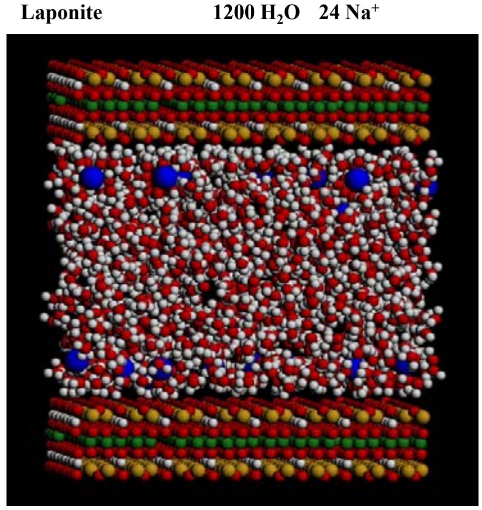
Particle Forces

- 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	$N = \sigma' d^2$	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	$Att = \frac{A_h}{24t^2} d$	
repulsion	$Rep = 0.0024 \sqrt{c_o}\ e^{-10^8 t \sqrt{c_o}} d$	
Cementation	$T = \pi \sigma_{ten} t d$	

Particle Forces

Skeletal

Weight

Buoyant

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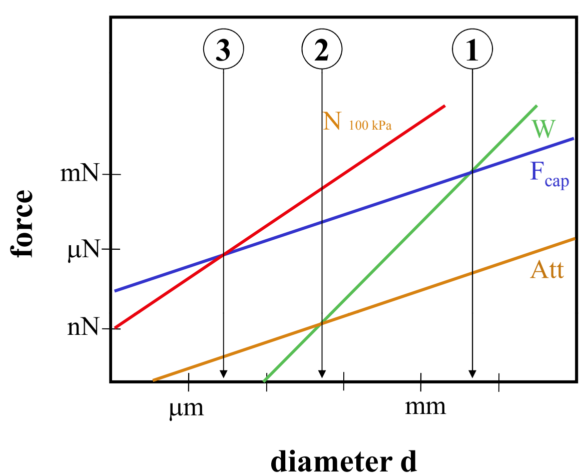
Cementation



Lessons Learned

Kingston Fossil Plant – 22 December 2008

Soil Properties and Behavior
- Soils: particulate media
- Particle-level forces
- Transition: d ~10μm

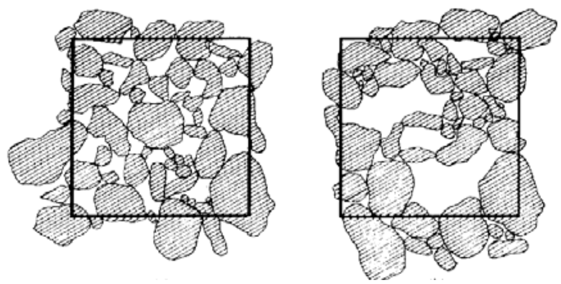
Energy Geotechnology
- Fly ash ponds
- Resource distribution
- Resource recovery
- Fines migration and formation damage
- Development of discontinuities – Fractures and lenses
- Mixed fluid conditions (oil-water; gas-water)
- Gas migration
- …

Hydraulic Conductivity & Fines Migration

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

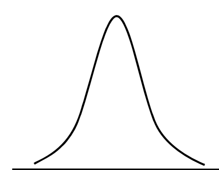
C. R. I. CLAYTON, M. B. HABABA and N. E. SIMONS (1985). *Géotechnique* **35**, No. 1, 19–31

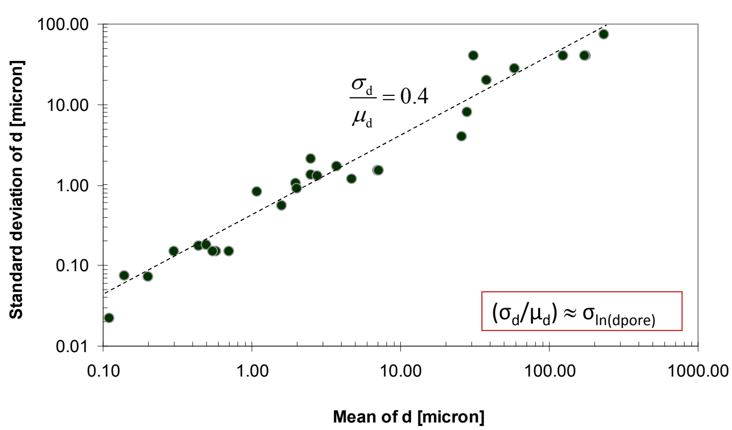
Professor G. A. Leonards, A. Alarcon, J. D. Frost, Y. E. Mohamedzein, J. C. Santamarina, S. Thevanayagam, J. E. Tomaz and J. L. Tyree, *Purdue University*



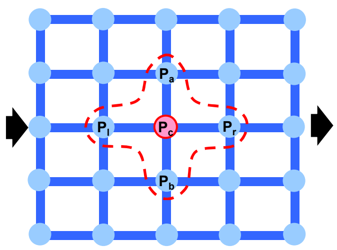
fabric *inherent and stress-induced anisotropy* *particle & pore-scale*

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

$$0 = \sum q_c$$

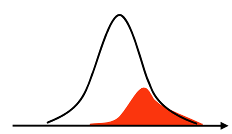
$$0 = \alpha_a (P_a - P_c) + \alpha_b (P_b - P_c) + \alpha_r (P_r - P_c) + \alpha_l (P_l - P_c)$$

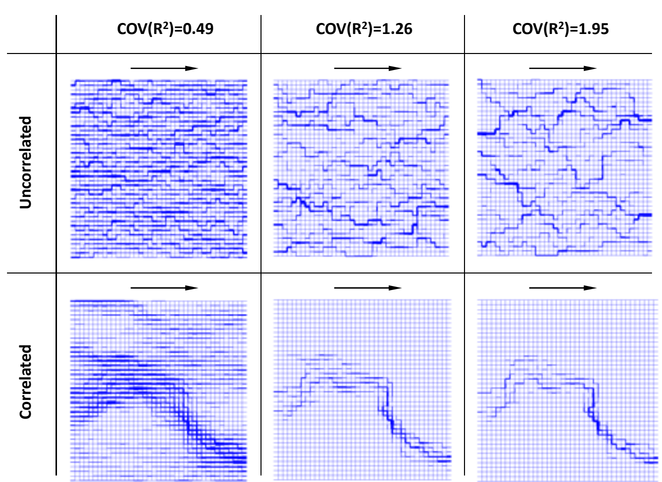
$$P_c = \frac{\alpha_a P_a + \alpha_b P_b + \alpha_r P_r + \alpha_l P_l}{(\alpha_a + \alpha_b + \alpha_r + \alpha_l)}$$

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

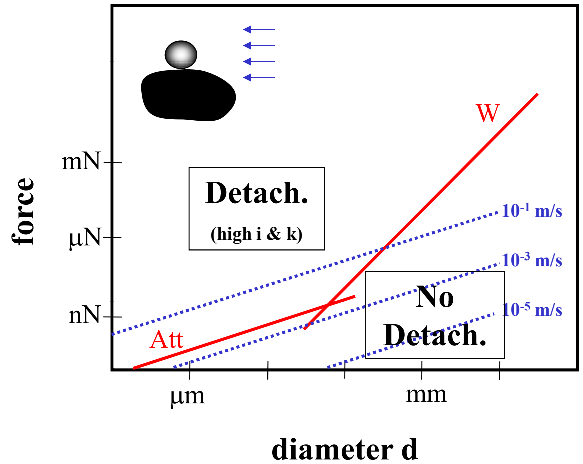
Hydrodynamic

Capillary

Electrical

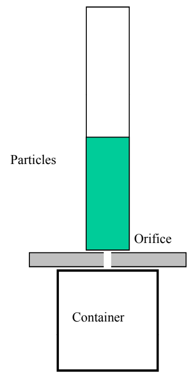
- attraction
- repulsion

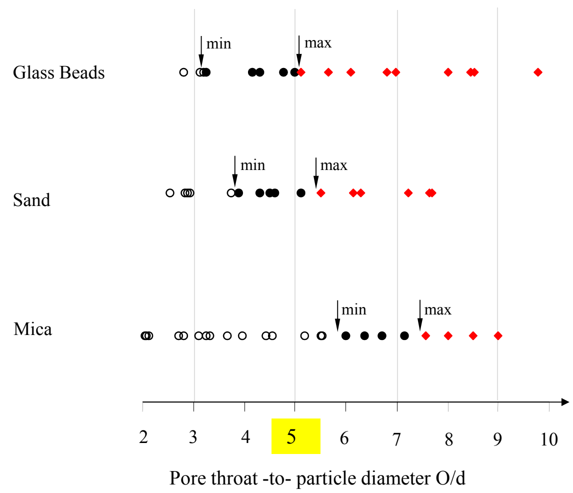
Cementation



Bridging

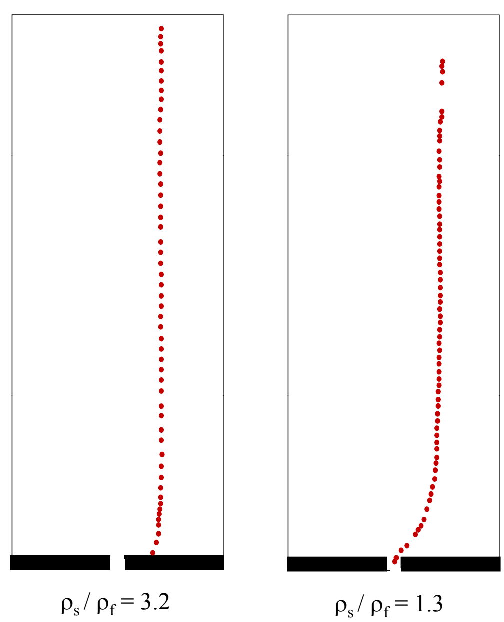
Bridging Conditions





J. Valdes

Grain-Fluid paths

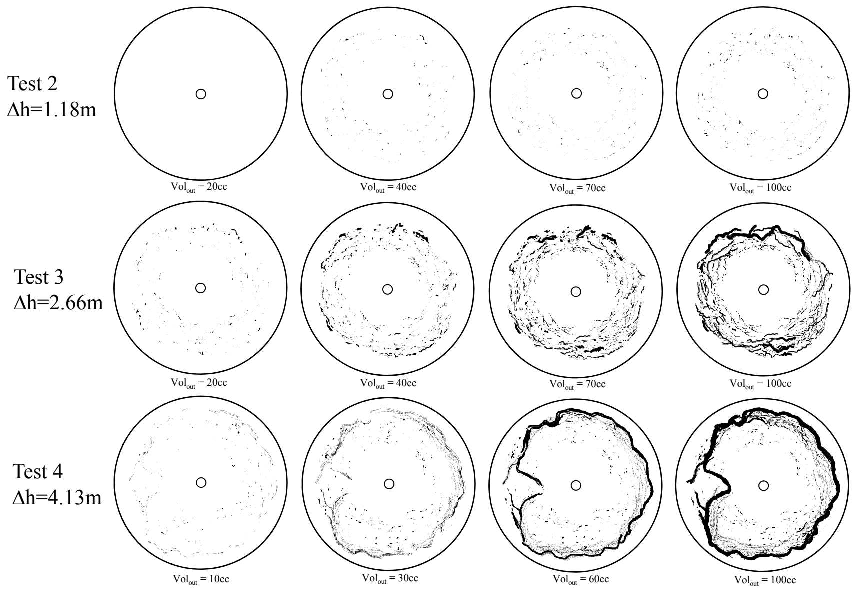


Deviation enhanced:

$\rho_s / \rho_f \uparrow$

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

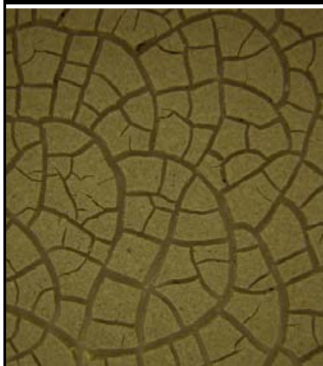
Journal of the
SOIL MECHANICS AND FOUNDATIONS DIVISION
Proceedings of the American Society of Civil Engineers

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

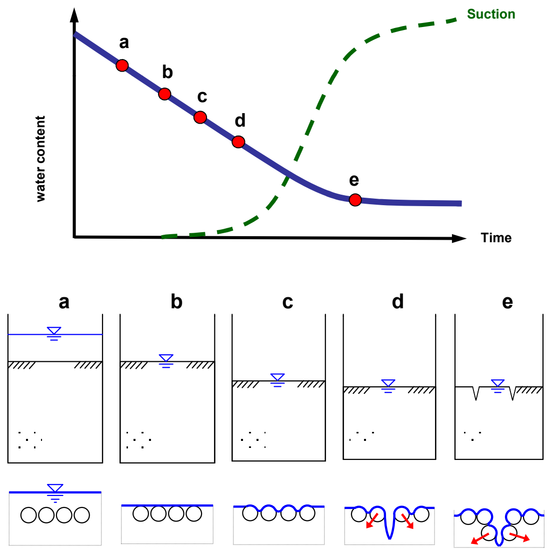


cm

Surface Tension

BBC News In pictures Visions of Science.jpg

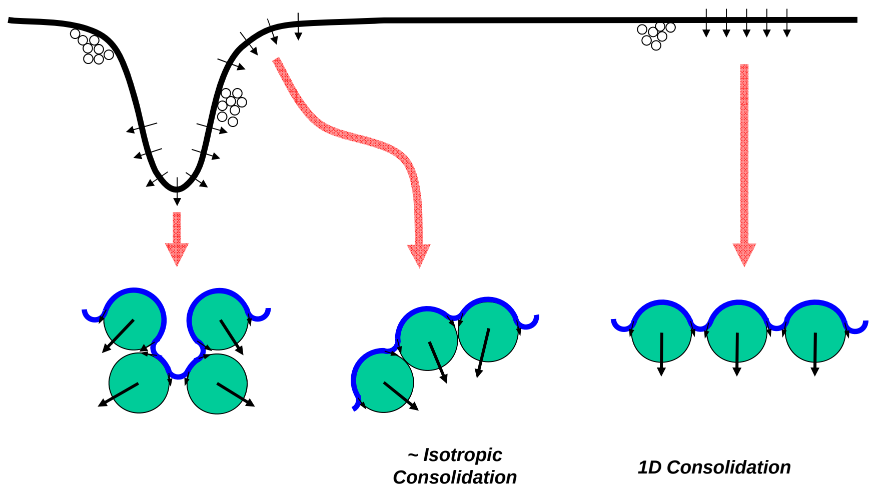
Desiccation Cracks - Evolution



Desiccation Cracks

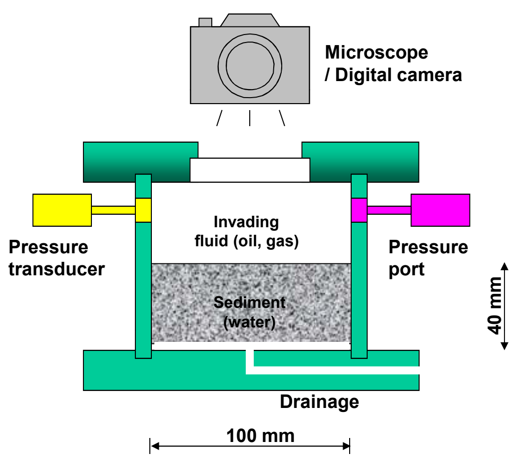
Hosung Shin

Desiccation Crack: Capillary Forces

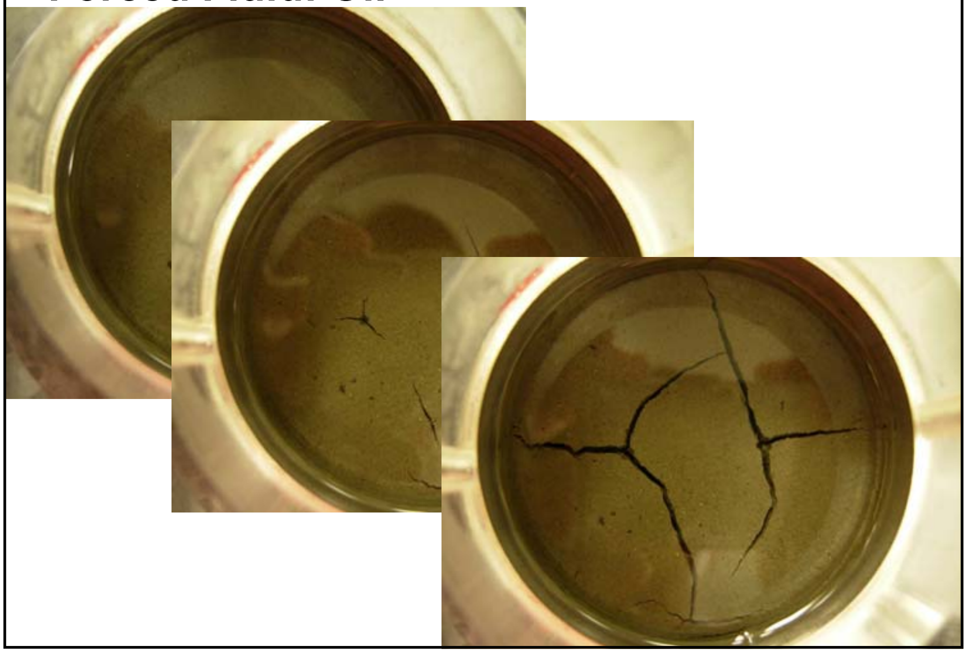


Soil is in compression EVERYwhere

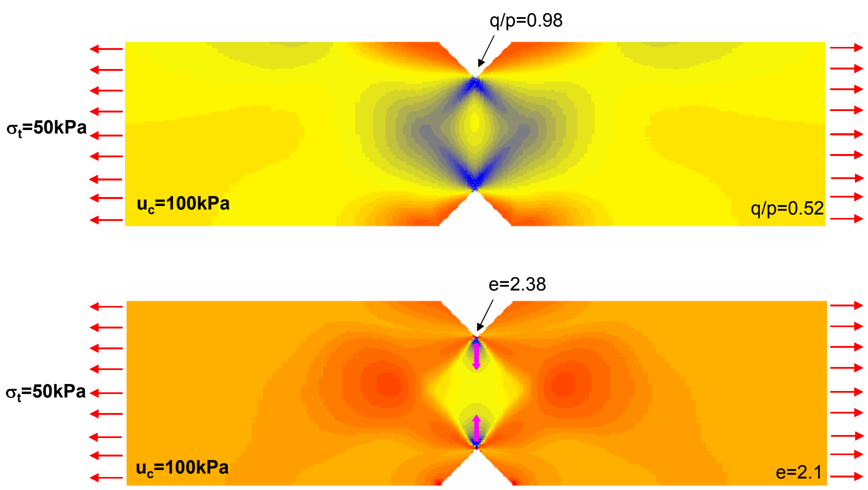
Forced Invasion of Immiscible Fluid



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

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

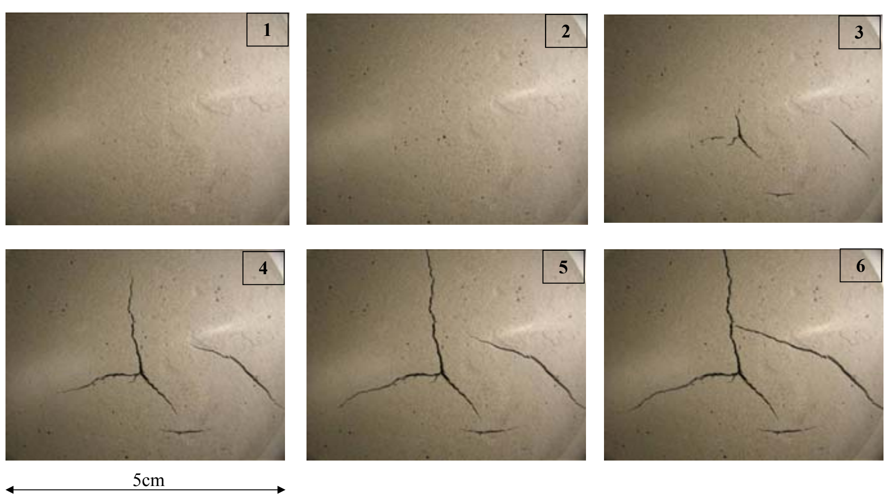
DISCONTINUITIES
Lenses
Fractures
Roots

← 0.1 — 1.0 — 10 →

coarse grained soils
high effective stress

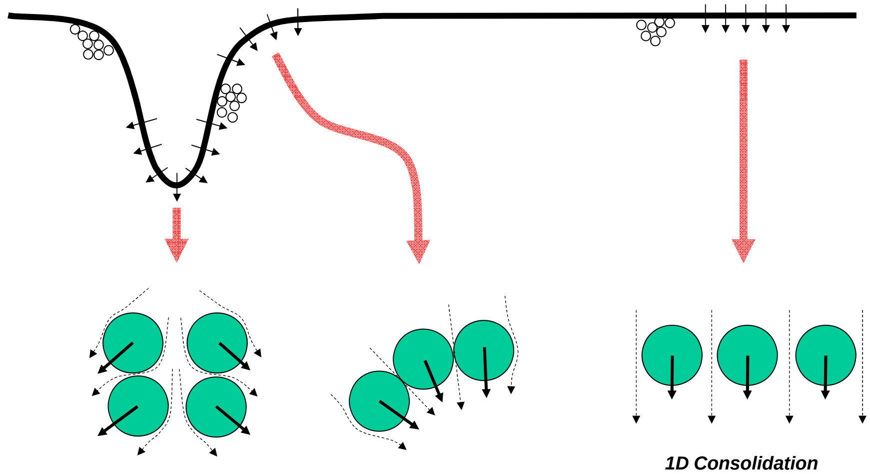
fine grained soils
low effective stress

Forced Miscible Fluid: Hydraulic Fracture



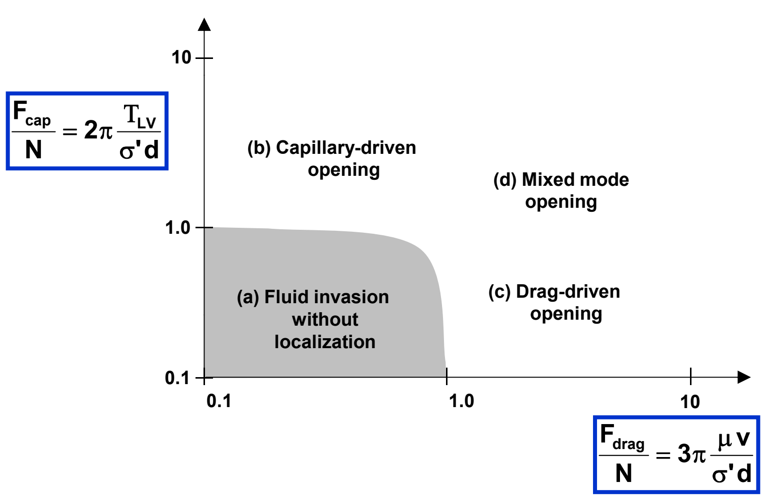
Hosung Shin

Hydraulic Fracture: Seepage Drag Forces

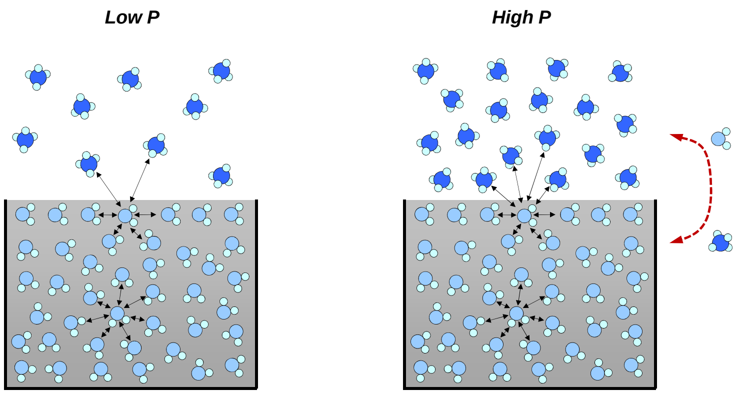


Soil is in compression EVERYwhere

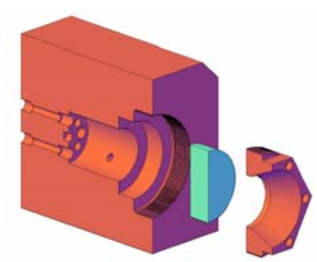
Miscible and/or Immiscible Fluid Invasion



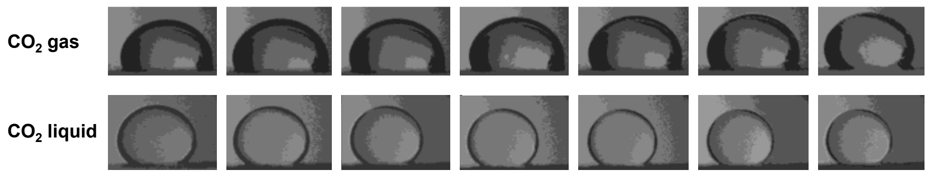
CO_2-H_2O Interfacial Interaction ?



Surface Tension and Contact Angle



Water droplet in



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

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

…. among others….

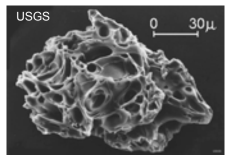
Mount St. Helens – May 18, 1980

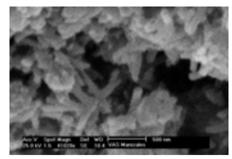
Mount St. Helens – May 18, 1980

Mount St. Helens – May 18, 1980

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

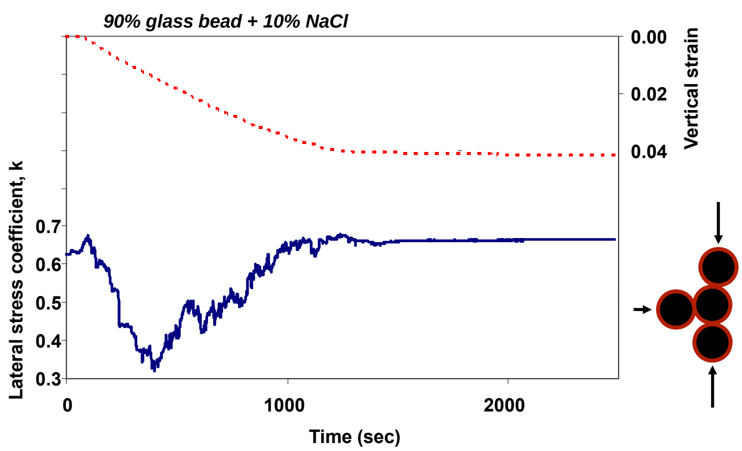




k_o=1-sinφ

k_o= ??

k_o: Experimental Results



Hosung Shin

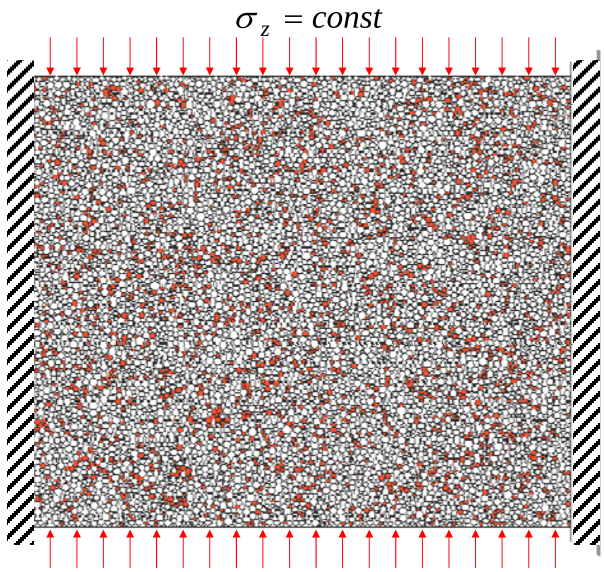
k_o: DEM Simulation

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

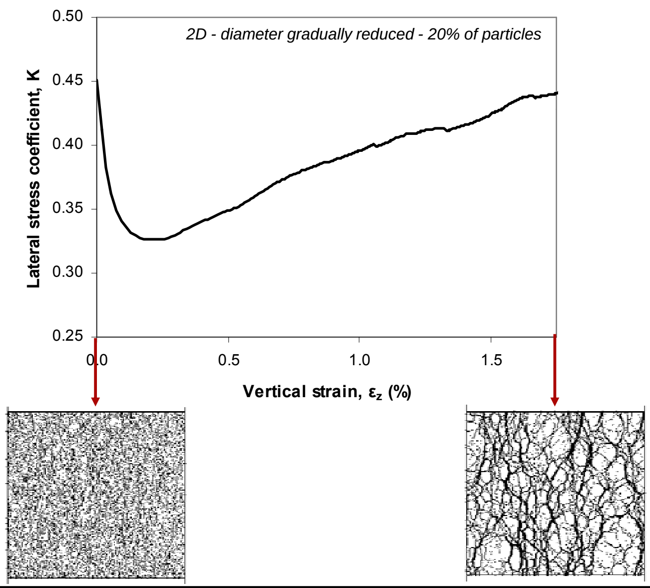
cov particle diameter: 0.25

Interparticle friction: 0.5

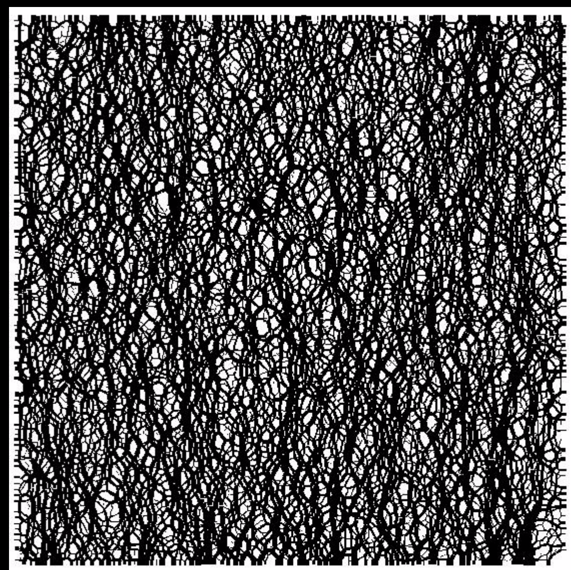
Simulation: reduce D or G



k_o: DEM Simulation

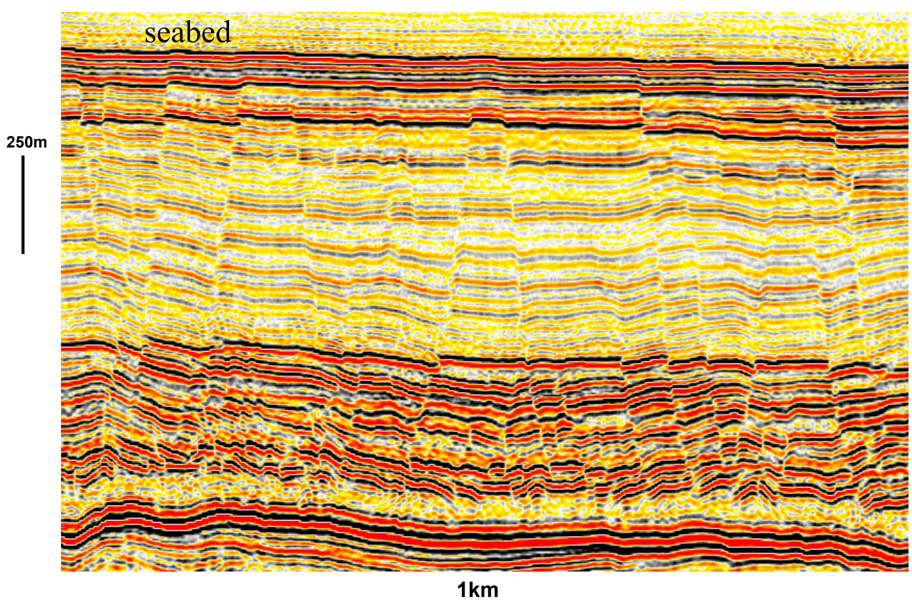


k_o: DEM Simulation – Pressure Solution



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)

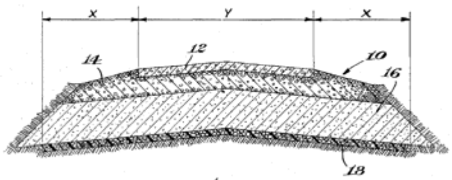


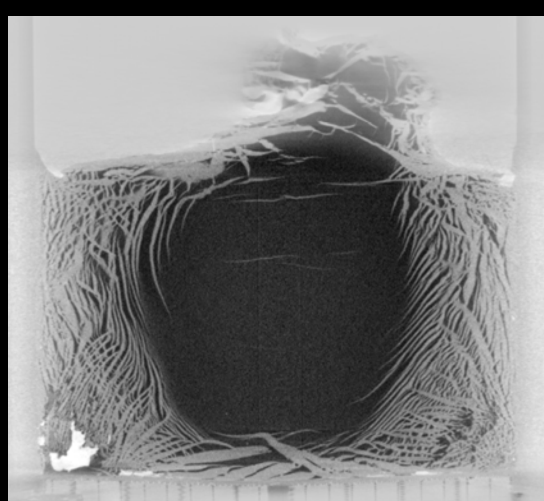
Fig. 1

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"

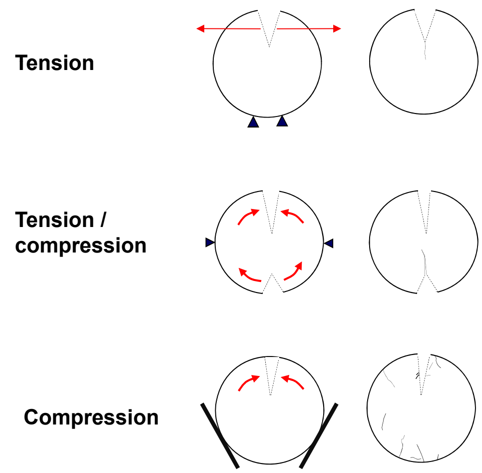
Ice Lenses



Kaolin

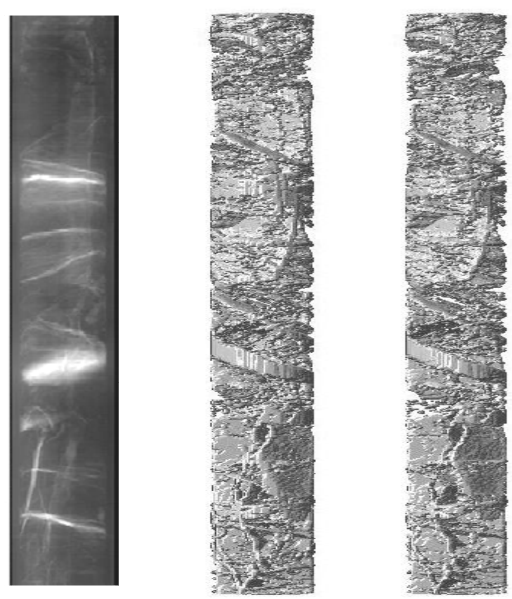
Viggiani – Grenoble

Ice Lens Formation Under Stress Boundary



Taesup Yun

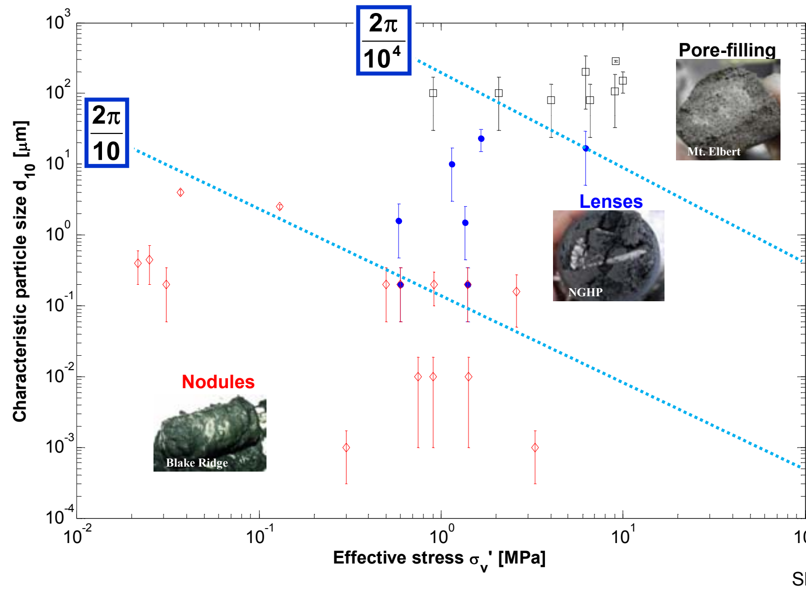
Hydrate lenses – Pressure cores



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

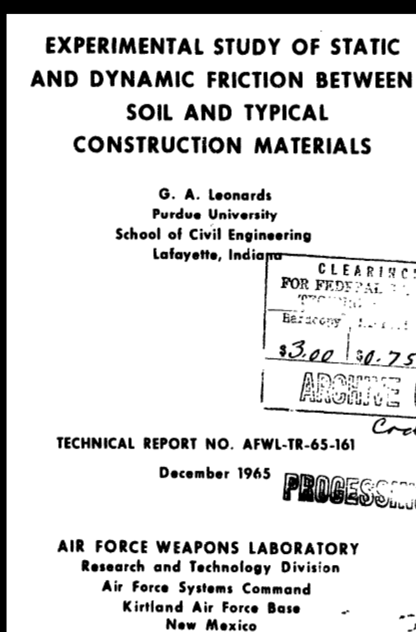
GREAT

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

$3.00 $0.75

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)

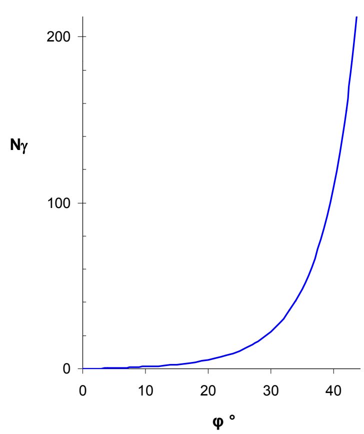
Subsidence and Vibration
Brumund & Leonards (1972)

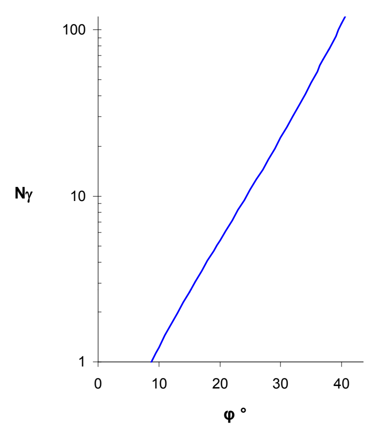
Friction and Vibration
Brumund & Leonards (1973)

Dynamic Compaction
Leonards, Cutter & Holtz (1980)

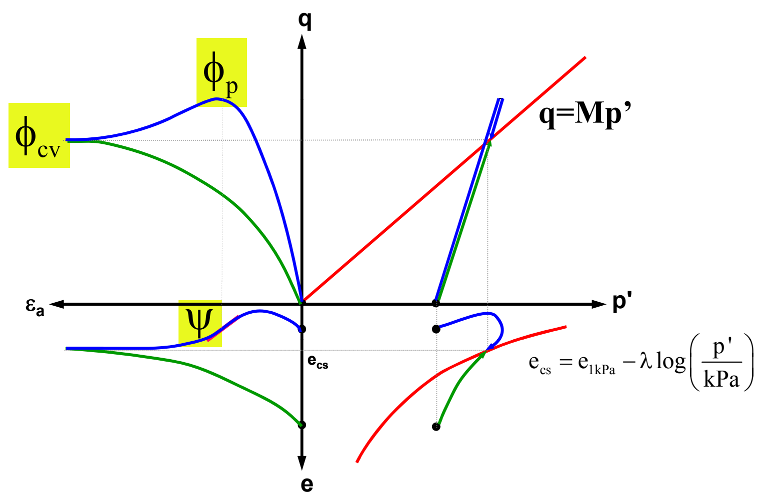
Undrained Monotonic And Cyclic Strength
Alarcon , Leonards & Chameau (1988)

Bearing Capacity – N factor

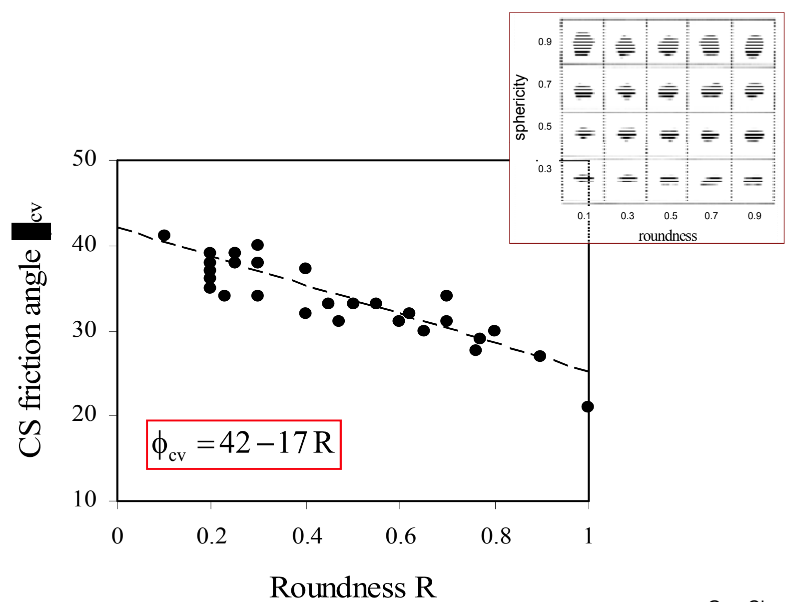




Macroscale Response in q, p’, e, ε

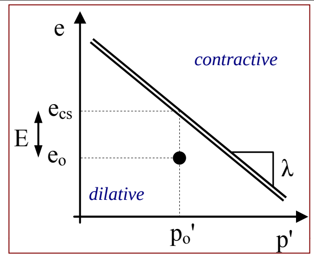


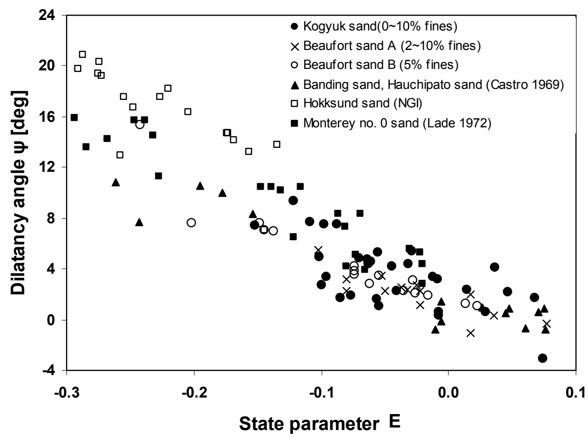
Constant Volume Shear ϕ_{cv}



Gye-Chun Cho

Dilatency Angle ψ



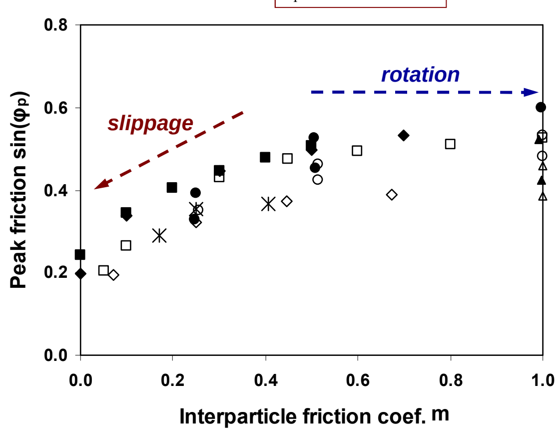


(Been and Jefferies 1985)

Peak Friction Angle ϕ_p

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

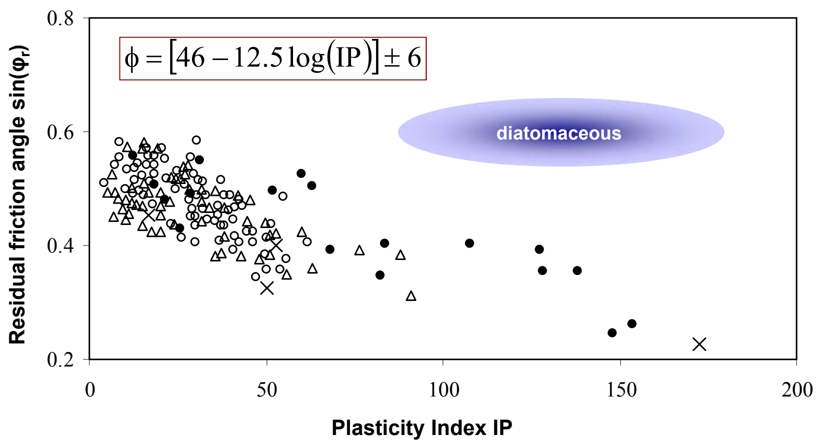
Bolton 1986: $\phi_p = \phi_{cv} + 0.8\psi$



□ (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.

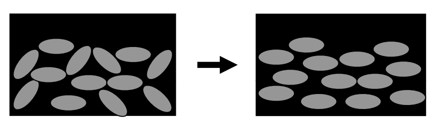
Residual Friction Angle ϕ_r

Note: clay fraction must exceed ~20%

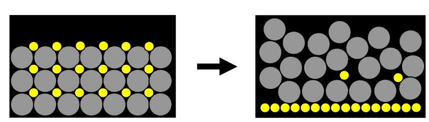


Very large strains $\phi_r < \phi_{cv}$

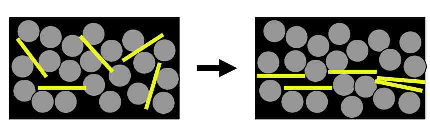
particle alignment



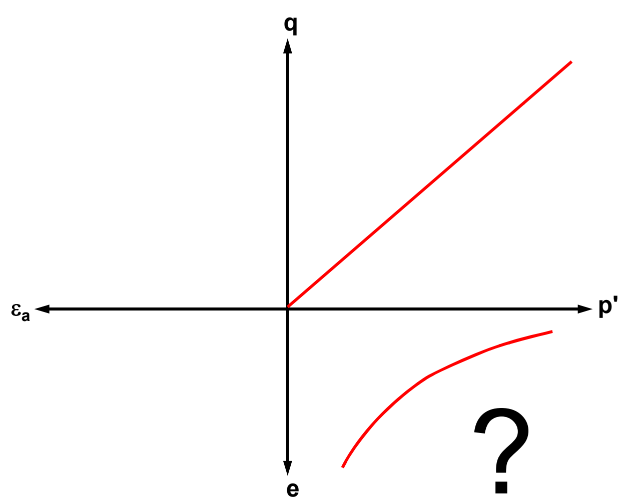
size segregation



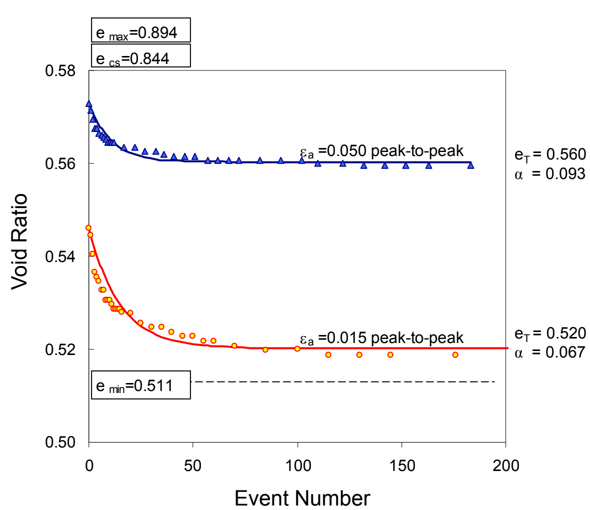
shape segregation



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

ϕ_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

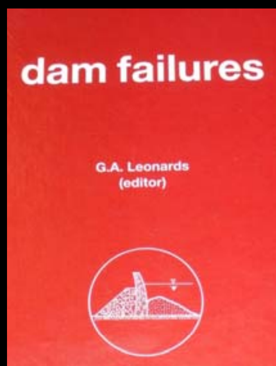
temperature: energy piles

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

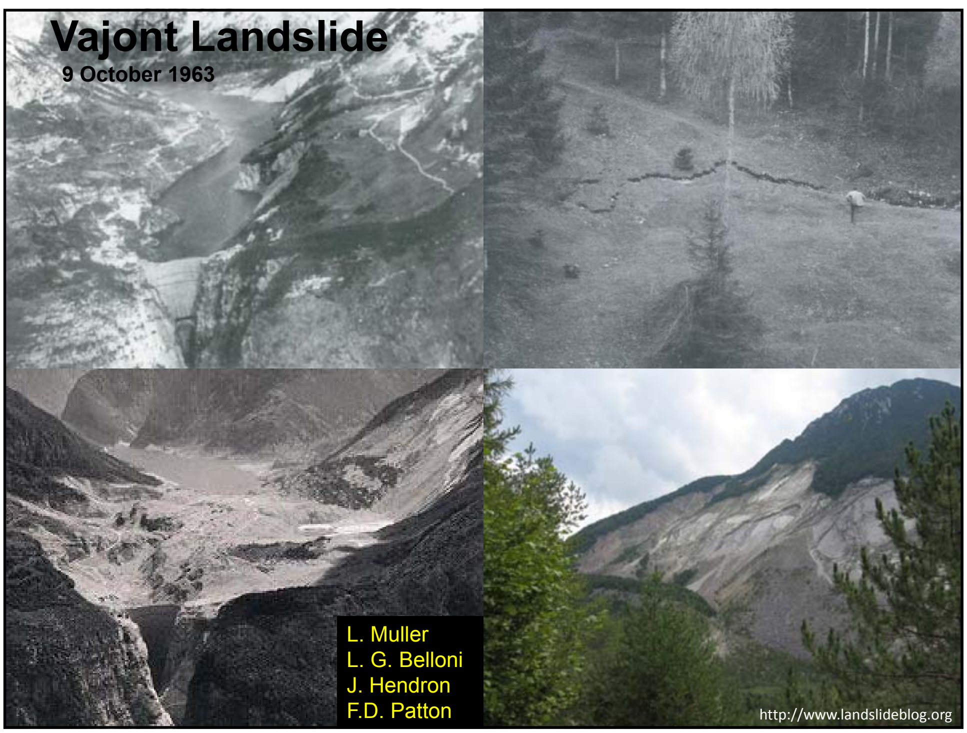
Slopes Instability & Dam Failures

GAL's analysis of failures: Multiple working hypotheses + Falsification

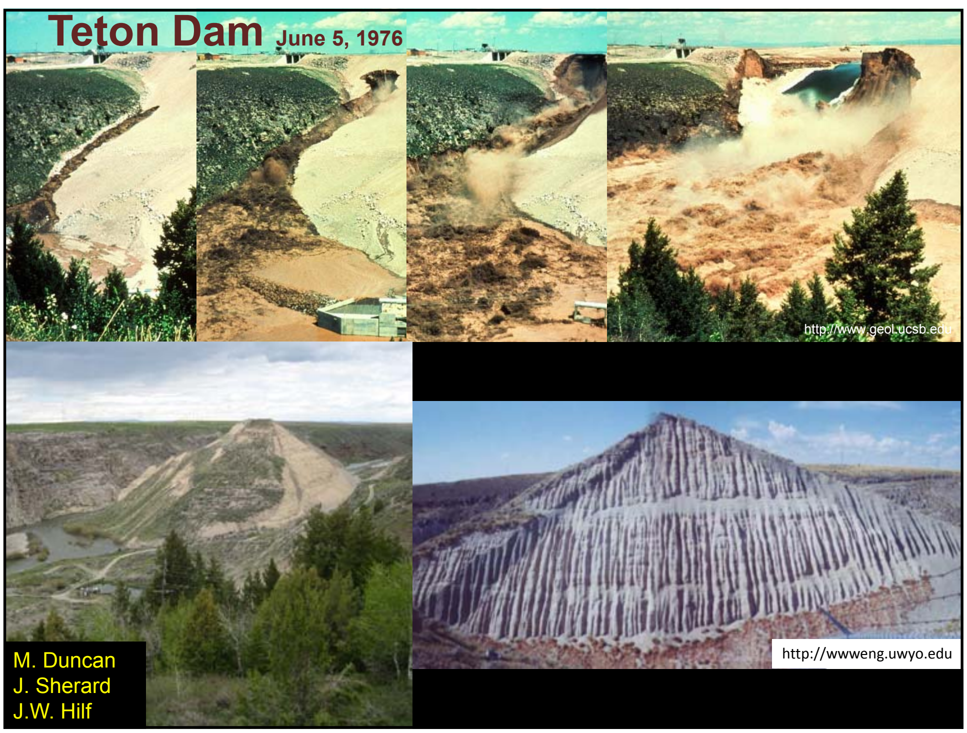
GAL's life: either PASSIONATE or SKEPTICAL



Pre-session meal ➔ "harmony"




Baldwin Hills Reservoir
14 December 1963
R.F. Scott
http://www3.gendisasters.com


Teton Dam June 5, 1976
http://www.geol.ucsb.edu
M. Duncan
J. Sherard
J.W. Hilf
http://wwweng.uwyo.edu


Malpasset Dam
December 2, 1959
P. Londe
J. L. Serafin
W. Wittke


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

Conclusions

GAL "Lessons Learned"

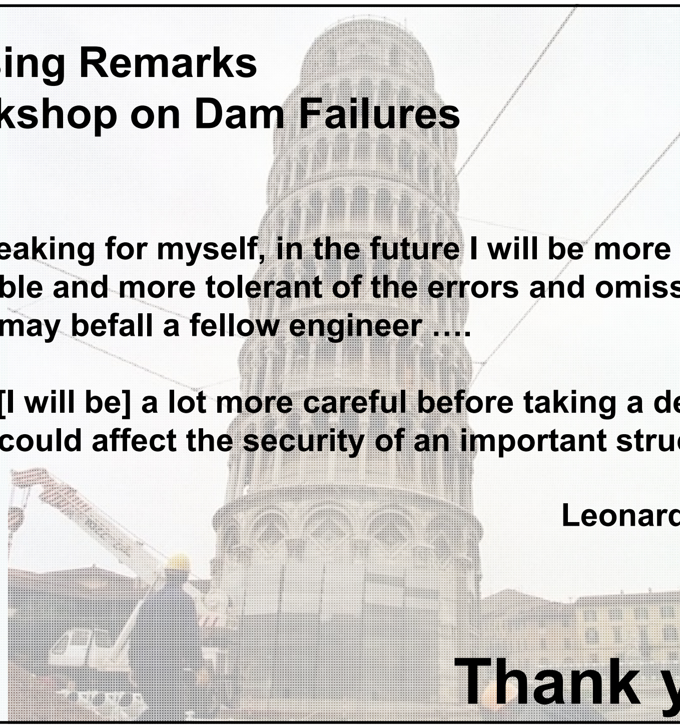
G.A. Leonards: (1) deepest clear-thinker (2) passion

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 !