Buenos Aires – November 2015

Soil and Rock Properties

- Preamble -

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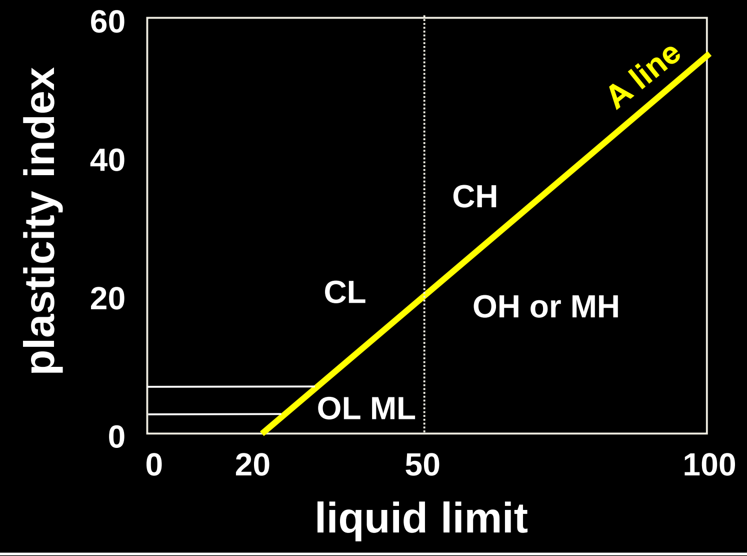
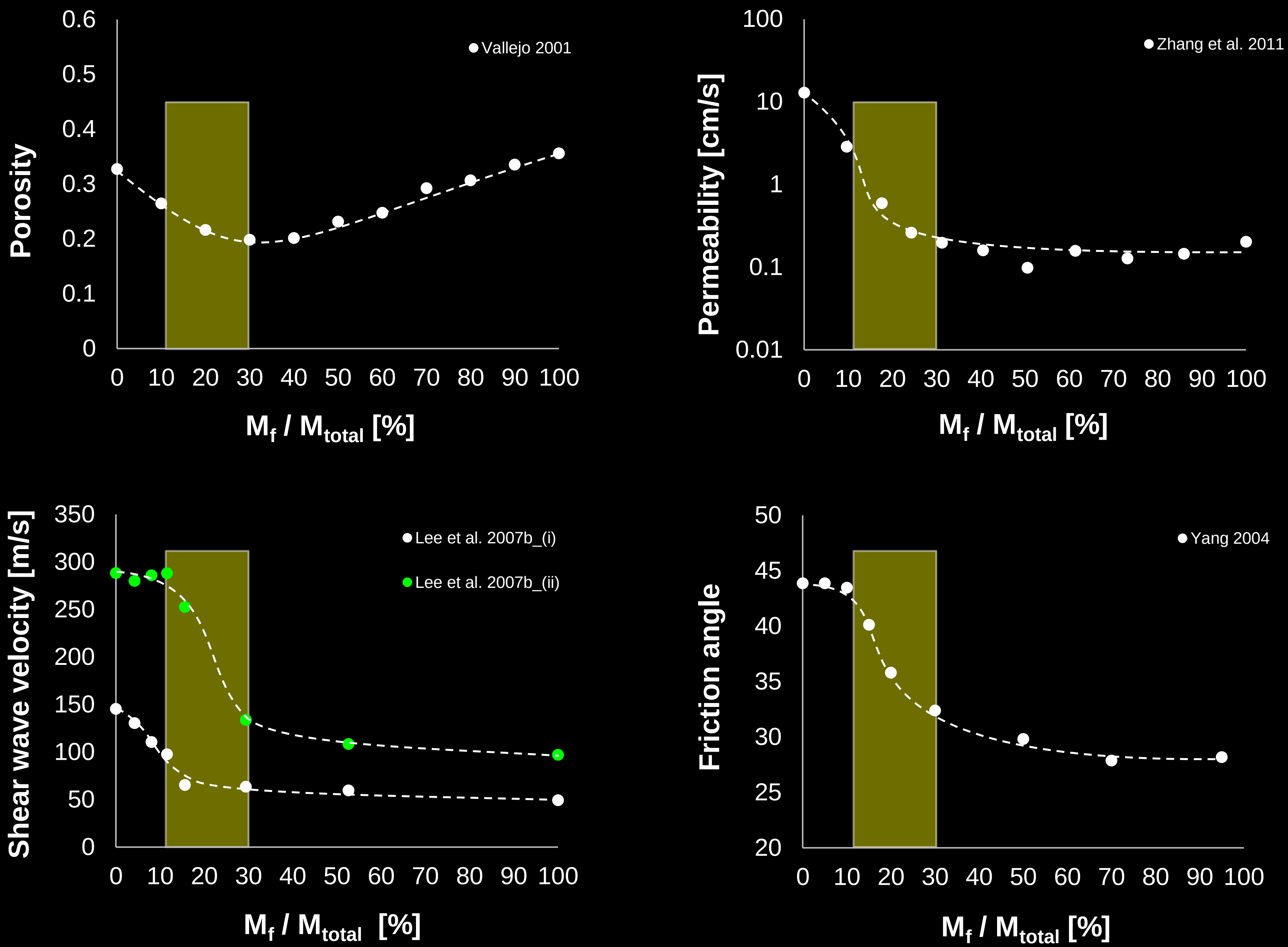
KAUST

1. Classification ➔ Properties
2. Permeability
3. Compressibility
4. Coupling
5. Stiffness: $G_{max} \leftrightarrow G_{tan}$ …Oedometer
6. Shear Strength - Localization
7. Repetitive Loads
8. Properties: Database & IT tool

1. **Classification → Properties**
2. **Permeability**
3. **Compressibility**
4. **Coupling**
5. **Stiffness: $G_{max} \leftrightarrow G_{tan}$ …Oedometer**
6. **Shear Strength - Localization**
7. **Repetitive Loads**
8. **Properties: Database & IT tool**

<table>
<tr><td rowspan="8">COARSE
R > 50%</td><td rowspan="4">Gravel
R > 50%</td><td rowspan="2">< 5% fines</td><td>$C_u>4,\ 1\le C_c\le 3$</td><td>GW</td></tr>
<tr><td>else</td><td>GP</td></tr>
<tr><td rowspan="2">% fines
> 12% fines</td><td>below A-line</td><td>GM</td></tr>
<tr><td>above A-line</td><td>GC</td></tr>
<tr><td rowspan="4"># 4
Sand
P > 50%</td><td rowspan="2">< 5% fines</td><td>$C_u>6,\ 1\le C_c\le 3$</td><td>SW</td></tr>
<tr><td>else</td><td>SP</td></tr>
<tr><td rowspan="2">% fines
> 12% fines</td><td>below A-line</td><td>SM</td></tr>
<tr><td>above A-line</td><td>SC</td></tr>
<tr><td rowspan="6"># 200
FINE
P > 50%</td><td rowspan="3">Low Plasticity
LL < 50</td><td colspan="2" rowspan="6"></td><td>ML</td></tr>
<tr><td>CL</td></tr>
<tr><td>OL</td></tr>
<tr><td rowspan="3">High Plasticity
LL > 50</td><td>MH</td></tr>
<tr><td>CH</td></tr>
<tr><td>OH</td></tr>
</table>

Coarse

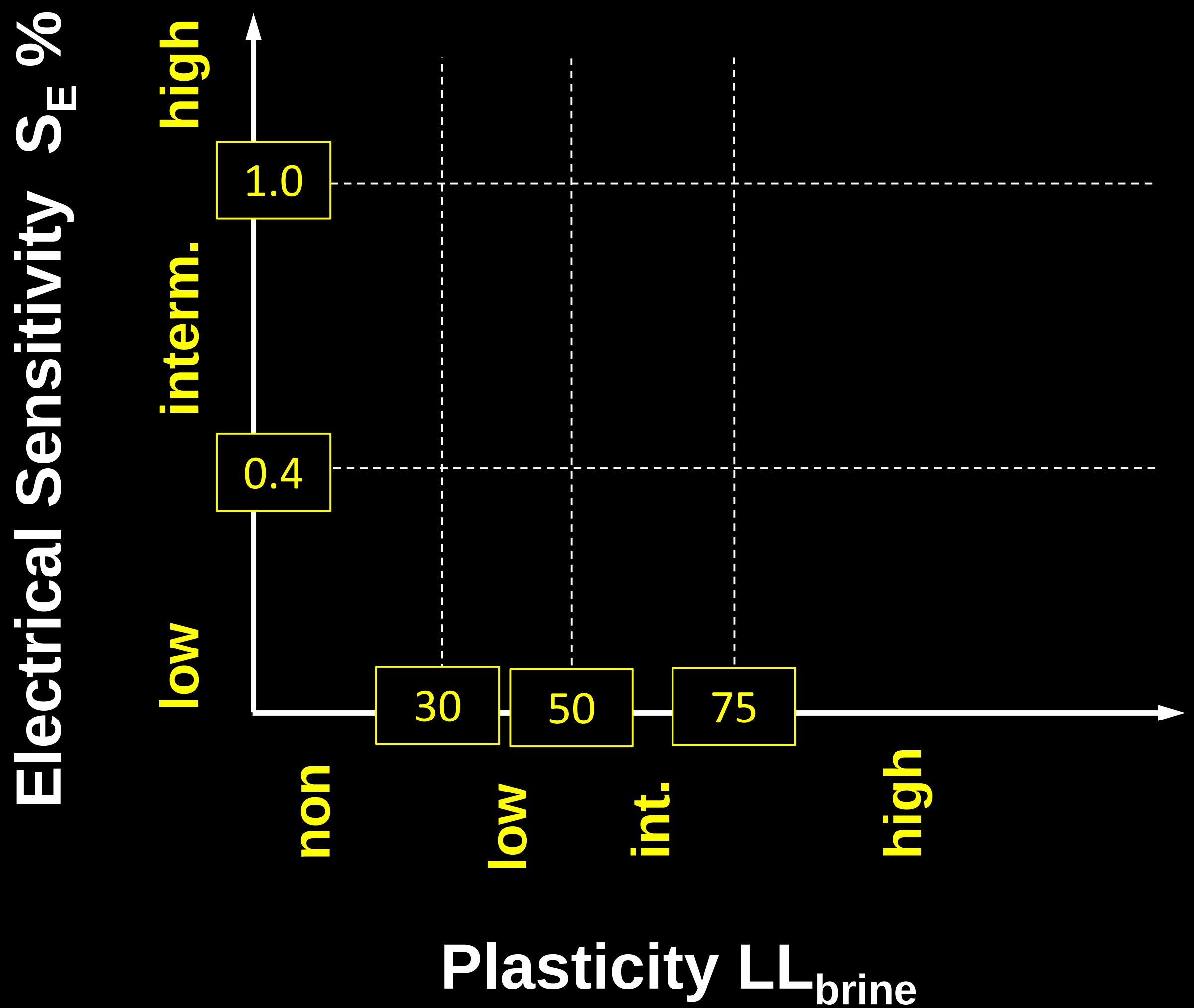


Porosity
0.6
0.5
0.4
0.3
0.2
0.1
0
Vallejo 2001
0 10 20 30 40 50 60 70 80 90 100
Mf / Mtotal [%]
Permeability [cm/s]
100
10
1
0.1
0.01
Zhang et al. 2011
0 10 20 30 40 50 60 70 80 90 100
Mf / Mtotal [%]
Shear wave velocity [m/s]
350
300
250
200
150
100
50
0
Lee et al. 2007b_(i)
Lee et al. 2007b_(ii)
0 10 20 30 40 50 60 70 80 90 100
Mf / Mtotal [%]
Friction angle
50
45
40
35
30
25
20
Yang 2004
0 10 20 30 40 50 60 70 80 90 100
Mf / Mtotal [%]

Fines:

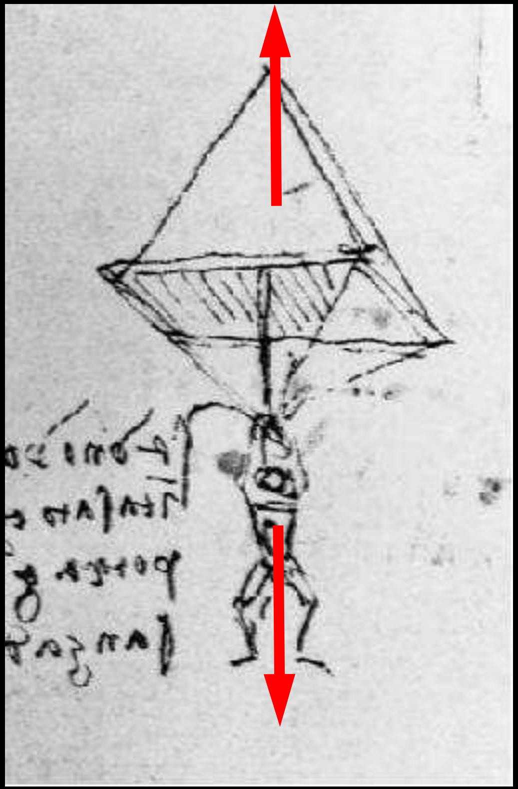
(Pass #200)

$$S_E = \sqrt{\left(\frac{LL_{DW}}{LL_{brine}}-1\right)^2+\left(\frac{LL_{ker}}{LL_{brine}}-1\right)^2}$$



1. Classification
2. Permeability

Leonardo's Parachute



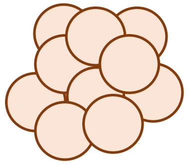
Hydraulic Conductivity: ***Physics***

Physics-inspired:

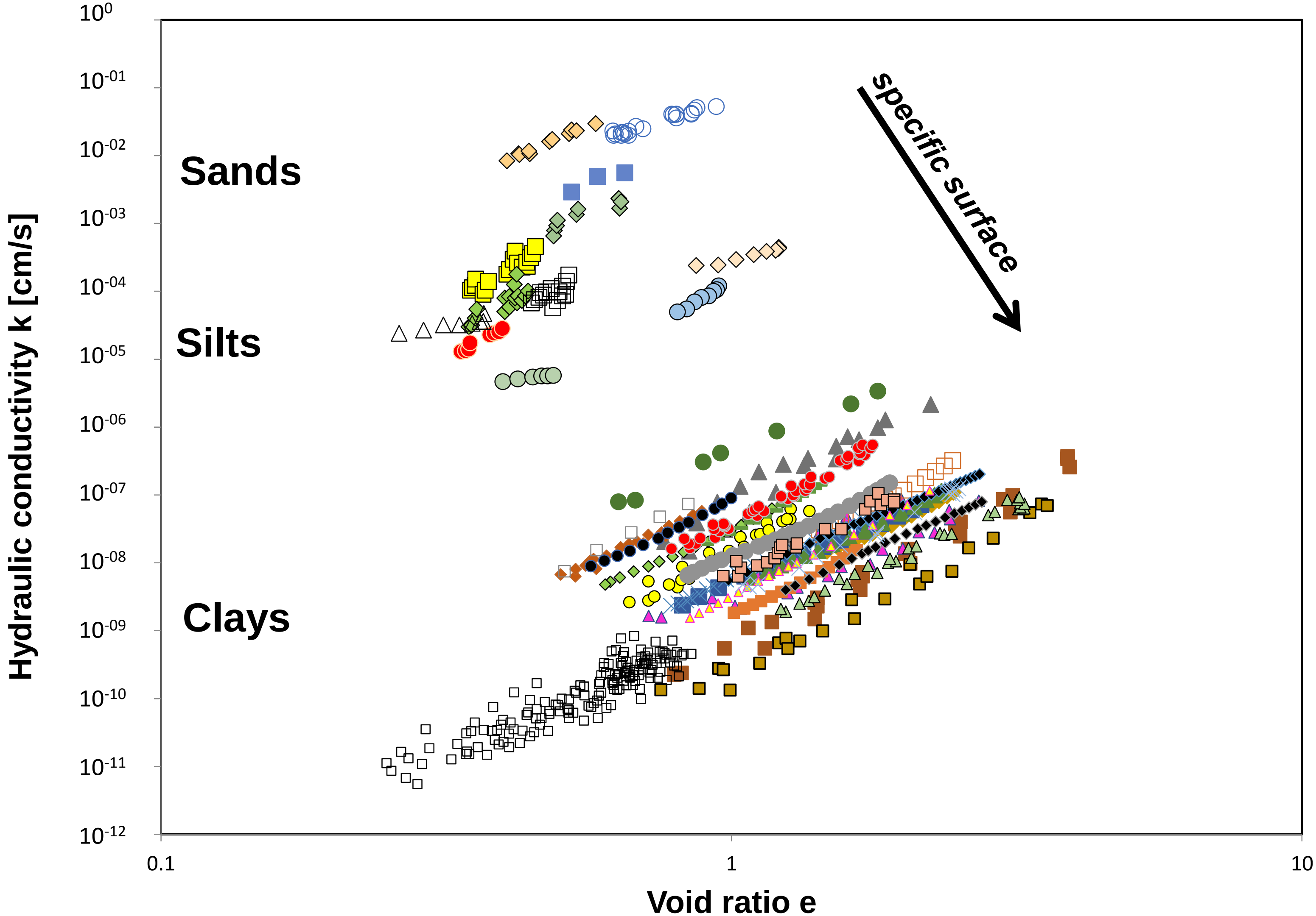
Hagen–Poiseuille

Kozeny-Carman

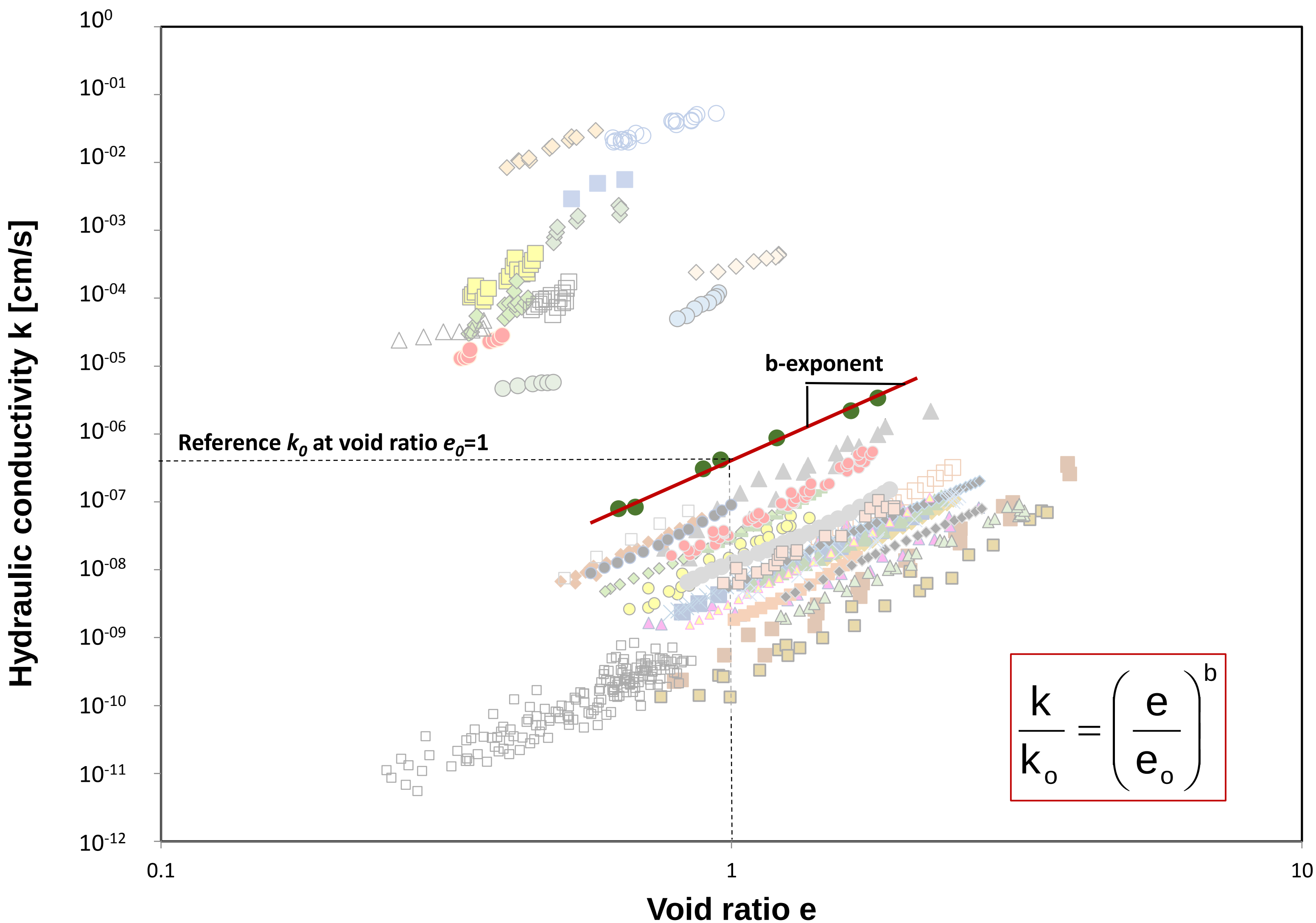
$$k = \frac{cg}{\mu_{fl}} \frac{\rho_{fl}}{\rho_m} \left(\frac{1}{S_s} \right)^2 \frac{e^3}{1+e}$$

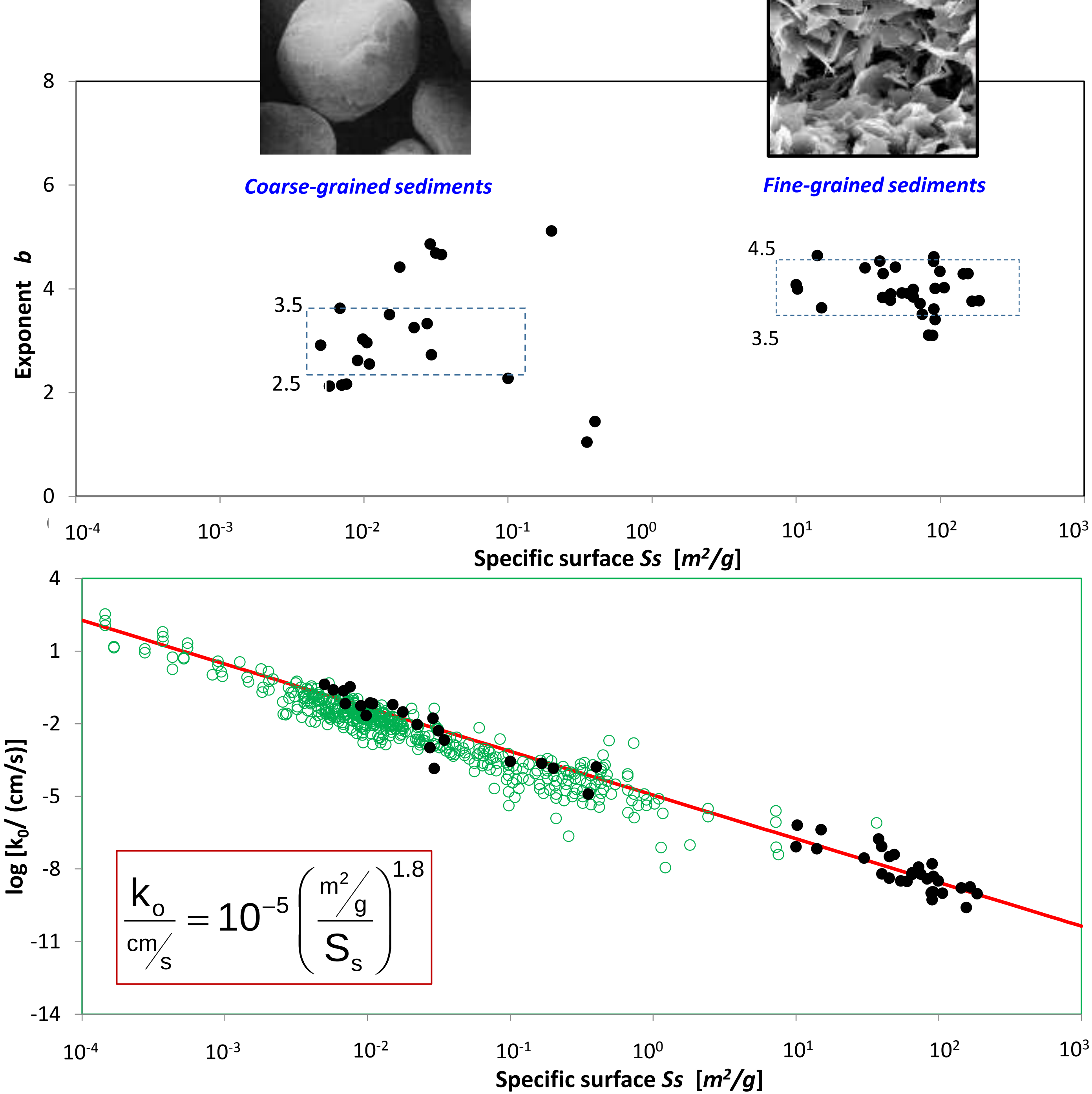


Hydraulic Conductivity: Data



Hydraulic Conductivity: <u>Data</u>




Coarse-grained sediments
Fine-grained sediments
Exponent b
8
6
4
2
0
3.5
2.5
4.5
3.5
10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^{0} 10^{1} 10^{2} 10^{3}
Specific surface *Ss* [m^2/g]
log [k_0/ (cm/s)]
4
1
-2
-5
-8
-11
-14
$\frac{k_o}{cm/s} = 10^{-5}\left(\frac{m^2/g}{S_s}\right)^{1.8}$
10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^{0} 10^{1} 10^{2} 10^{3}
Specific surface *Ss* [m^2/g]

Hydraulic Conductivity

Physics-inspired:

Hagen–Poiseuille
Kozeny-Carman

$$k = \frac{cg}{\mu_{fl}} \frac{\rho_{fl}}{\rho_m} \left(\frac{1}{S_s} \right)^2 \frac{e^3}{1+e}$$

Data-driven:

$$\begin{cases} \dfrac{k}{k_o} = \left(\dfrac{e}{e_o} \right)^b \\[2ex] \dfrac{k_o}{\mathrm{cm}/\mathrm{s}} = 10^{-5} \left(\dfrac{\mathrm{m}^2/\mathrm{g}}{S_s} \right)^{1.8} \end{cases}$$

(for water)

Robust model

$$\frac{k}{\mathrm{cm}/\mathrm{s}} = 10^{-5} \left(\frac{\mathrm{m}^2/\mathrm{g}}{S_s} \right)^{1.8} e^b$$

(for water)

Hydraulic Conductivity

Physics-inspired:

Hagen–Poiseuille

Kozeny-Carman

$$k = \frac{cg}{\mu_{fl}} \frac{\rho_{fl}}{\rho_m} \boxed{\left(\frac{1}{S_s}\right)^2} \boxed{\frac{e^3}{1+e}}$$

~$e^{1.85}$

Data-driven:

$$\begin{cases} \dfrac{k}{k_o} = \left(\dfrac{e}{e_o}\right)^b \\[2ex] \dfrac{k_o}{cm/s} = 10^{-5}\left(\dfrac{m^2/g}{S_s}\right)^{1.8} \end{cases}$$

(for water)

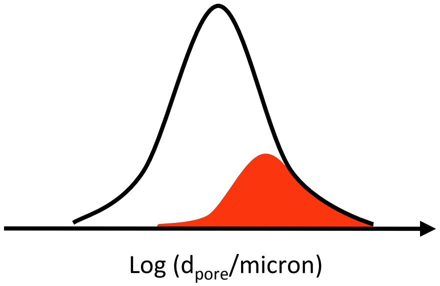
Robust model

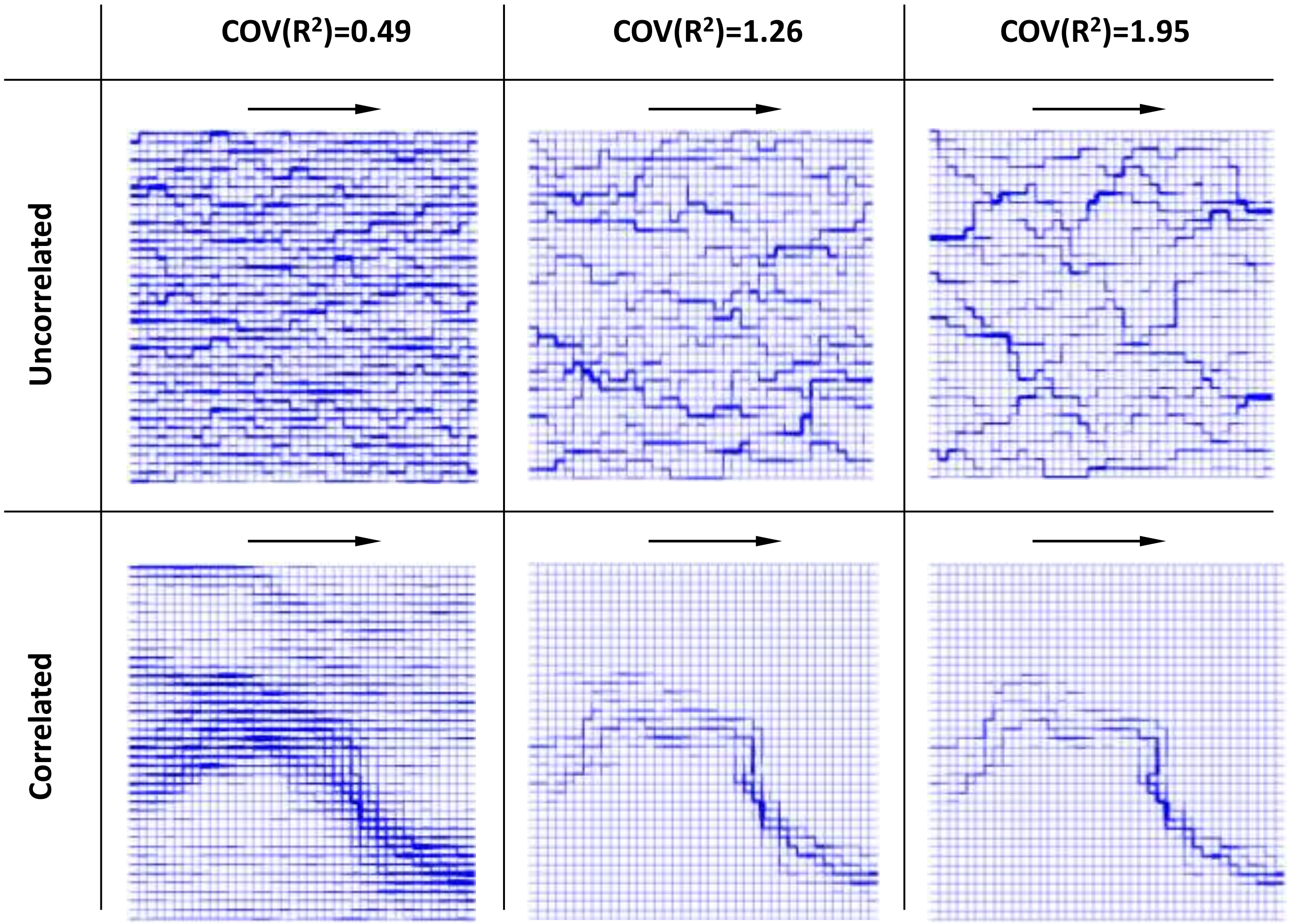
$$\frac{k}{cm/s} = 10^{-5} \boxed{\left(\frac{m^2/g}{S_s}\right)^{1.8}} \boxed{e^b}$$

b=2-to-5

(for water)

Pore Network



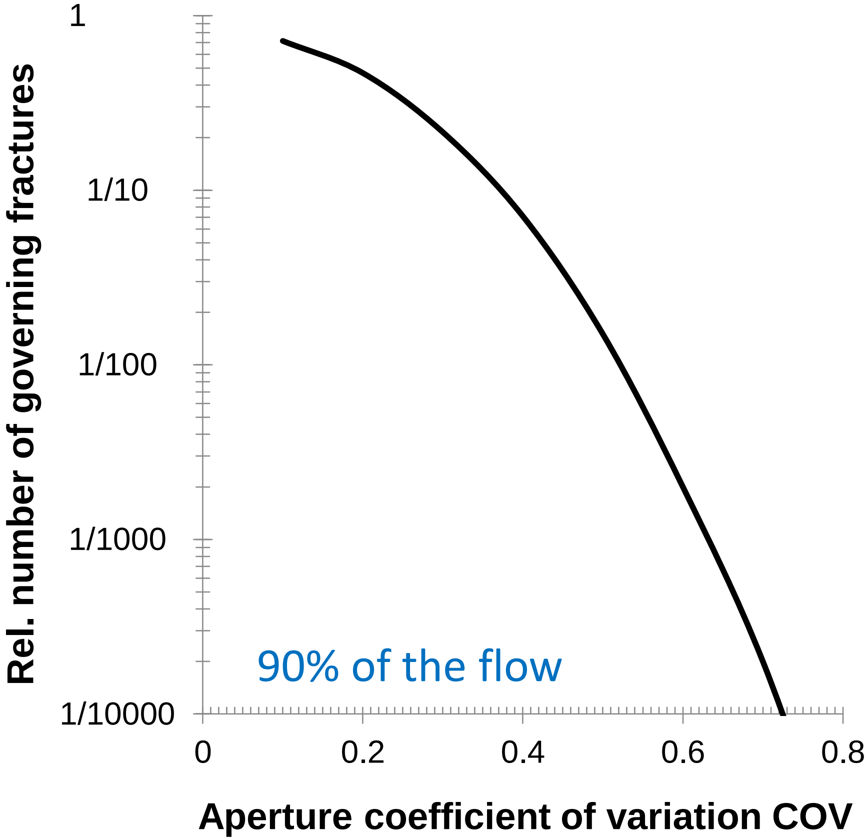


preferential flow along interconnected large pores

Hydraulic Conductivity: Fractured Rocks

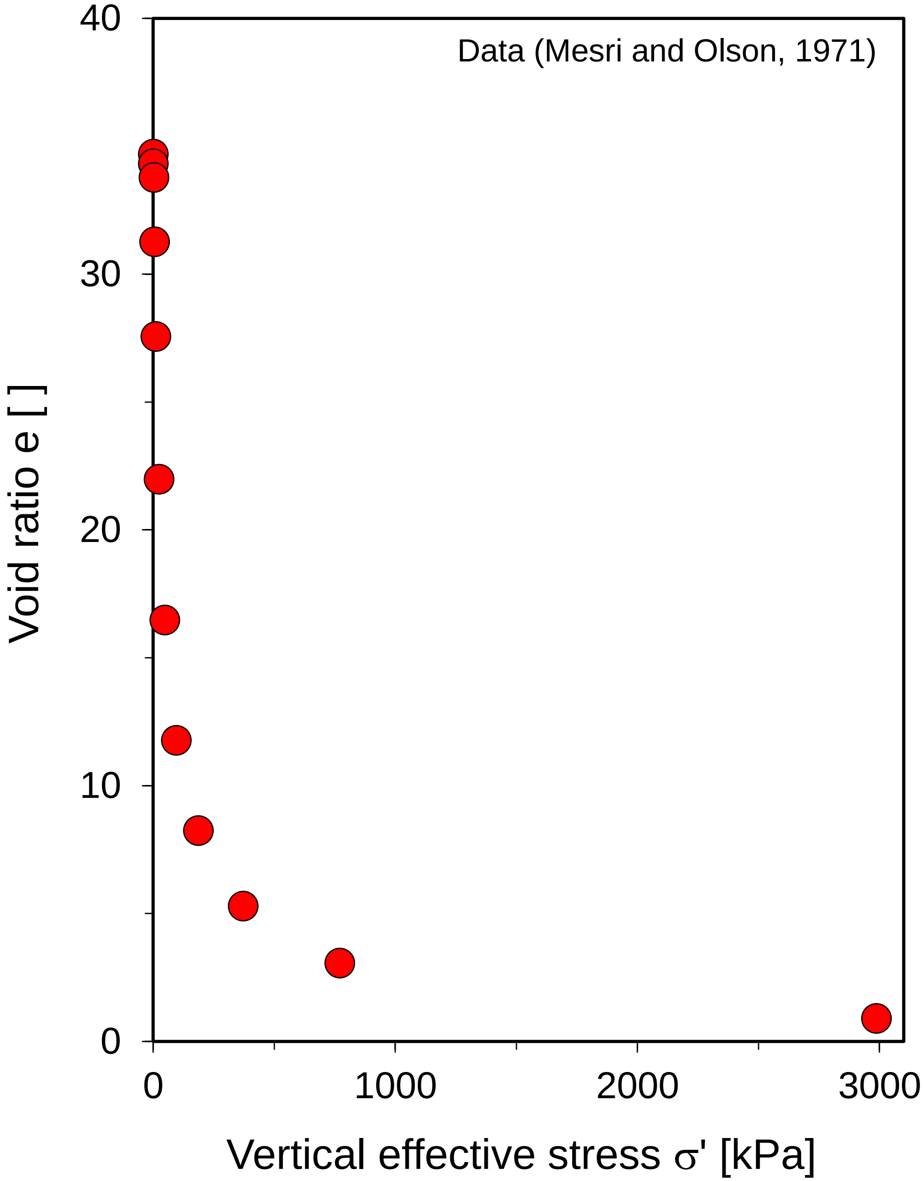
Marcellus shale outcrop

Don Duggan-Haas

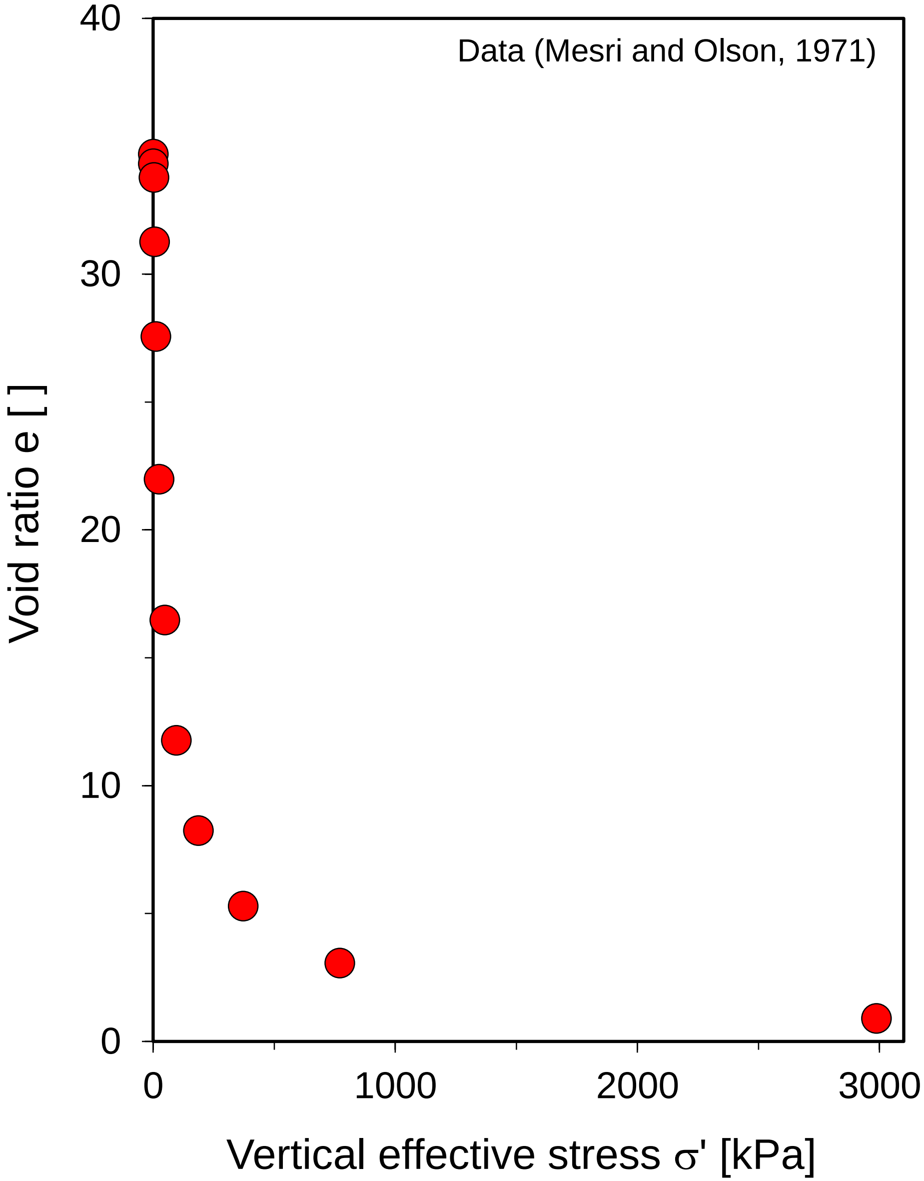


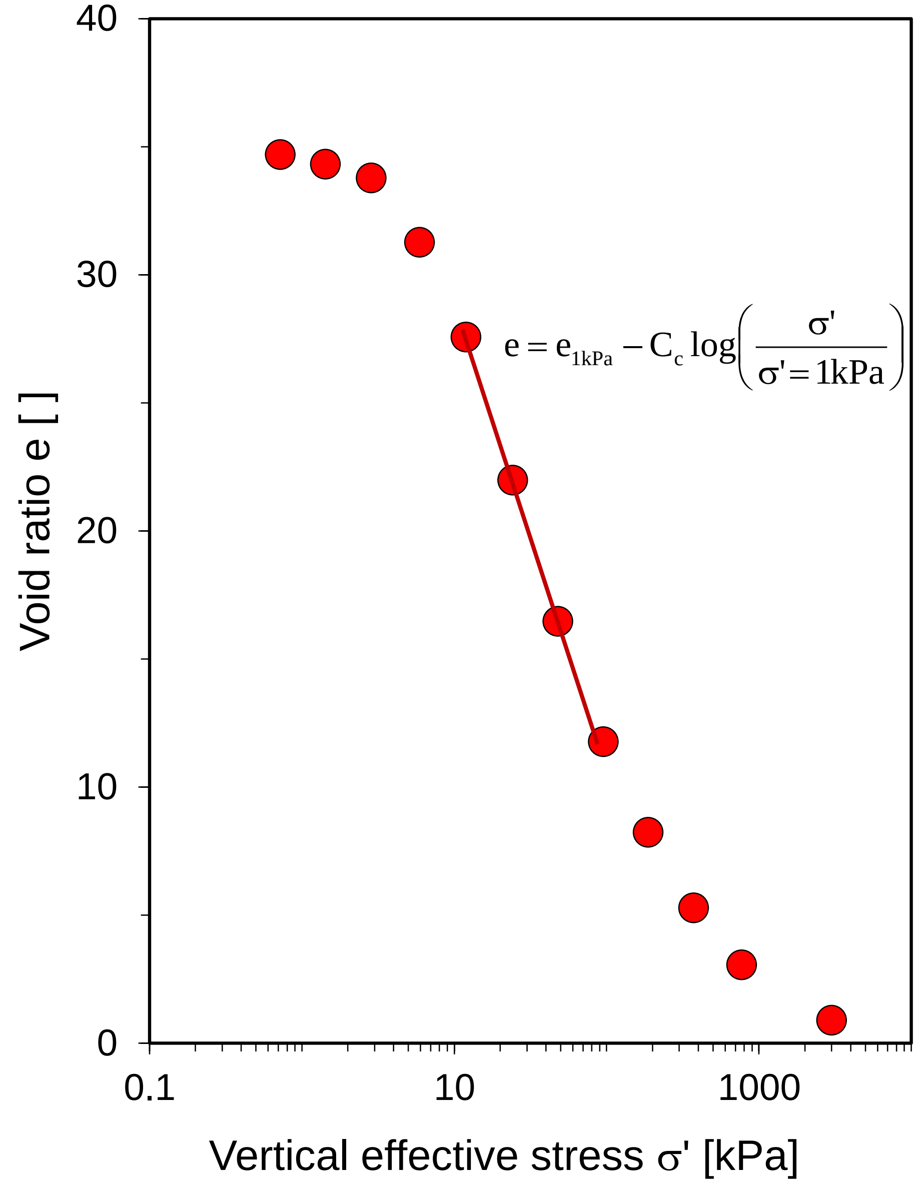
1. Classification
2. Permeability
3. Compressibility

k_o Compression: Data



k_o Compression: Model





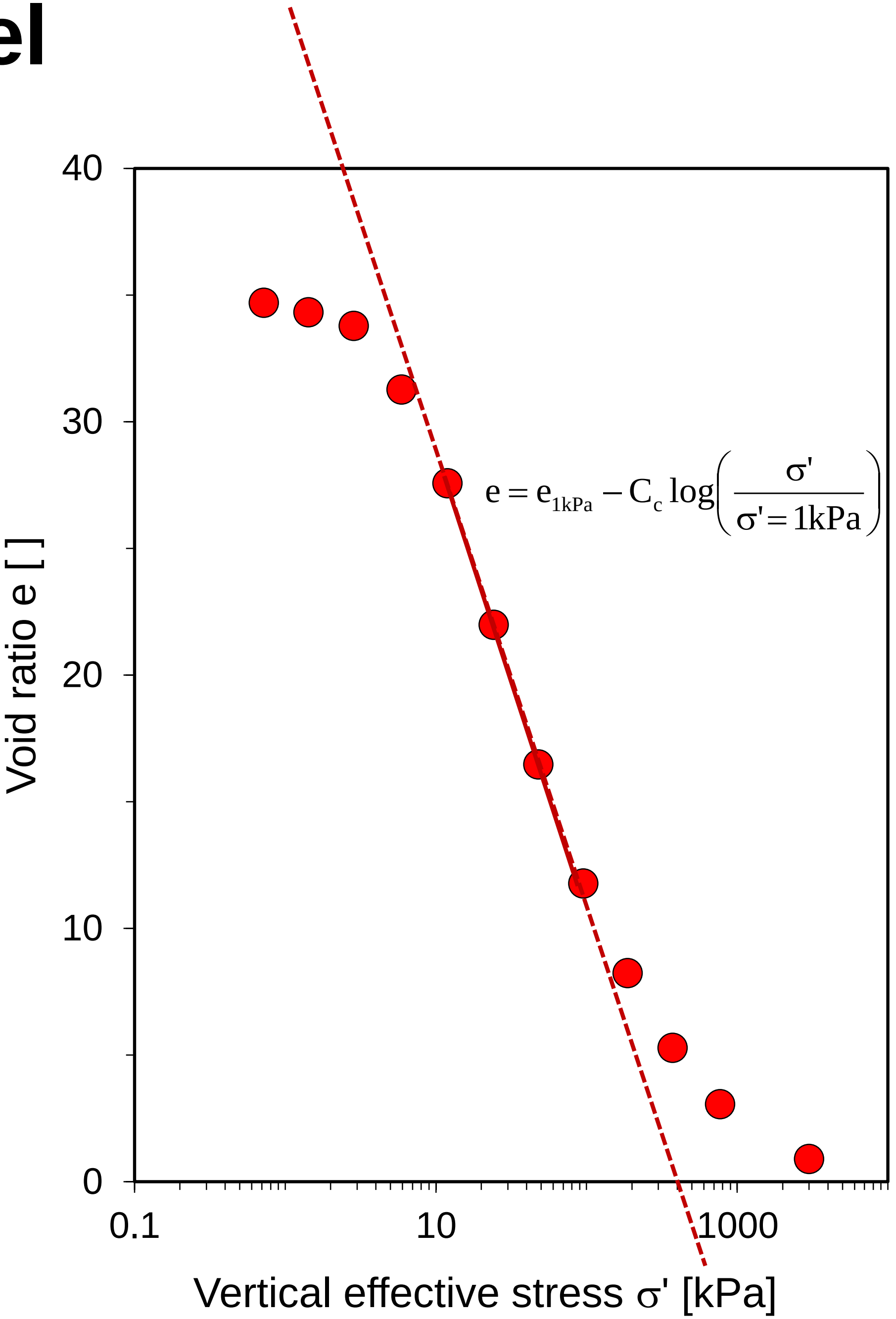
k_o Compression: Model

Low-stress e-asymptote:

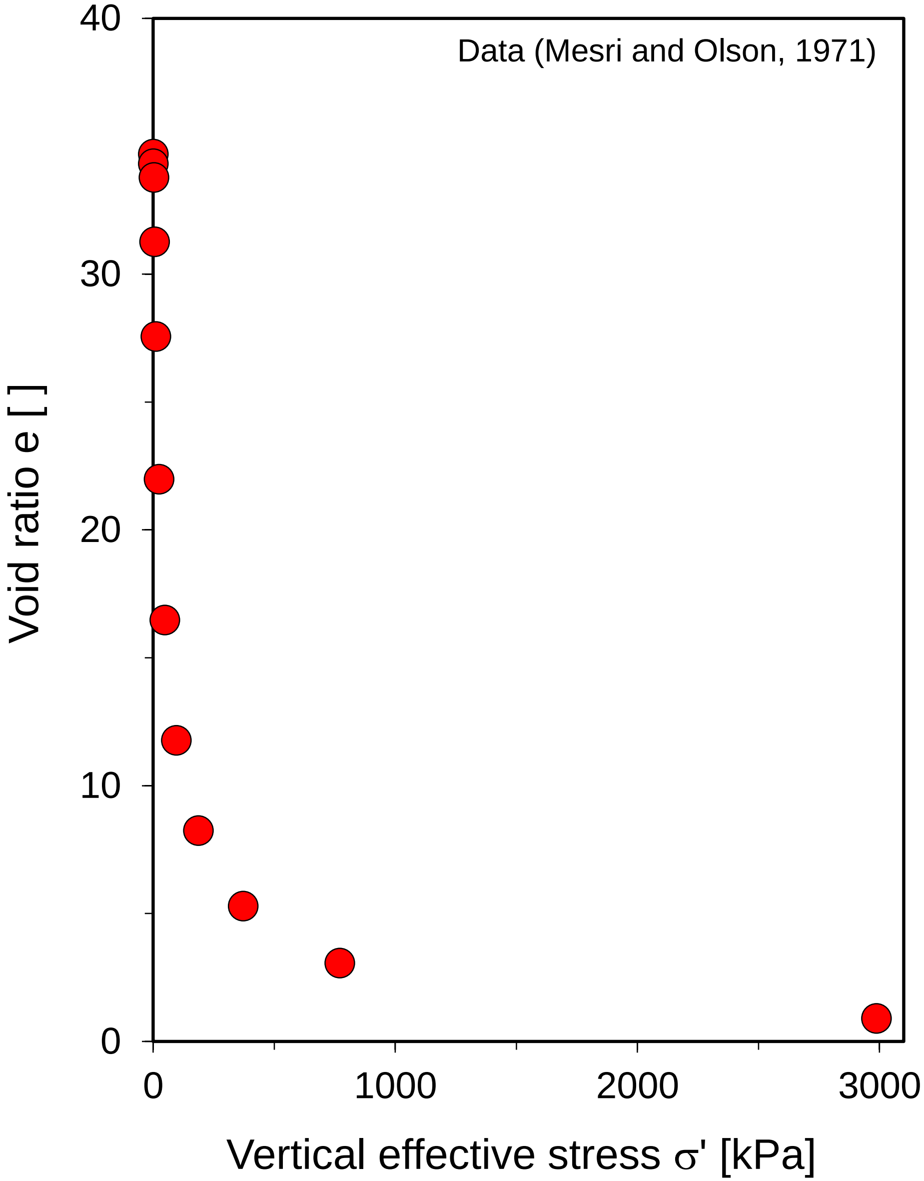
suspension-skeleton transition

High-stress e-asymptote:

shales ➔ e>0



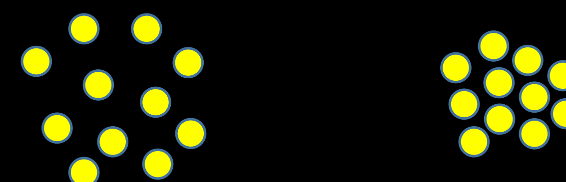
Compression: Data



Physics Inspired

Boyle-Mariotte $P\,V = \alpha$

van der Waals $(\sigma' + \sigma_A - \sigma_R)(V_t - V_s) = \alpha$



Semi-log	*Classical*	$e = e_{ref} - C_c \log\left(\frac{\sigma'}{\sigma'_{ref}}\right)$	Terzaghi & Peck (1948) Schofield & Wroth (1968)
	Cubic (3rd order)	$e = e_{ref} - \alpha \cdot \log\left(\frac{\sigma'}{\sigma'_{ref}}\right) + \beta \cdot \left[\log\left(\frac{\sigma'}{\sigma'_{ref}}\right)\right]^3$	Burland (1990)
	Modified	$e = e_c - C_c \log\left(\frac{1\mathrm{kPa}}{\sigma' + \sigma'_L} + \frac{1\mathrm{kPa}}{\sigma'_H}\right)^{-1}$	
Power	*From gas to soil*	$e = e_H + (e_L - e_H)\left(\frac{\sigma' + \sigma'_c}{\sigma'_c}\right)^{-\beta}$	Hansen (1969) Butterfield (1979) Juárez-Badillo (1981) Houlsby & Wroth, (1991) Pestana & Whittle (1995)
Exponential	*Gompertz function*	$e = e_H + (e_L - e_H) \cdot \exp^{-\left(\frac{\sigma'}{\sigma'_c}\right)^{\beta}}$	Gregory et al. (2006) Cargill (1984 – β=1)
Hyperbolic	*Hyperbolic function (classical hyp: β=1)*	$e = e_L - (e_L - e_H)\frac{1}{1 + \left(\frac{\sigma'_c}{\sigma'}\right)^{\beta}}$	
Arctangent	*S-shaped function*	$e = e_L + \frac{2}{\pi}(e_L - e_H)\arctan\left[-\left(\frac{\sigma'}{\sigma'_c}\right)^{\beta}\right]$	

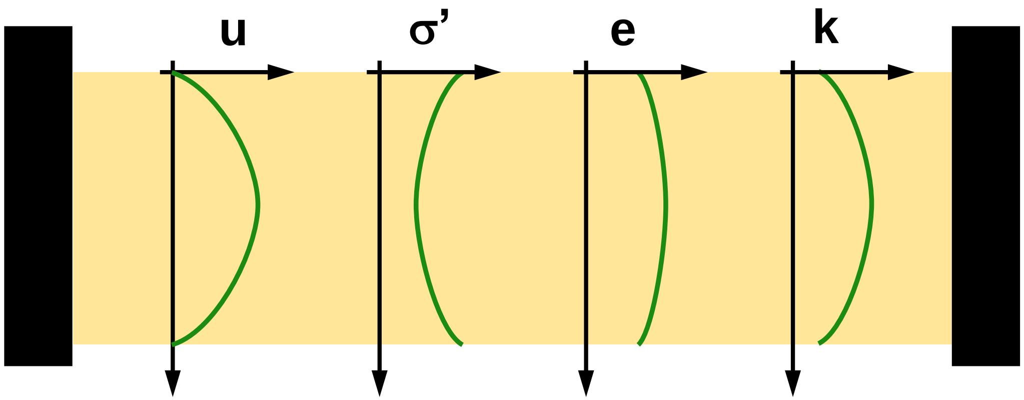
SH Chong

1. Classification
2. Permeability
3. Compressibility
4. Coupling - Implications

Compressibility + Permeability: Coupled HM

$$e = e_H + (e_L - e_H)\left(\frac{\sigma' + \sigma_c'}{\sigma_c'}\right)^{-\beta} \qquad \frac{k}{k_o} = \left(\frac{e}{e_o}\right)^{b}$$

Oedometer

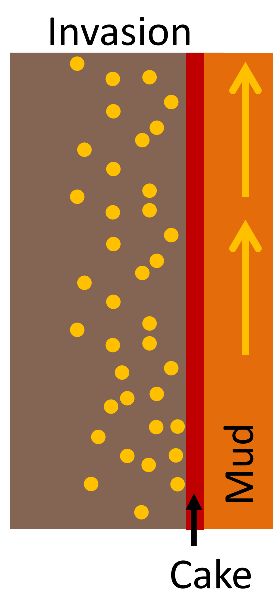


Compressibility + Permeability: Coupled HM

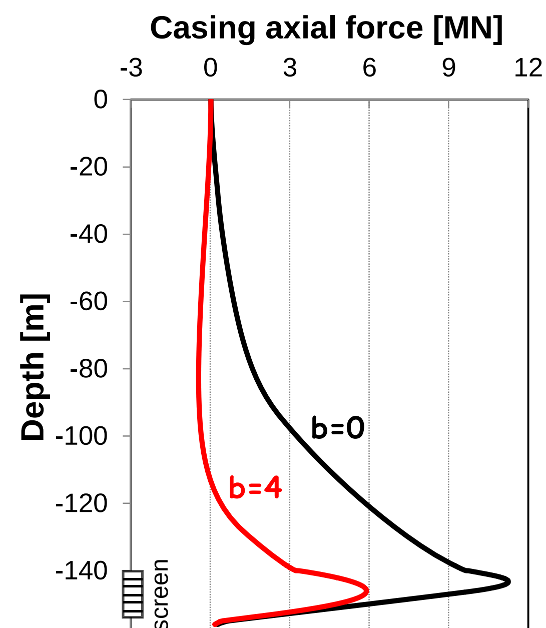
$$e = e_H + \left(e_L - e_H\right)\left(\frac{\sigma' + \sigma'_c}{\sigma'_c}\right)^{-\beta} \qquad \frac{k}{k_o} = \left(\frac{e}{e_o}\right)^{b}$$

suction caissons

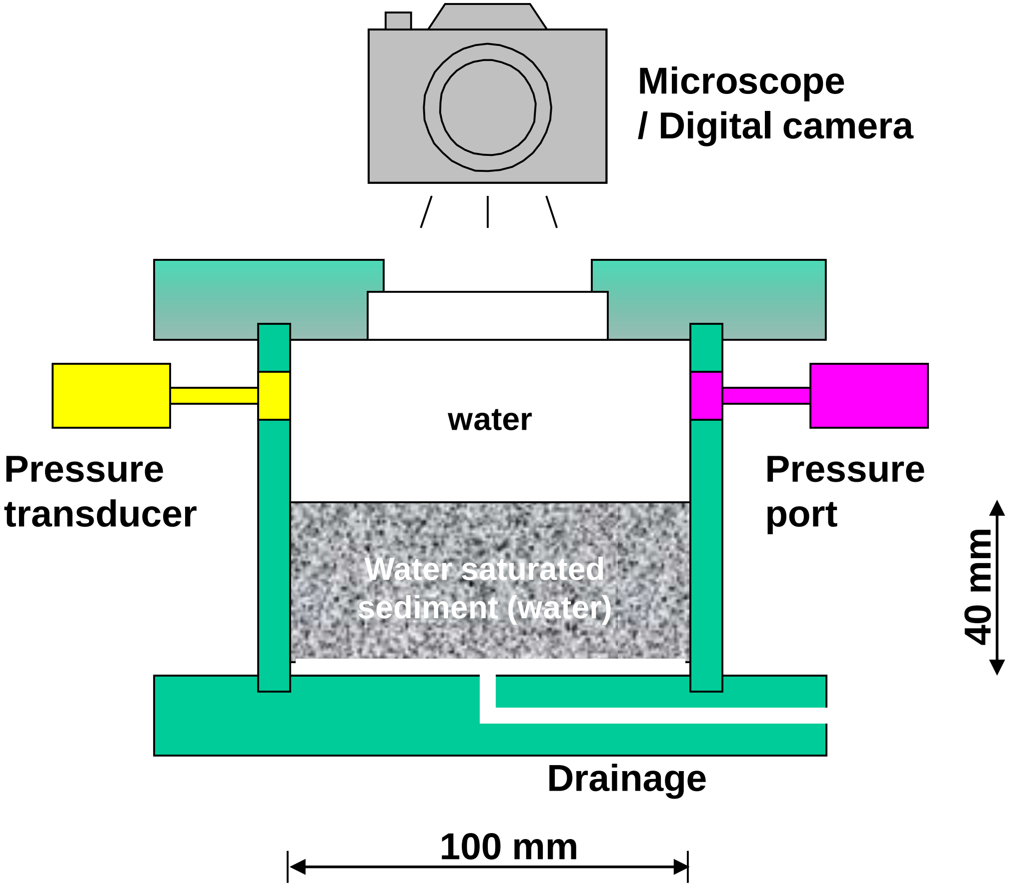
cake formation & borehole stability

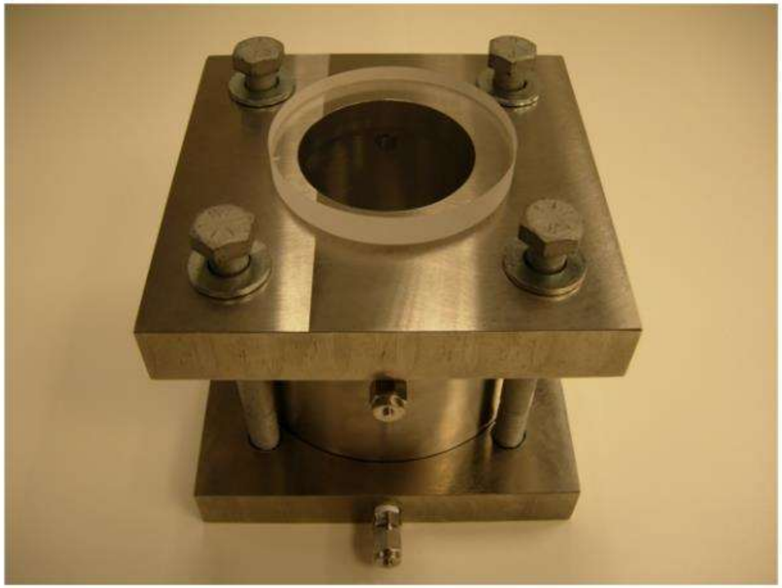


seafloor & pumping

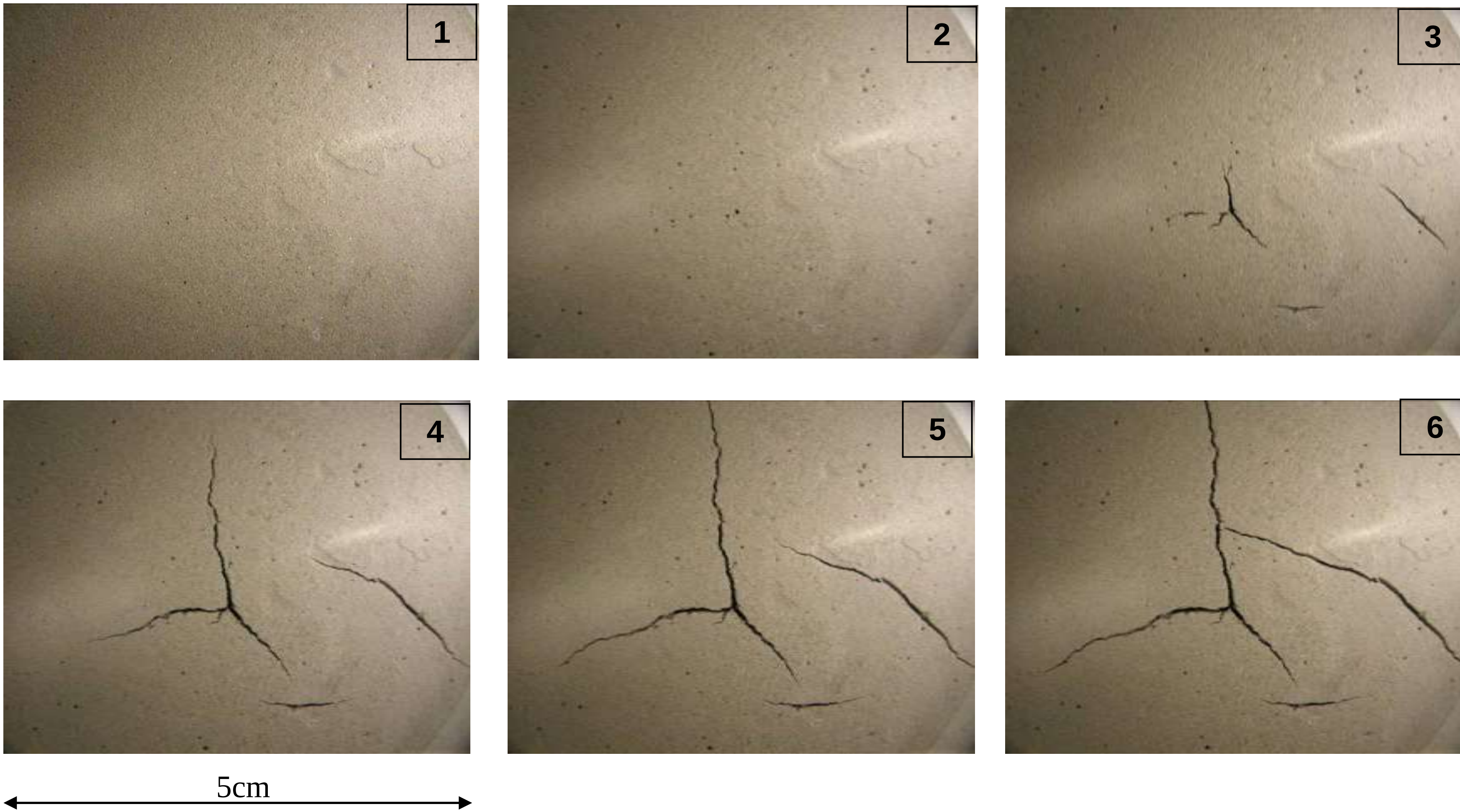


Compressibility + Permeability: Hydro-Frac.



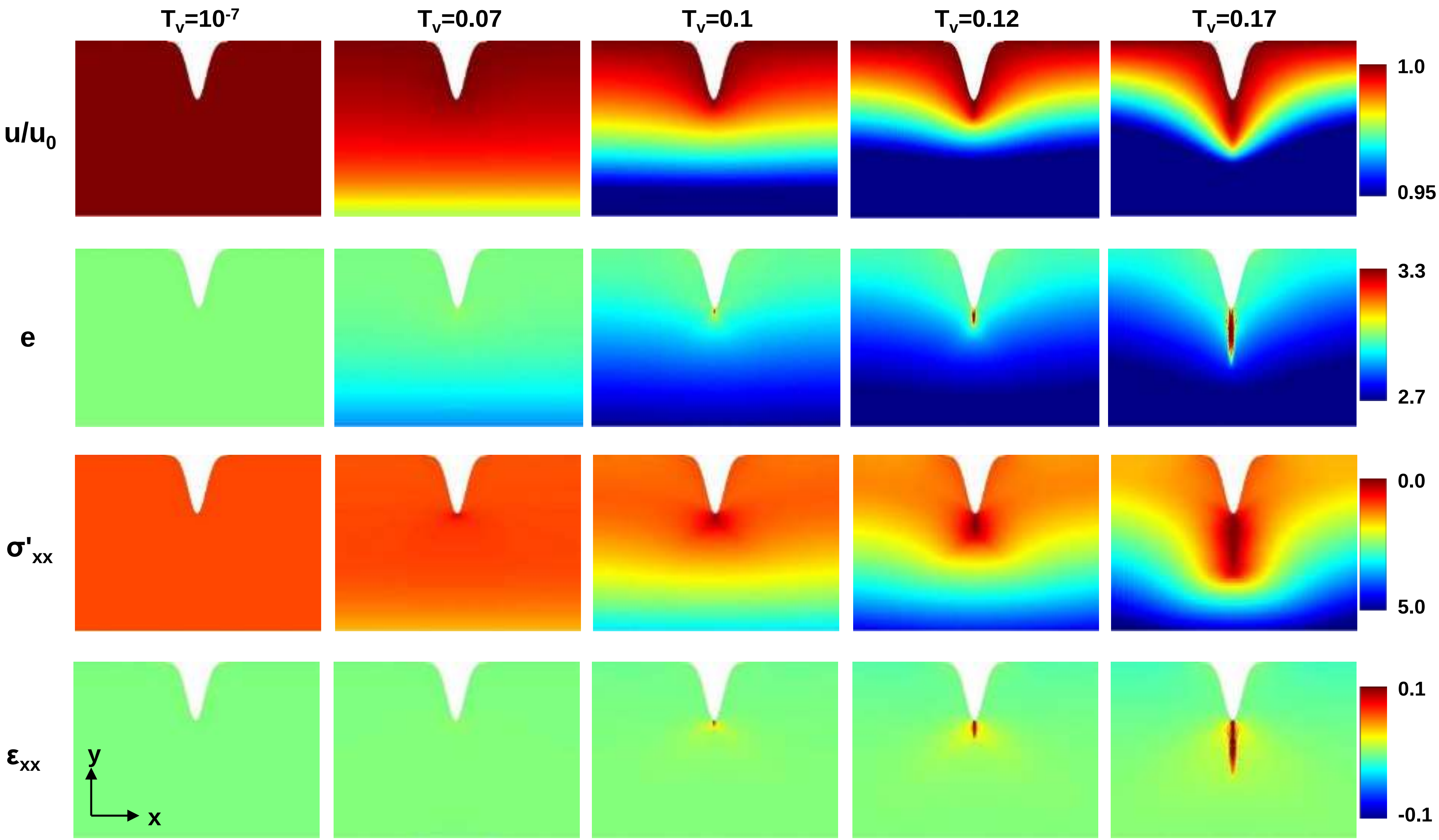


Compressibility + Permeability: Hydro-Frac.

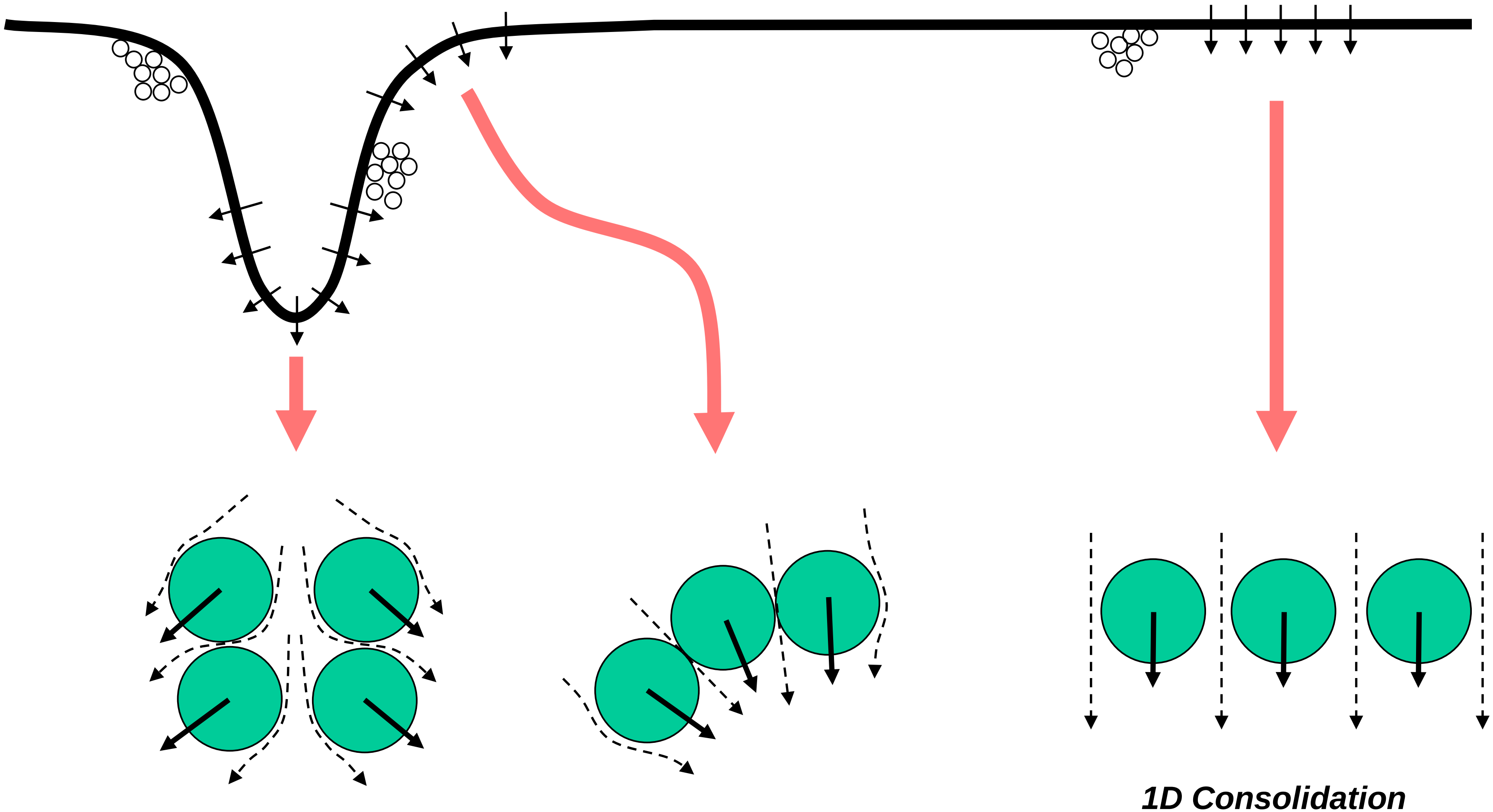


Hydraulic Fracture: FEM

(MCC - no cohesion)



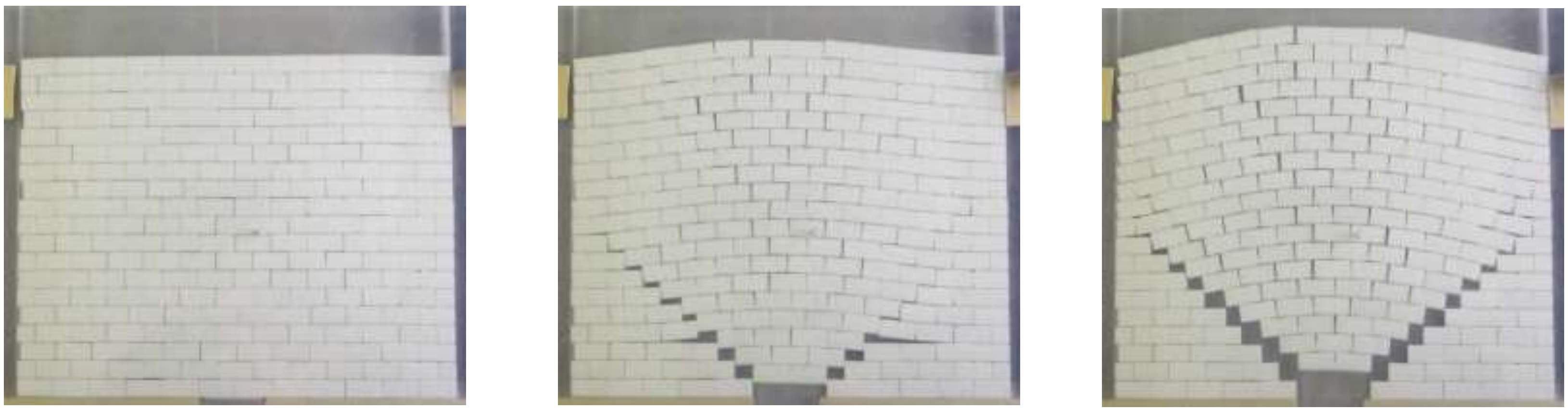
HF in Soils: *ab initio*



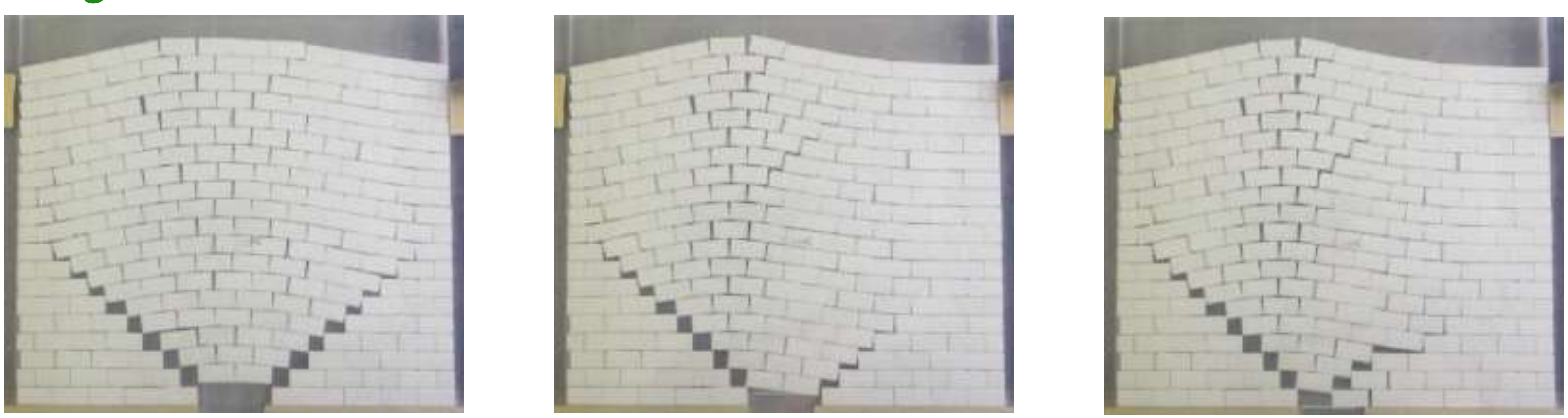
Soil is in compression EVERYwhere

HF in Pre-structured Media (Shales)

opening

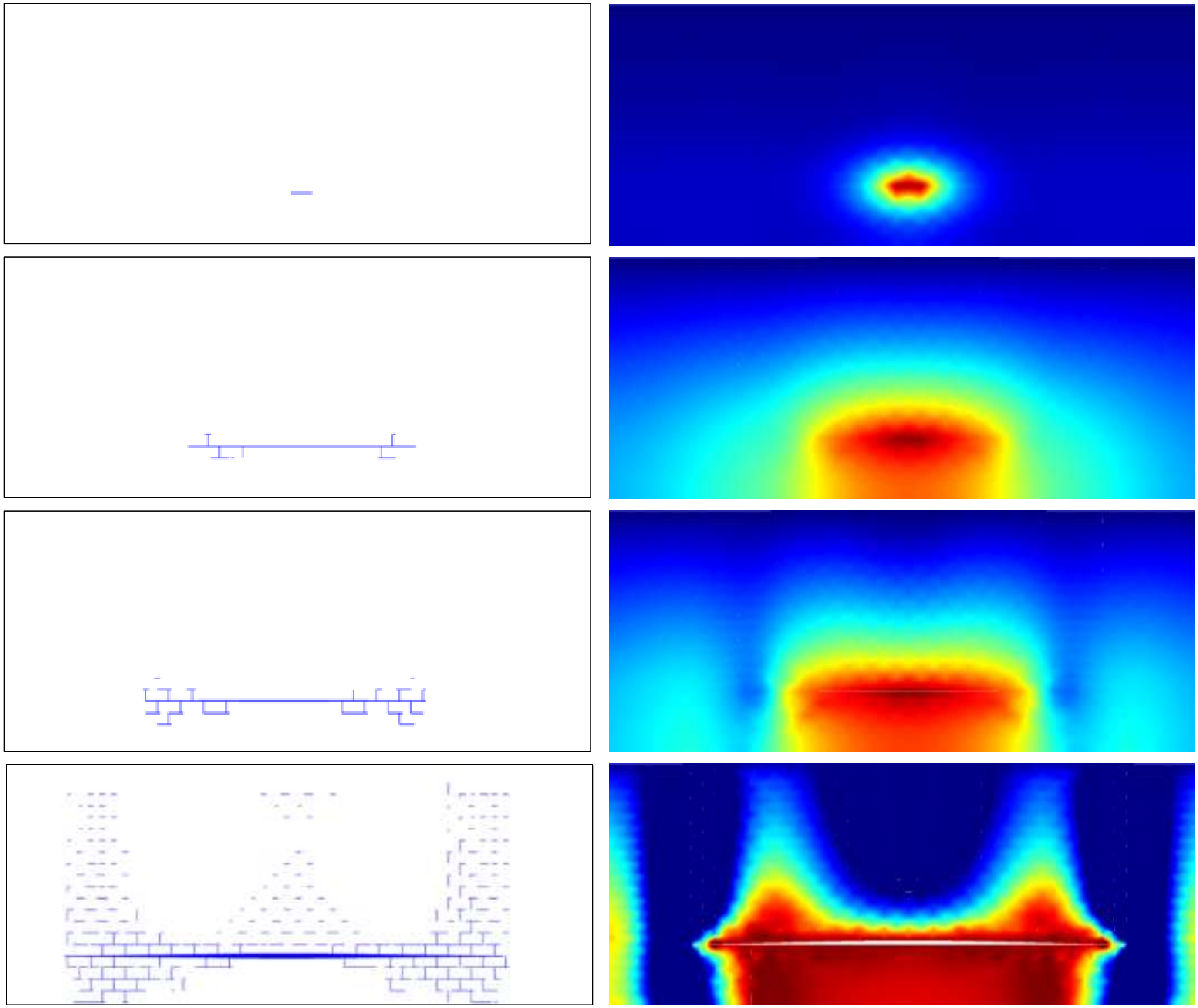


closing



Self-propping

HF in Pre-structured Media (Shales)



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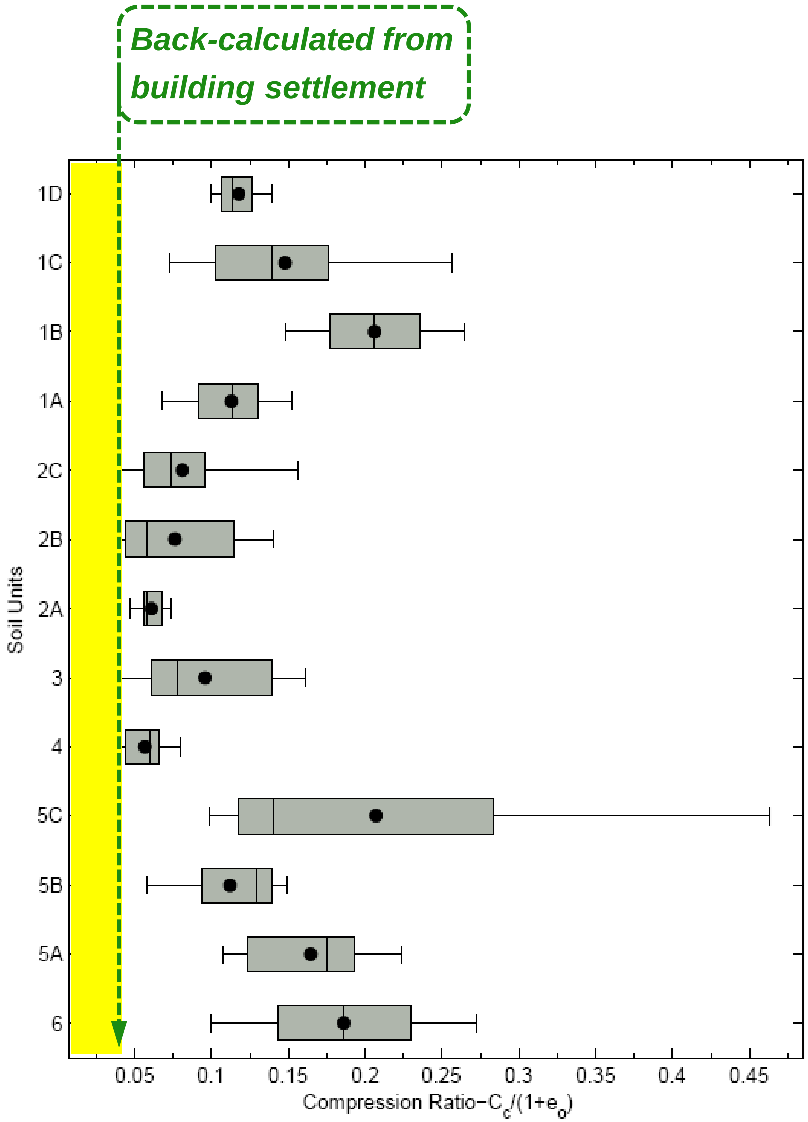
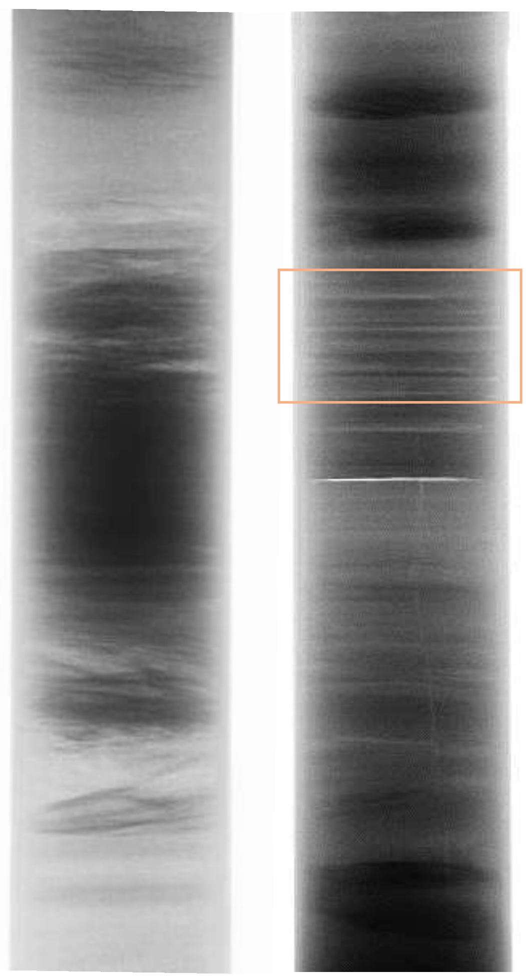
5. Stiffness: $G_{max} \leftrightarrow G_{tan}$ …Oedometer

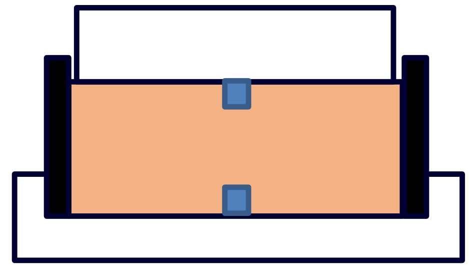
k_o Loading



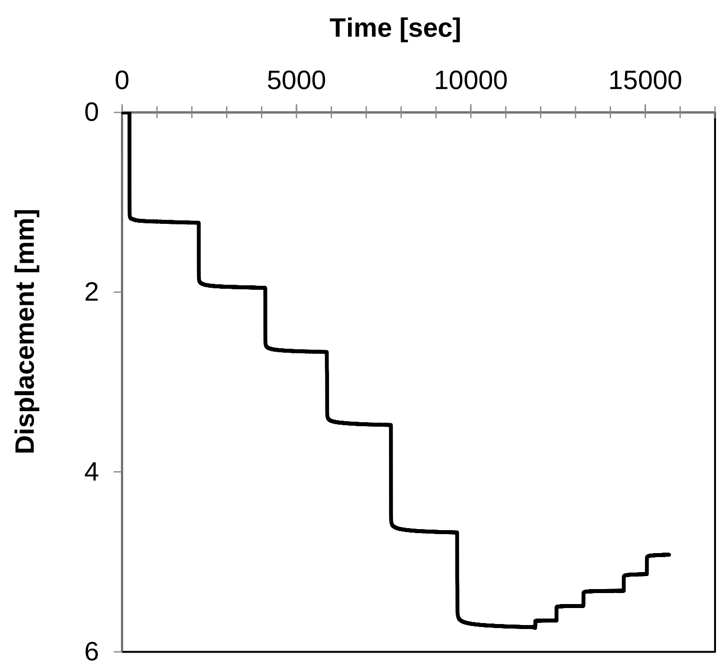
Back-calculated from building settlement
Soil Units
1D
1C
1B
1A
2C
2B
2A
3
4
5C
5B
5A
6
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
Compression Ratio−$C_c/(1+e_o)$

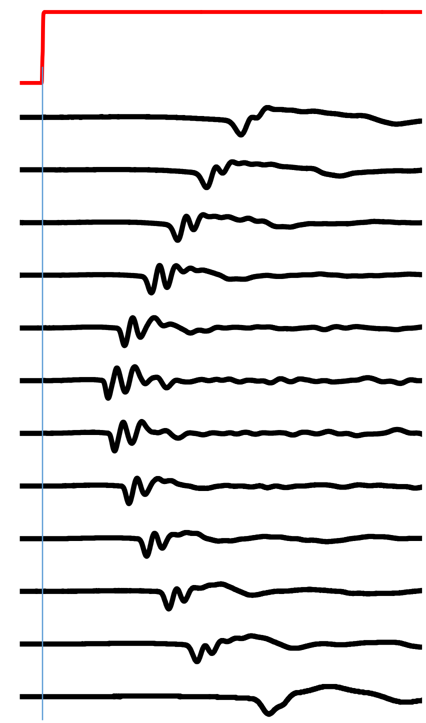
Oedometer: Improvements



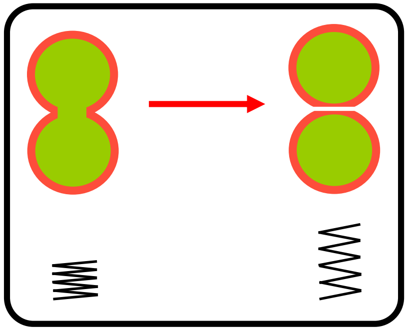


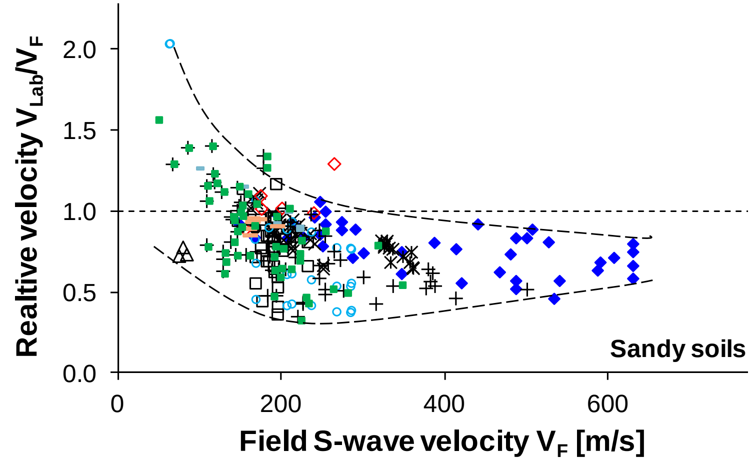
In-Shelby



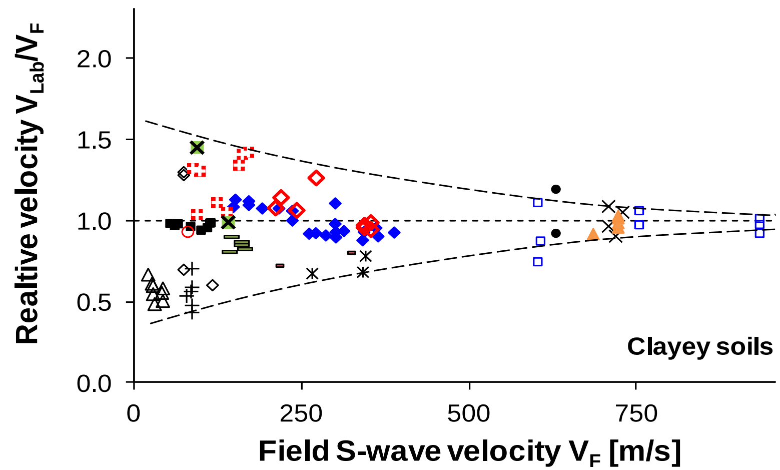


Sampling effect

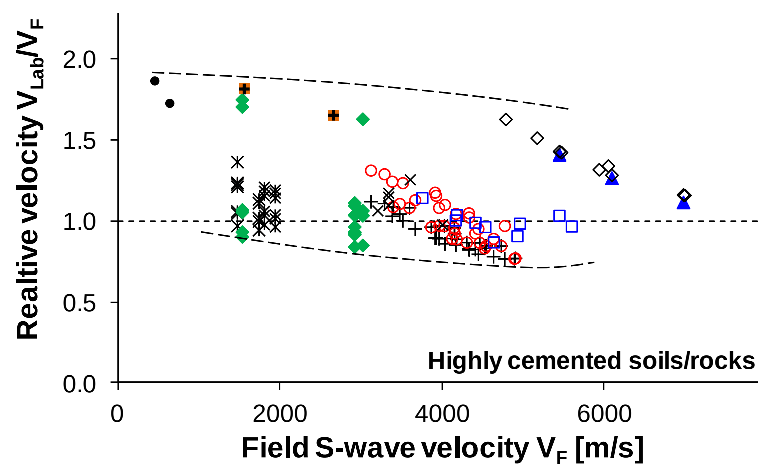




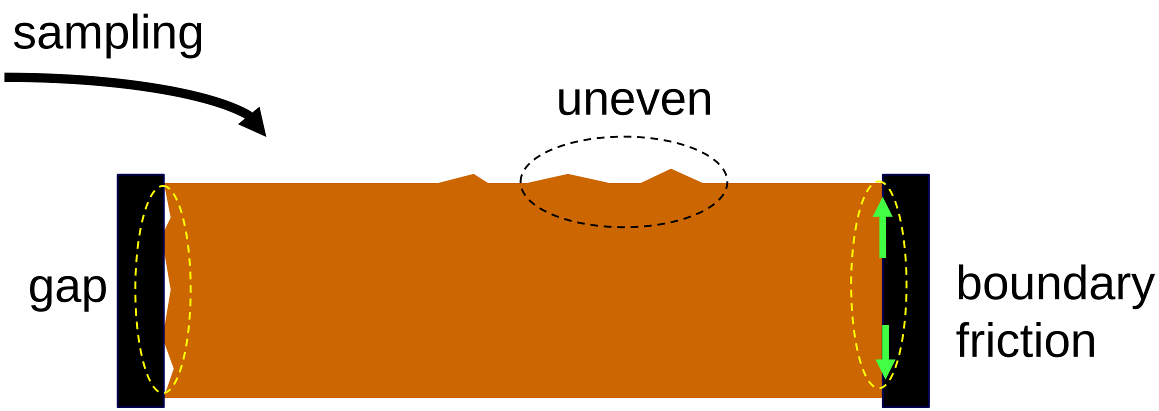
compaction

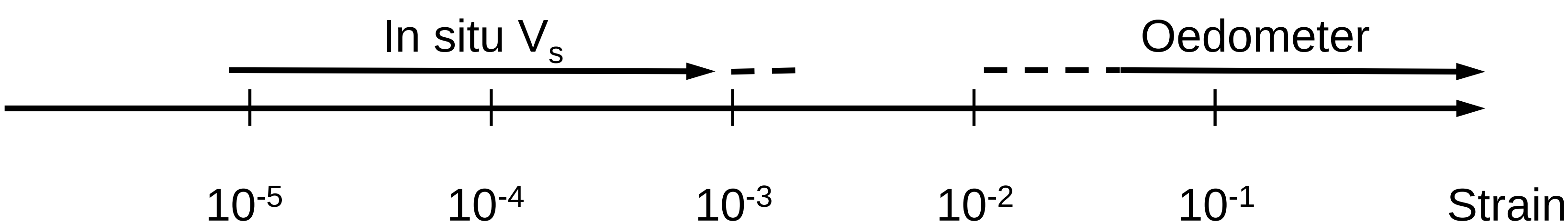


biased sampling?



Oedometer?



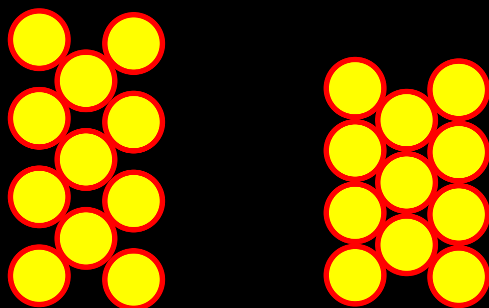


$$\frac{\Delta e}{1+e_o} = C_c \log\left(\frac{\sigma_o' + \Delta\sigma'}{\sigma_o'}\right)$$

Small Strain Stiffness

$$V_S = \alpha \left(\frac{\sigma'_x + \sigma'_y}{2P_a} \right)^{\beta}$$

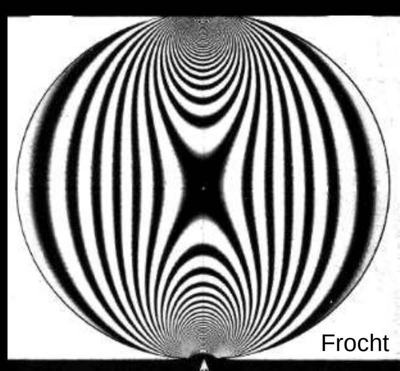
k_o Loading: Fabric change

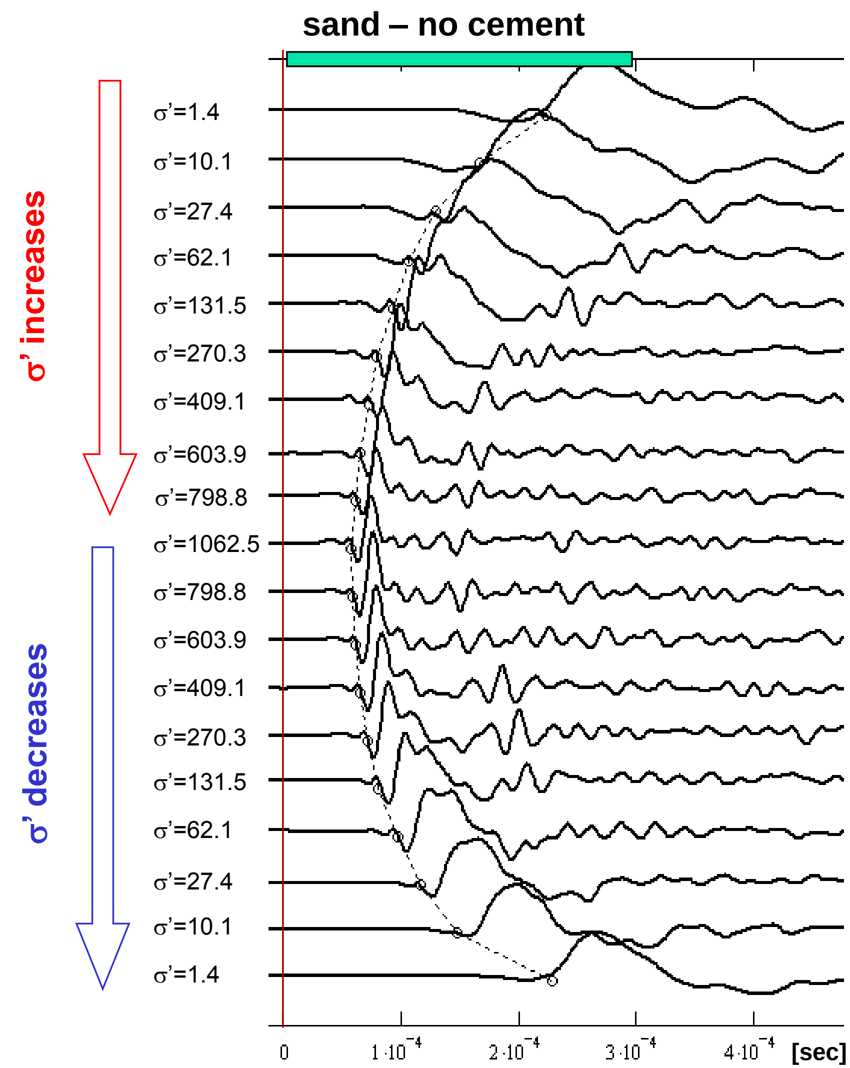


V_s measurement:

Contact deformation

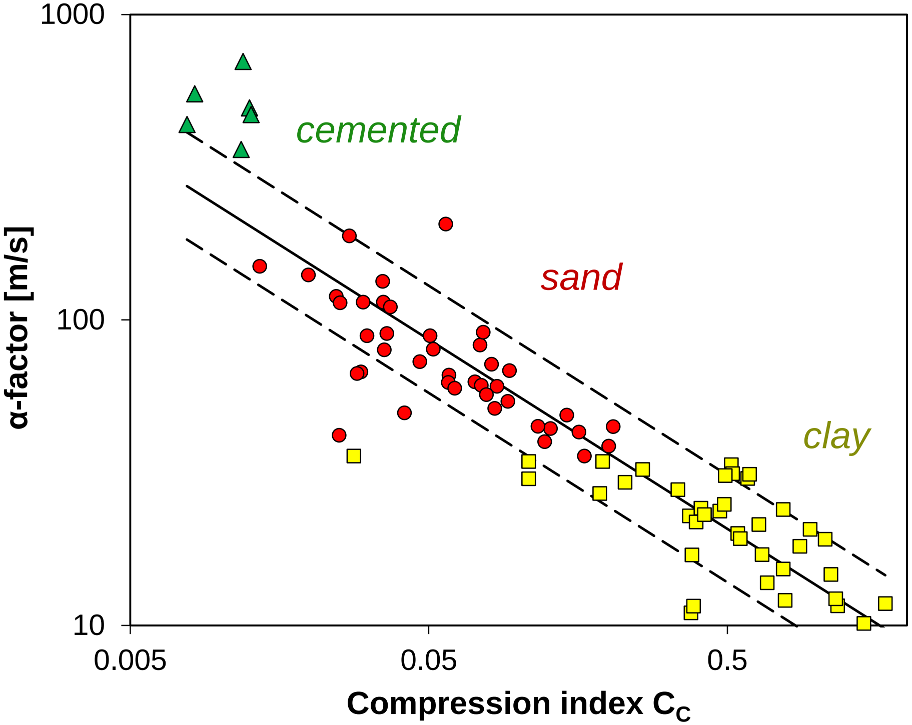
Stiffness @ constant fabric

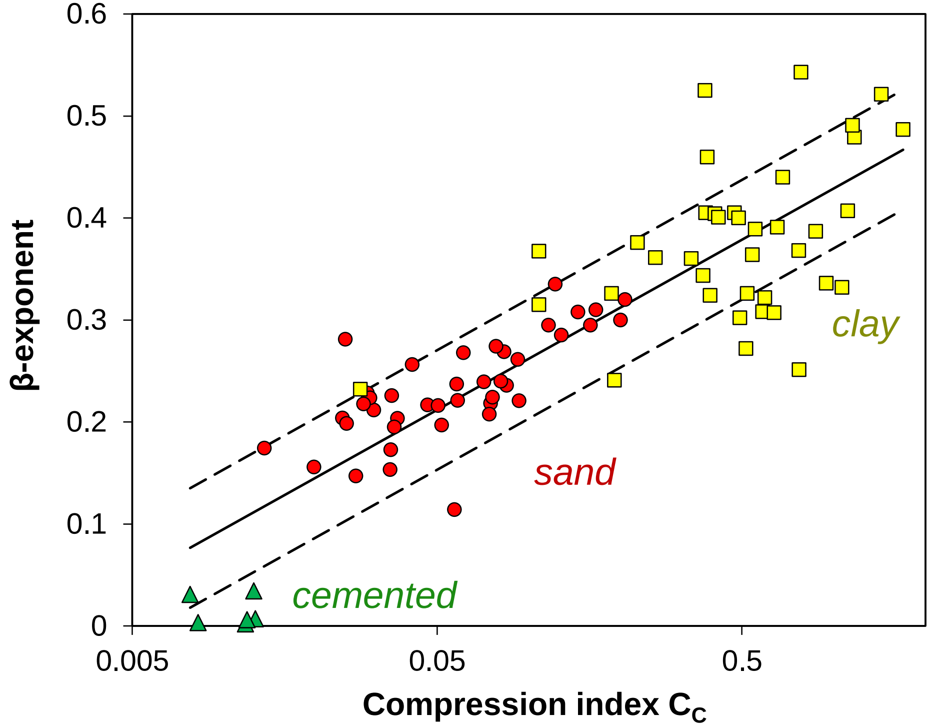




$C_c \leftrightarrow$ α β parameters

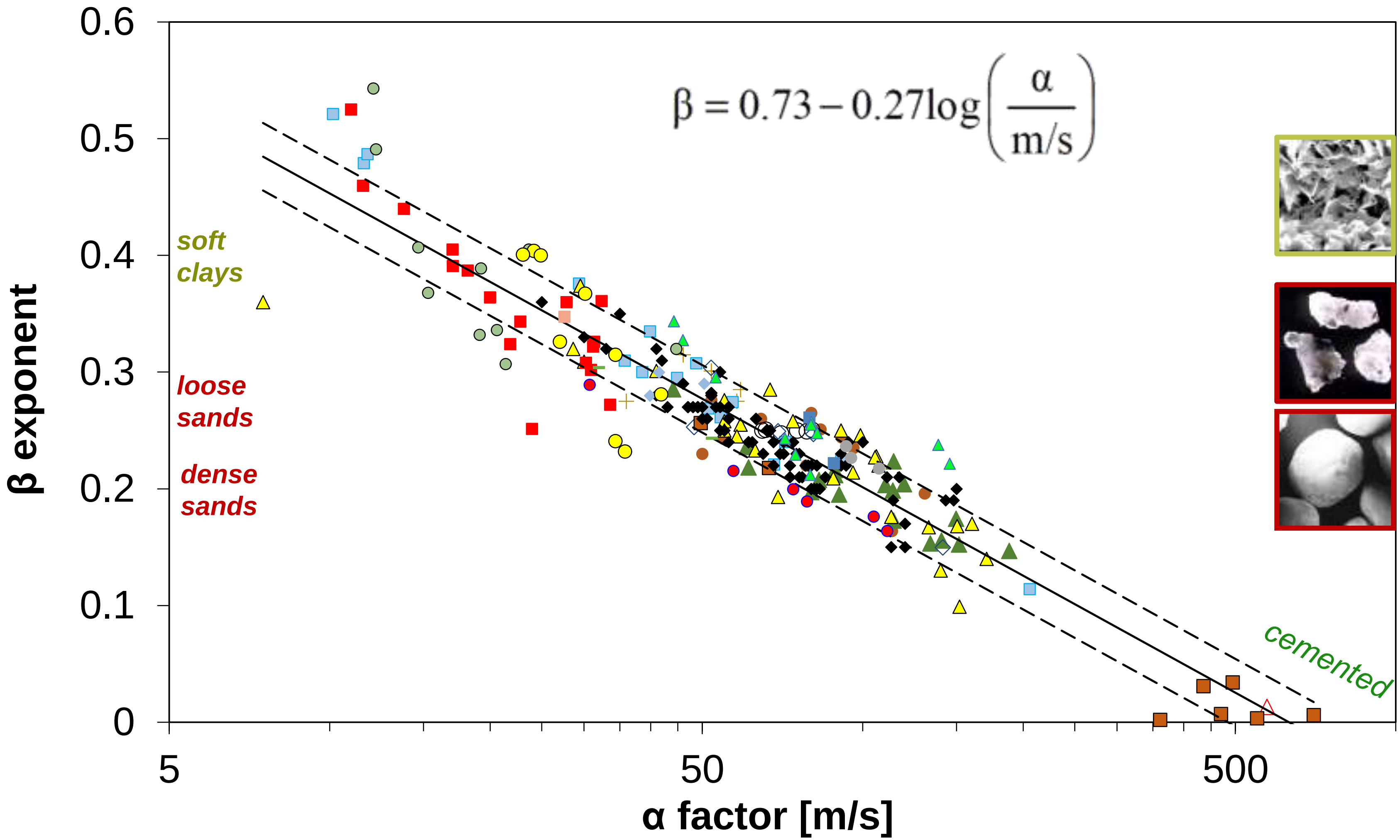
$$V_S = \alpha \left(\frac{\sigma'_x + \sigma'_y}{2P_a} \right)^{\beta}$$





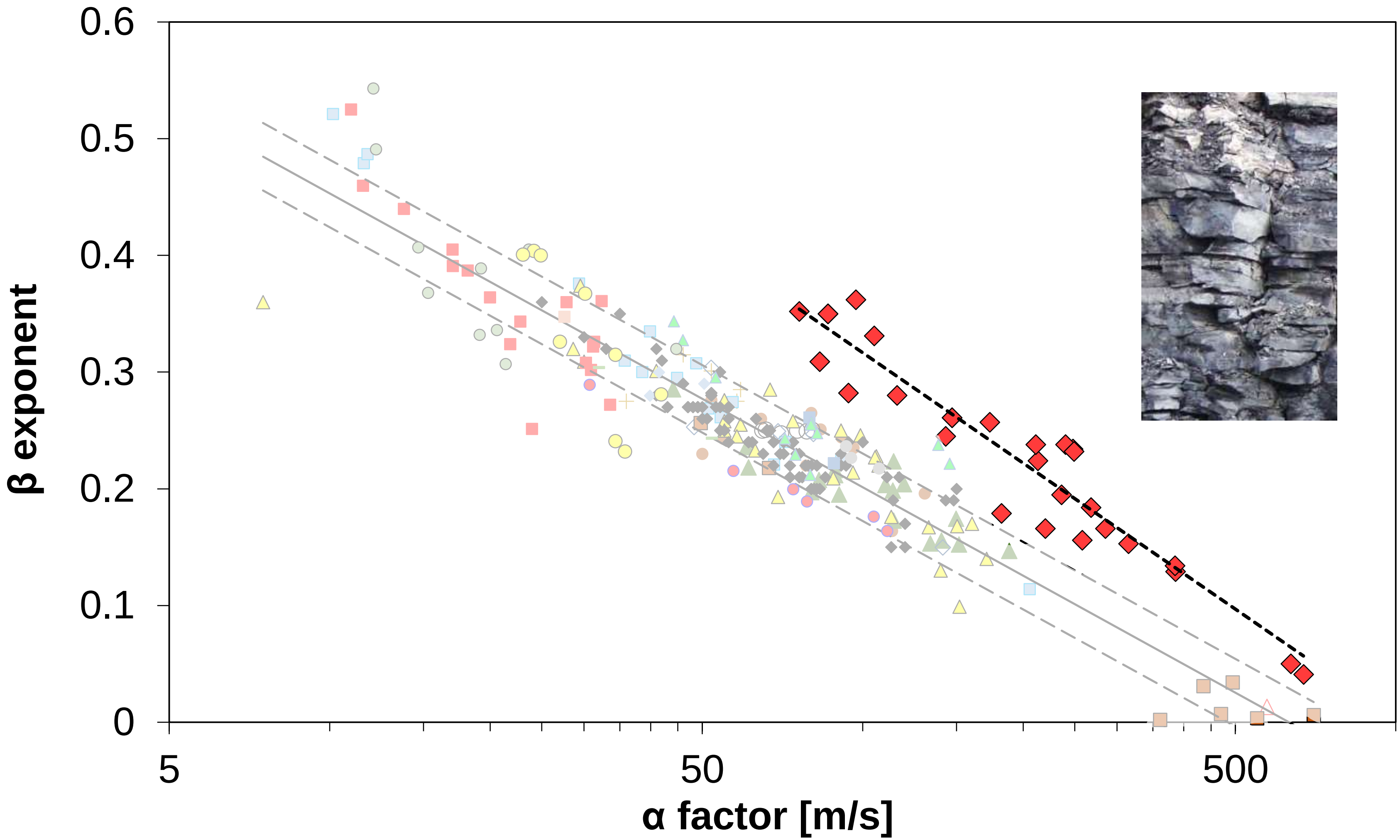
Velocity-Stress: Soils

$$V_S = \alpha \left(\frac{\sigma'_x + \sigma'_y}{2P_a} \right)^{\beta}$$



Velocity-Stress: Fractured Rock

$$V_s = \alpha \left(\frac{\sigma'_\perp}{P_a} \right)^\beta$$



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2. Permeability
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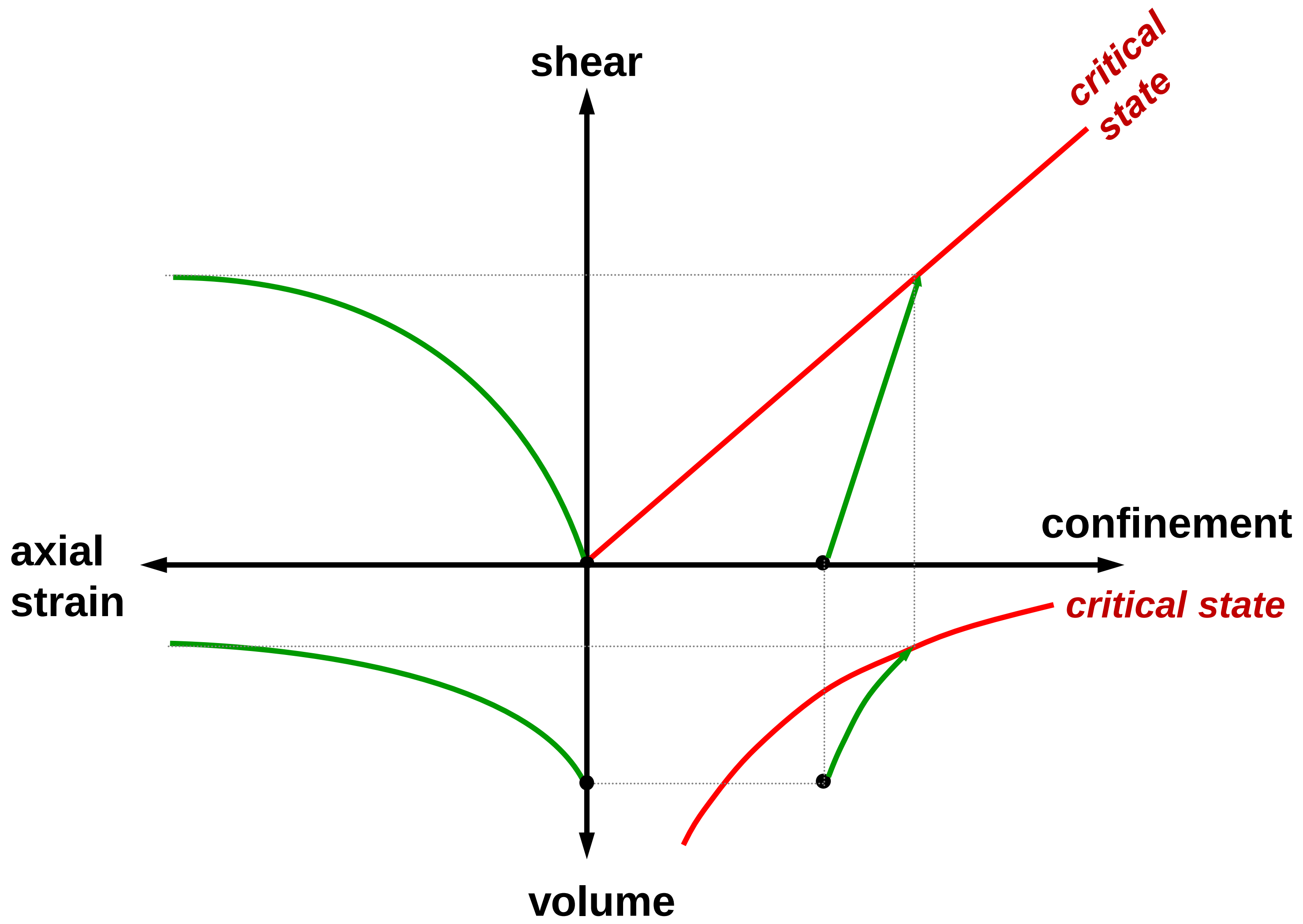
6. Shear Strength - Localization

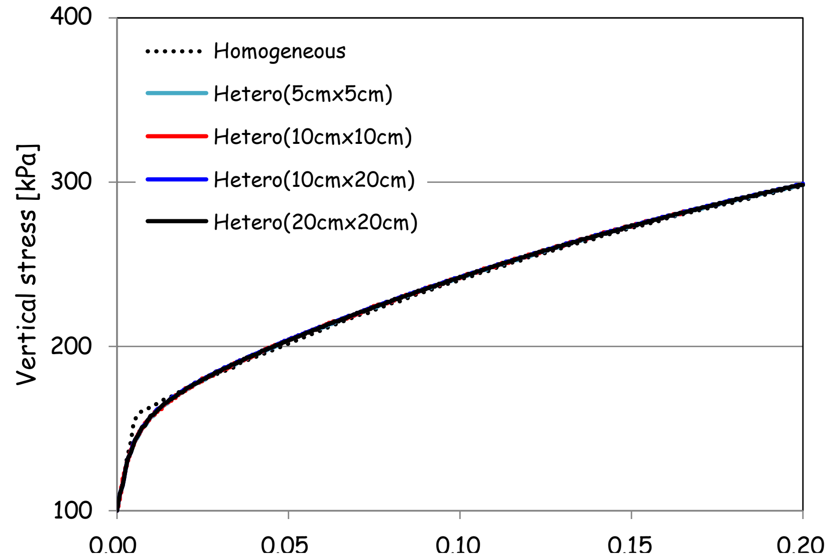
Sediment Response During Shear

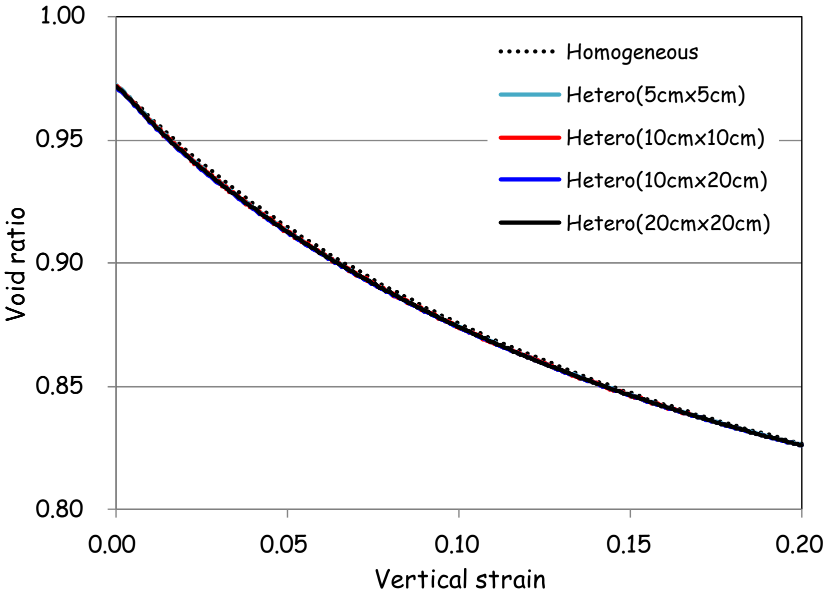


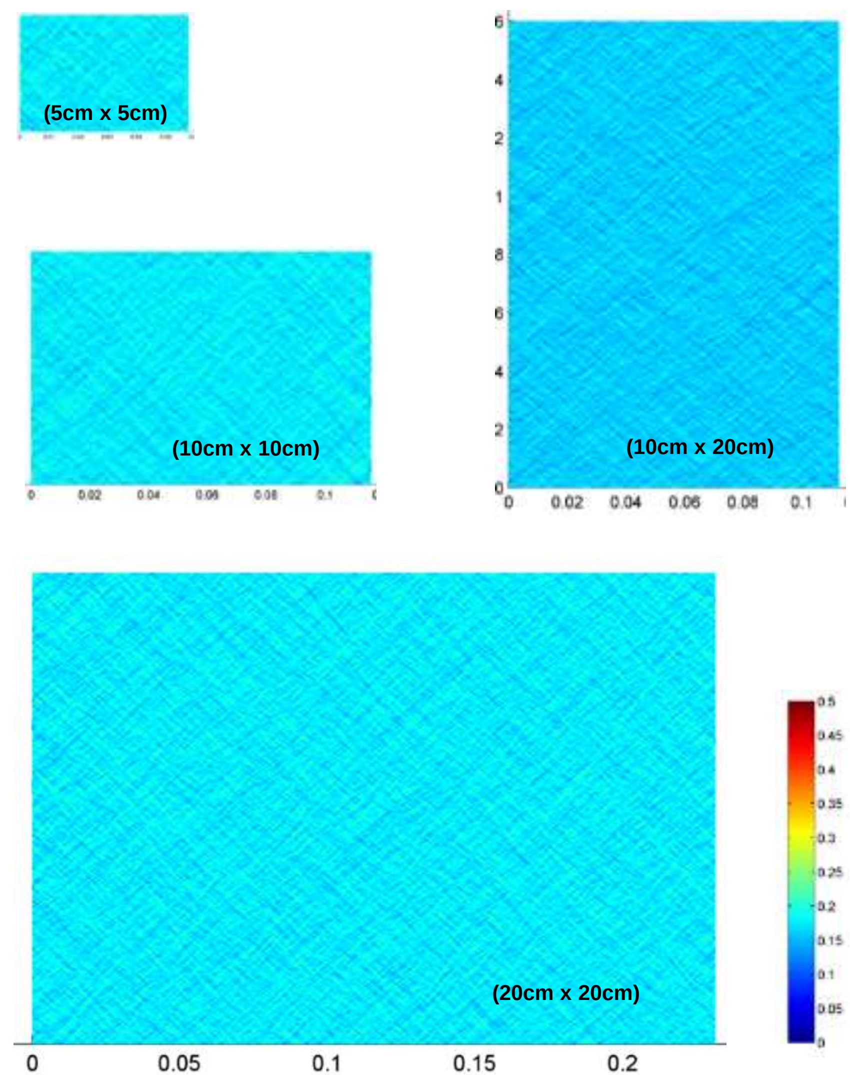
Plane Strain

Contractive sample: rnd(e)=0.92-1.02 (Note: e_{cs}= 0.82)

δ-fields @ ε_z=20%

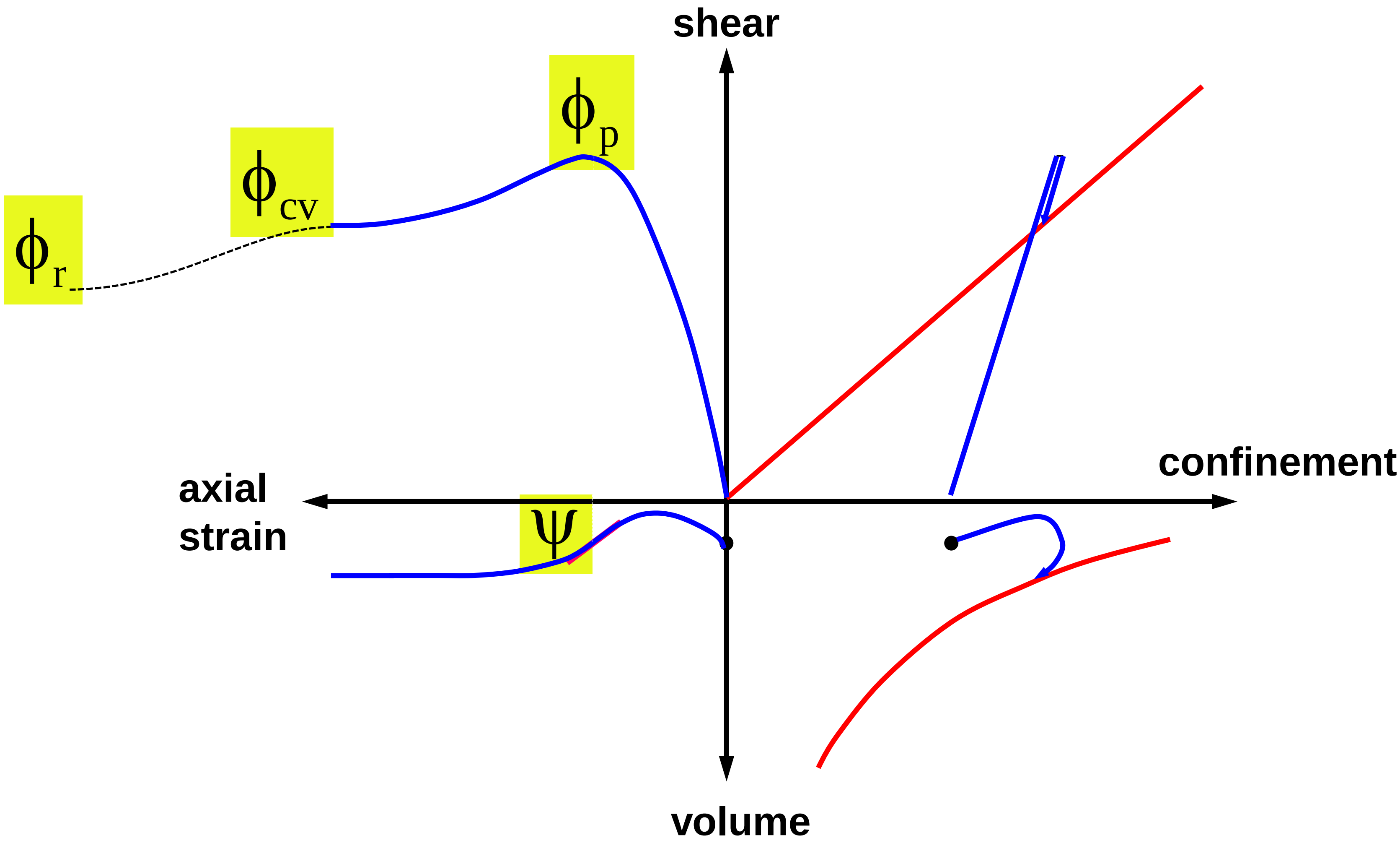






H. Shin – Ulsan Univ.

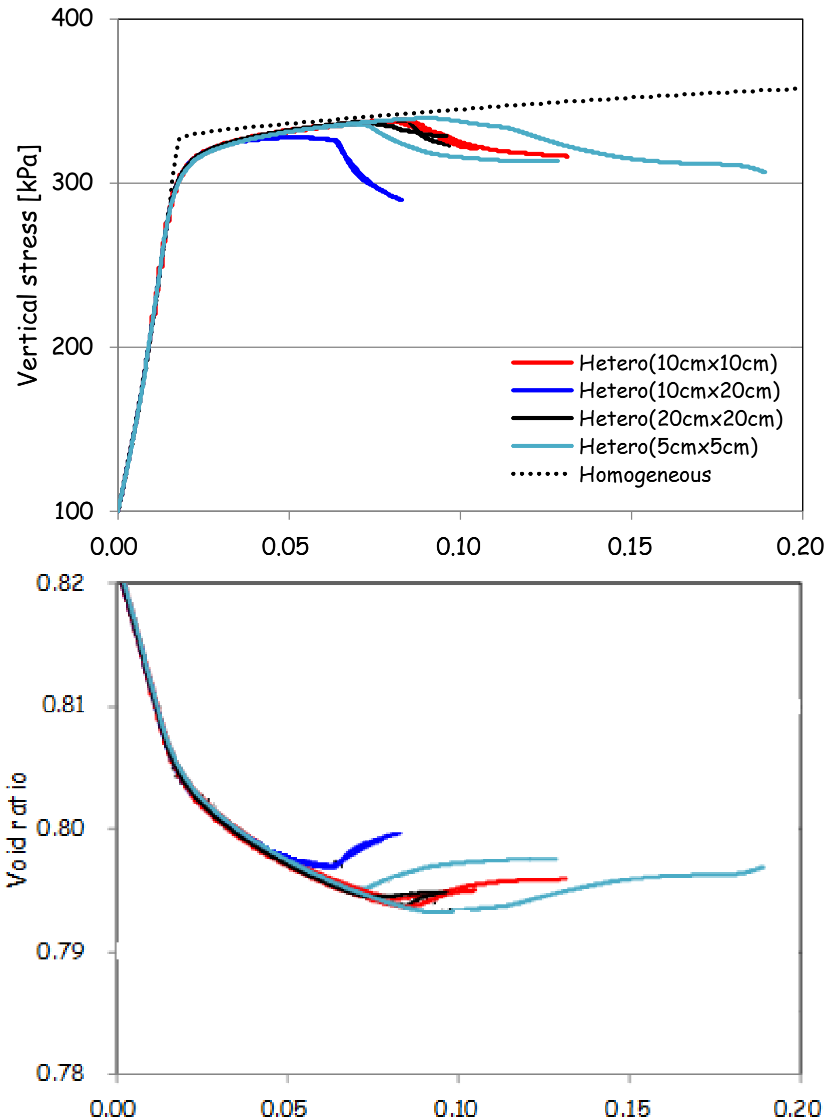
Sediment Response During Shear

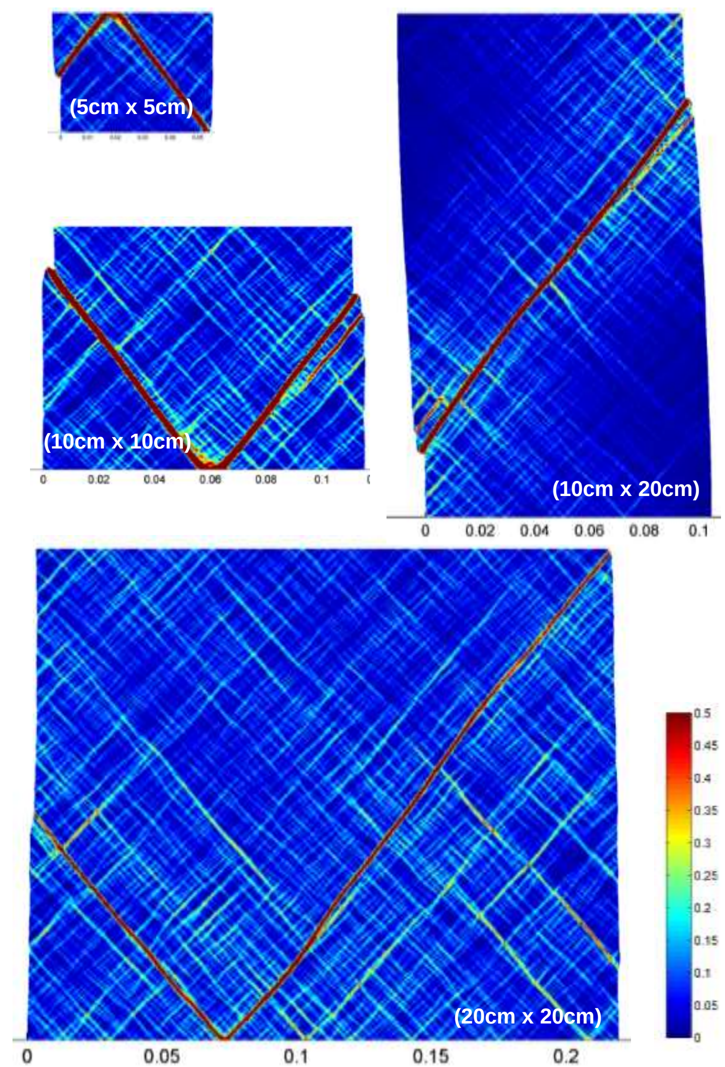


Plane Strain

At Critical State: rnd(e)=0.77-0.87 (Note: e_{cs}= 0.82)

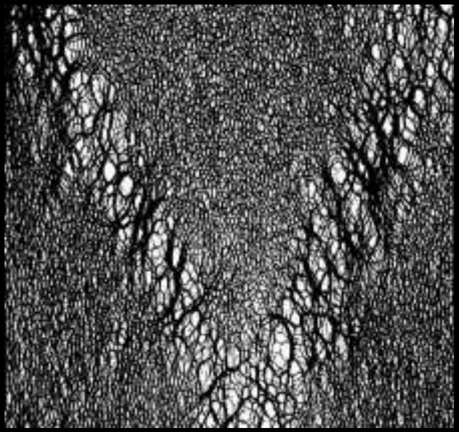
δ-fields @ end of test

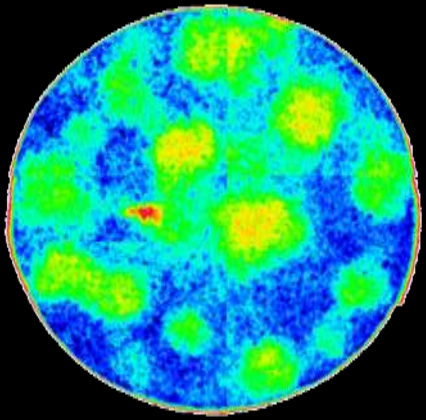


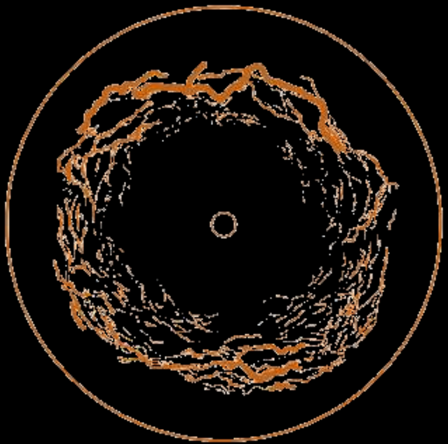


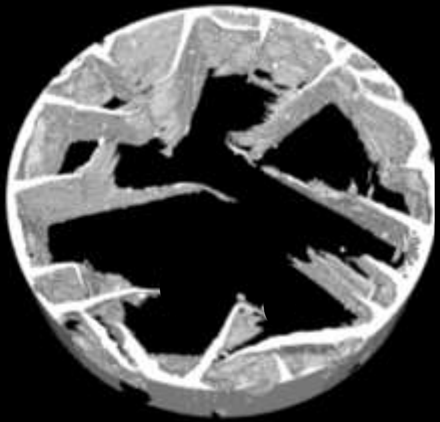
H. Shin – Ulsan Univ.

Localization?









Strain localization
shear band
compaction band

Grains migration
clogging
piping erosion
sand production

Fluids
viscous fingering
density tears

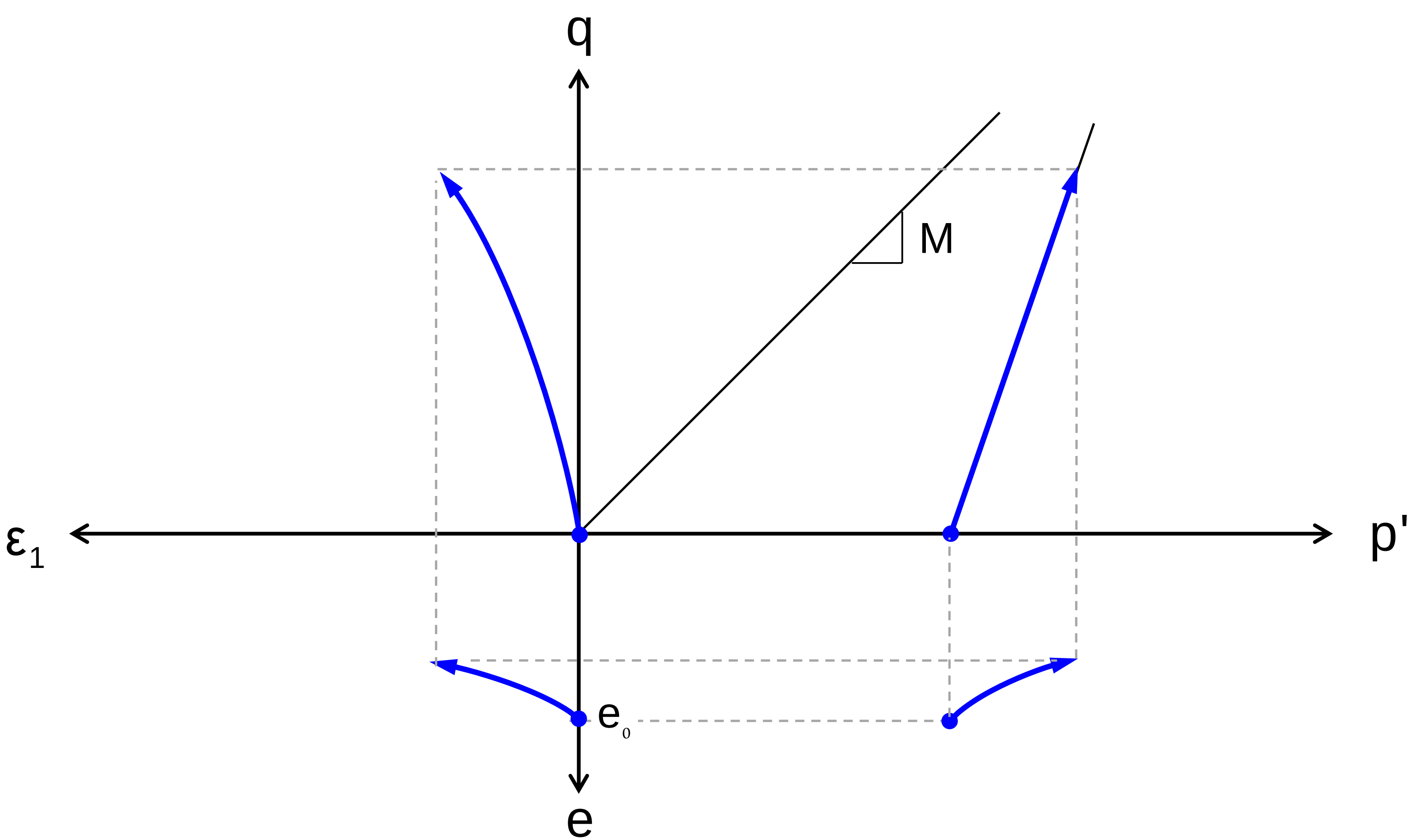
Fluid-driven
desiccation cracks
gas or oil-driven
hydraulic fracture

Lenses
ice & hydrate

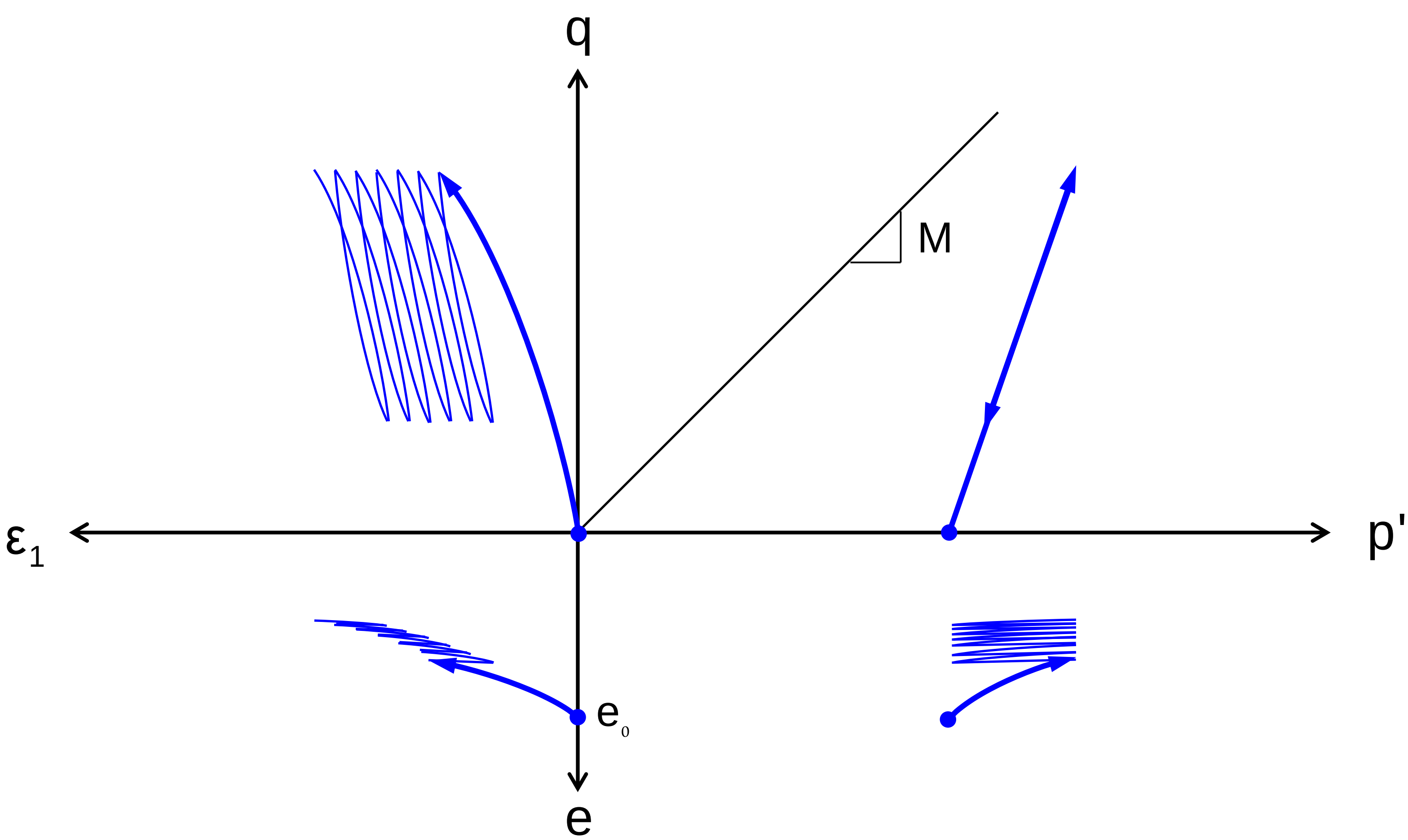
Dissolution
shear in contraction
piping & wormholes

1. Classification
2. Permeability
3. Compressibility
4. Coupling
5. Stiffness: $G_{max} \leftrightarrow G_{tan}$ …Oedometer
6. Shear Strength - Localization
7. Repetitive Loads

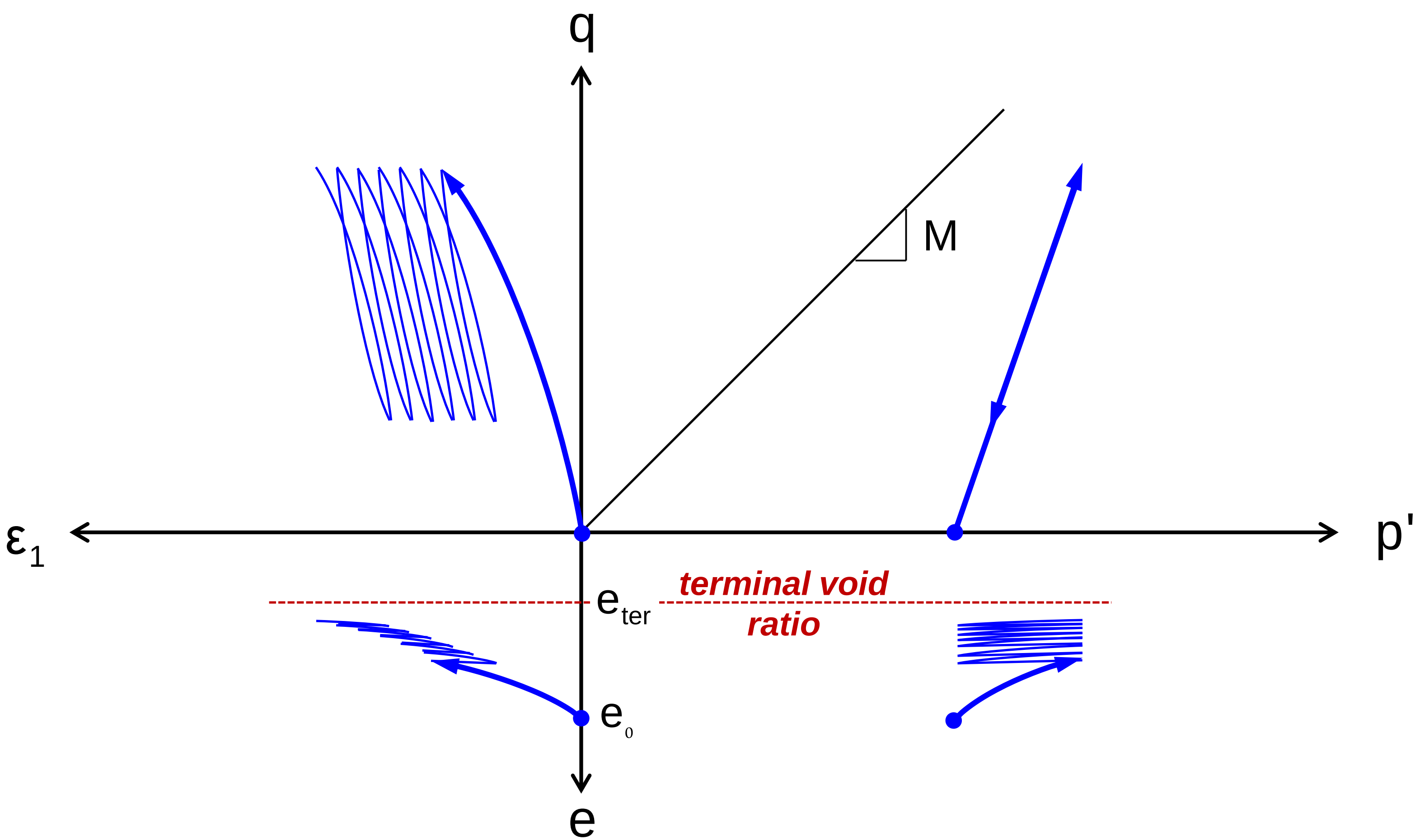
Stress - Strain - Void Ratio *First Cycle*



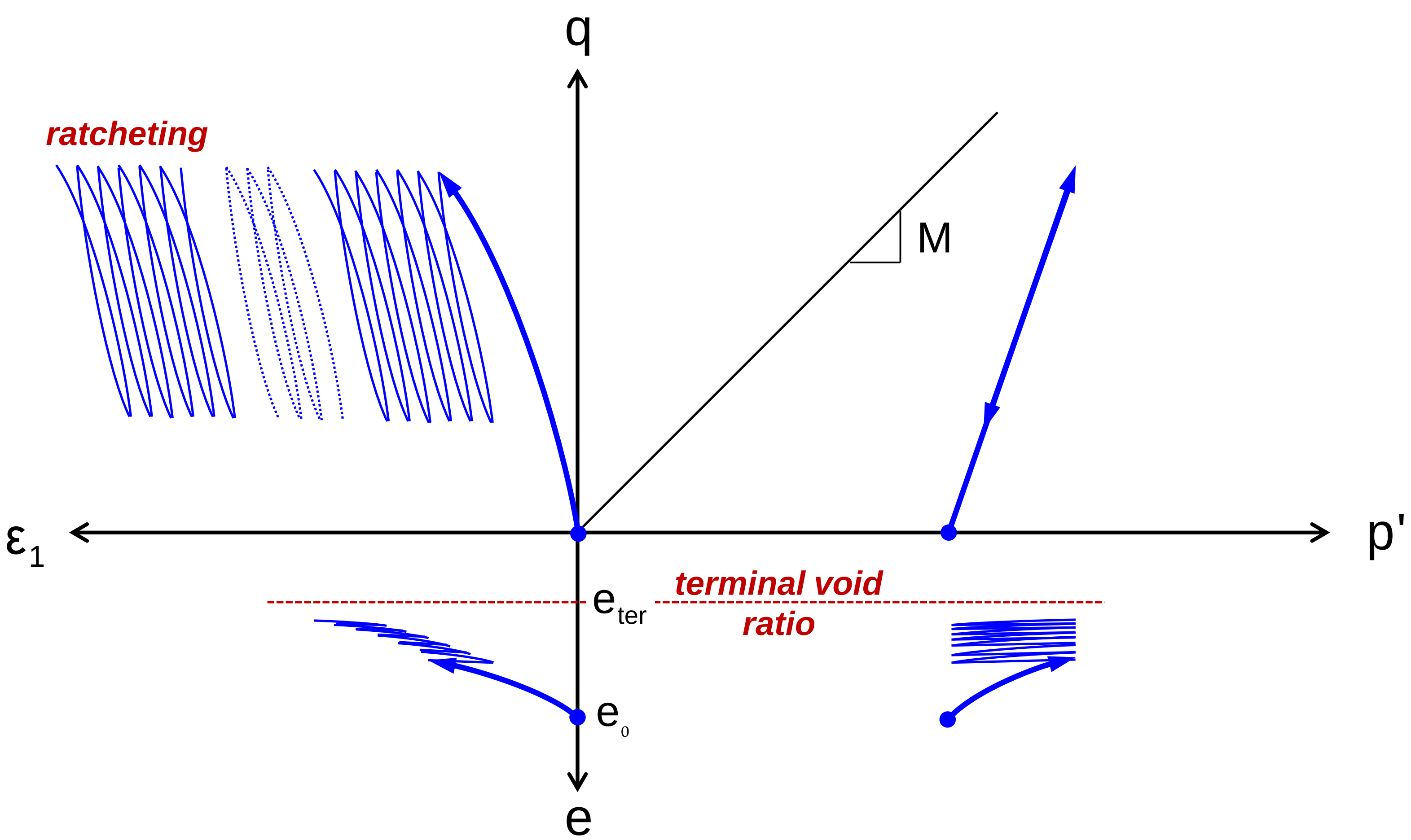
Stress - Strain - Void Ratio *N^{th} Cycle*



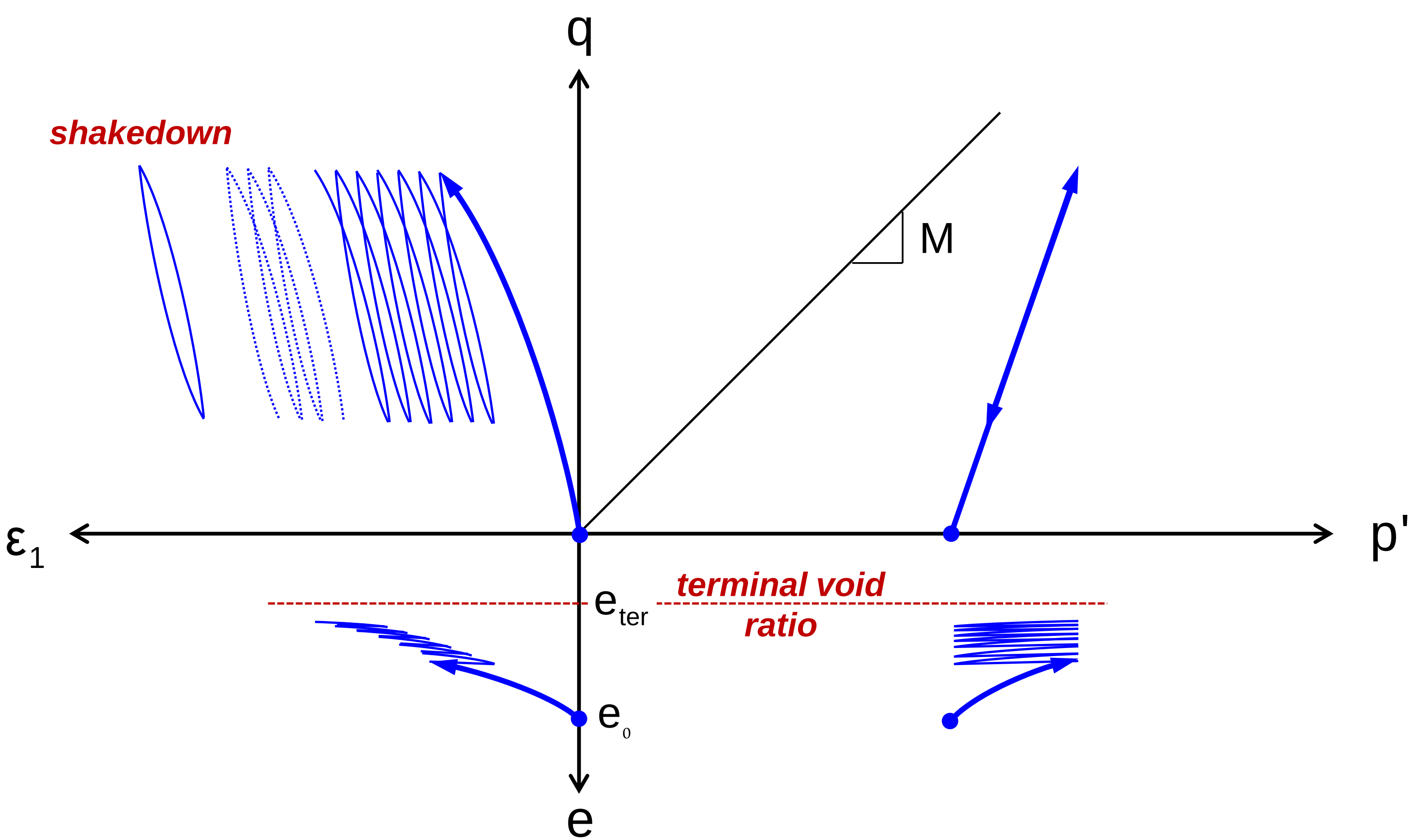
Stress - Strain - Void Ratio N^{th} Cycle



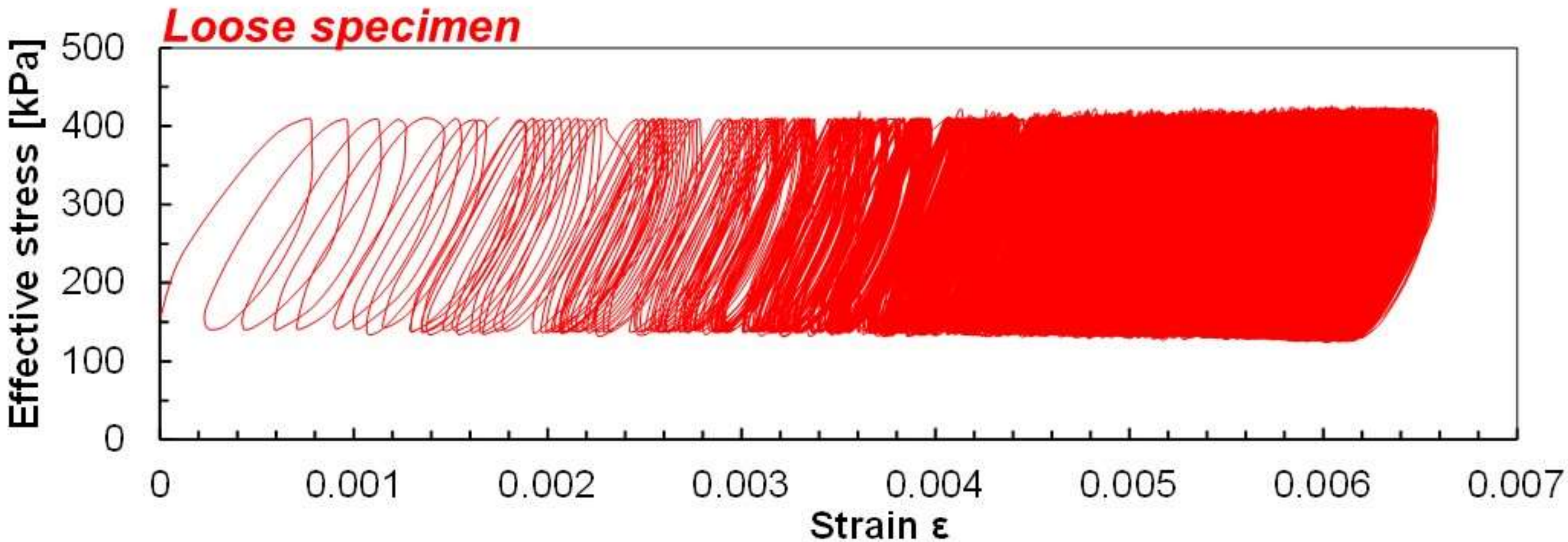
Stress - Strain - Void Ratio N^{th} Cycle

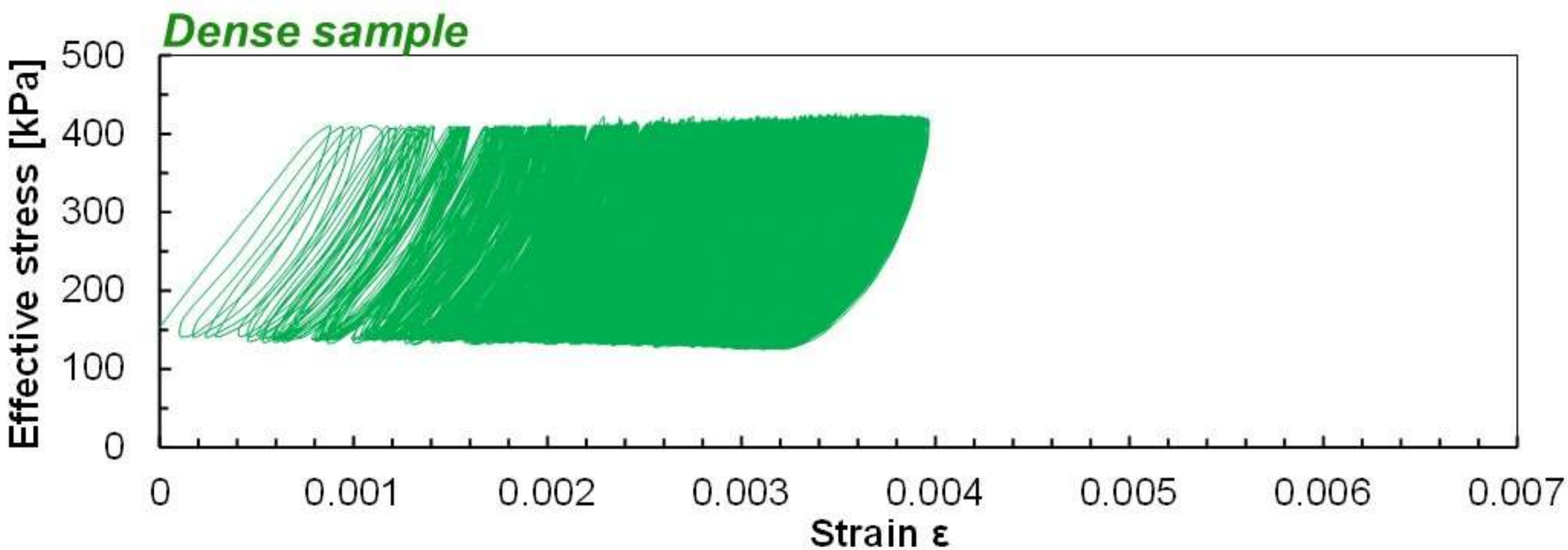


Stress - Strain - Void Ratio *N^{th} Cycle*

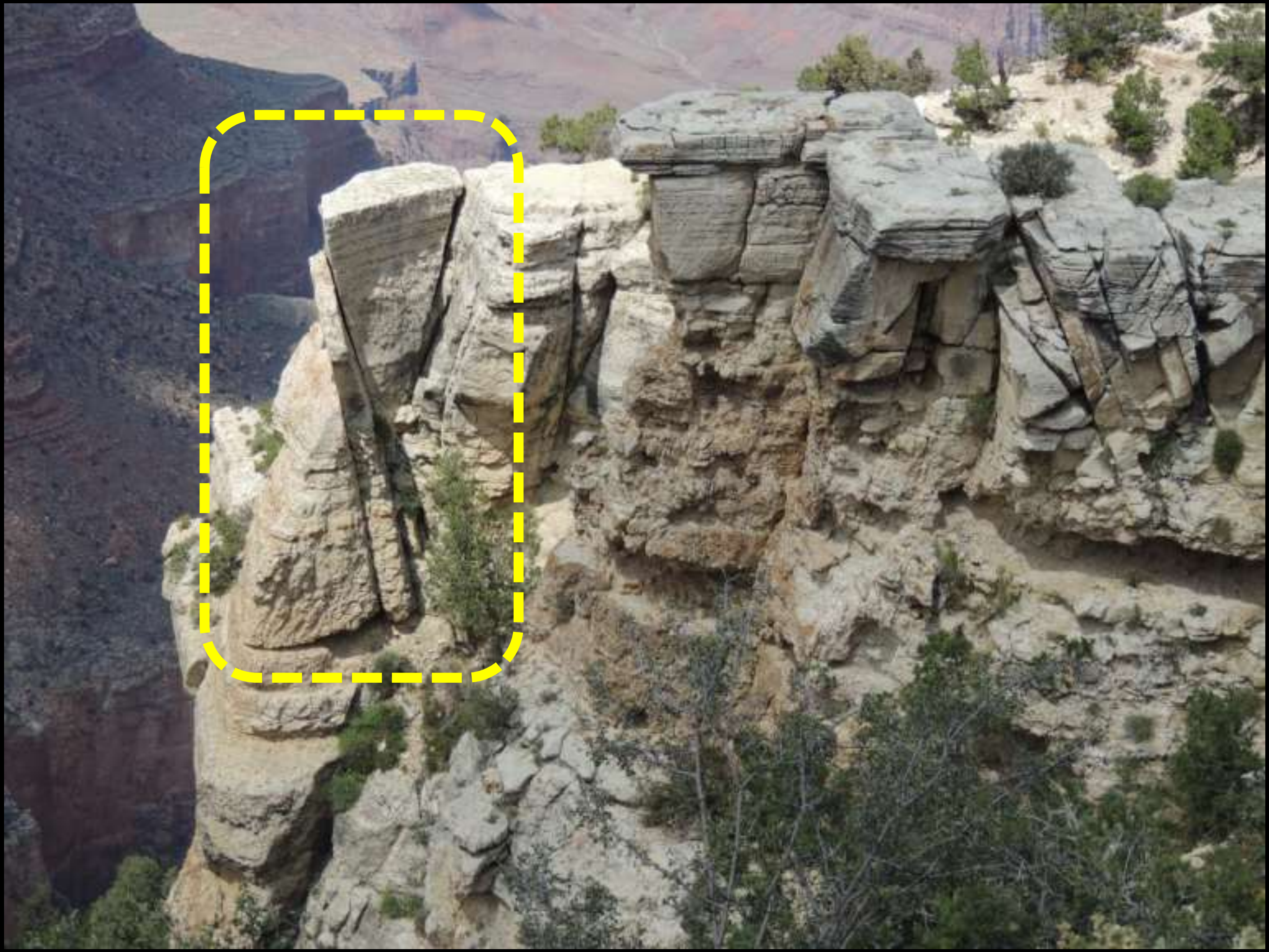


Settlement k_o Conditions (coarse sand)





Eugenia Canyon

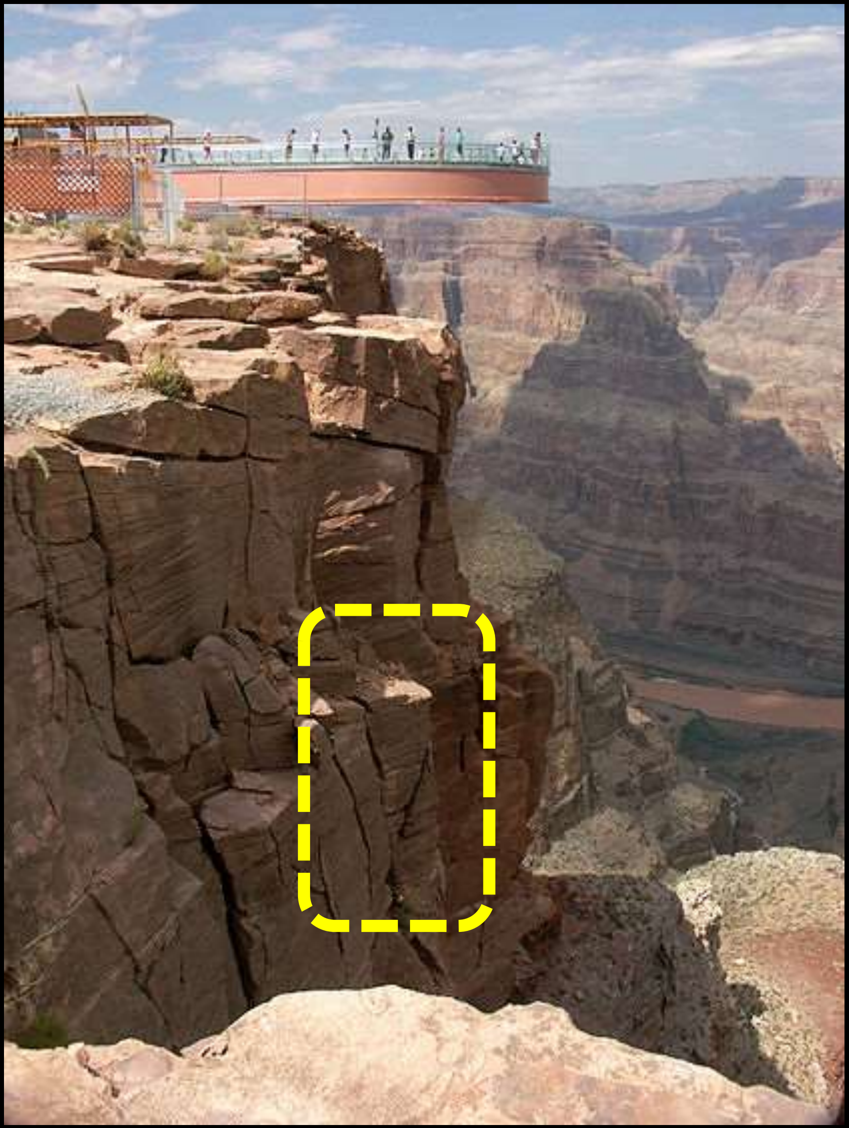


Masada (Israel)

Masada (Israel)

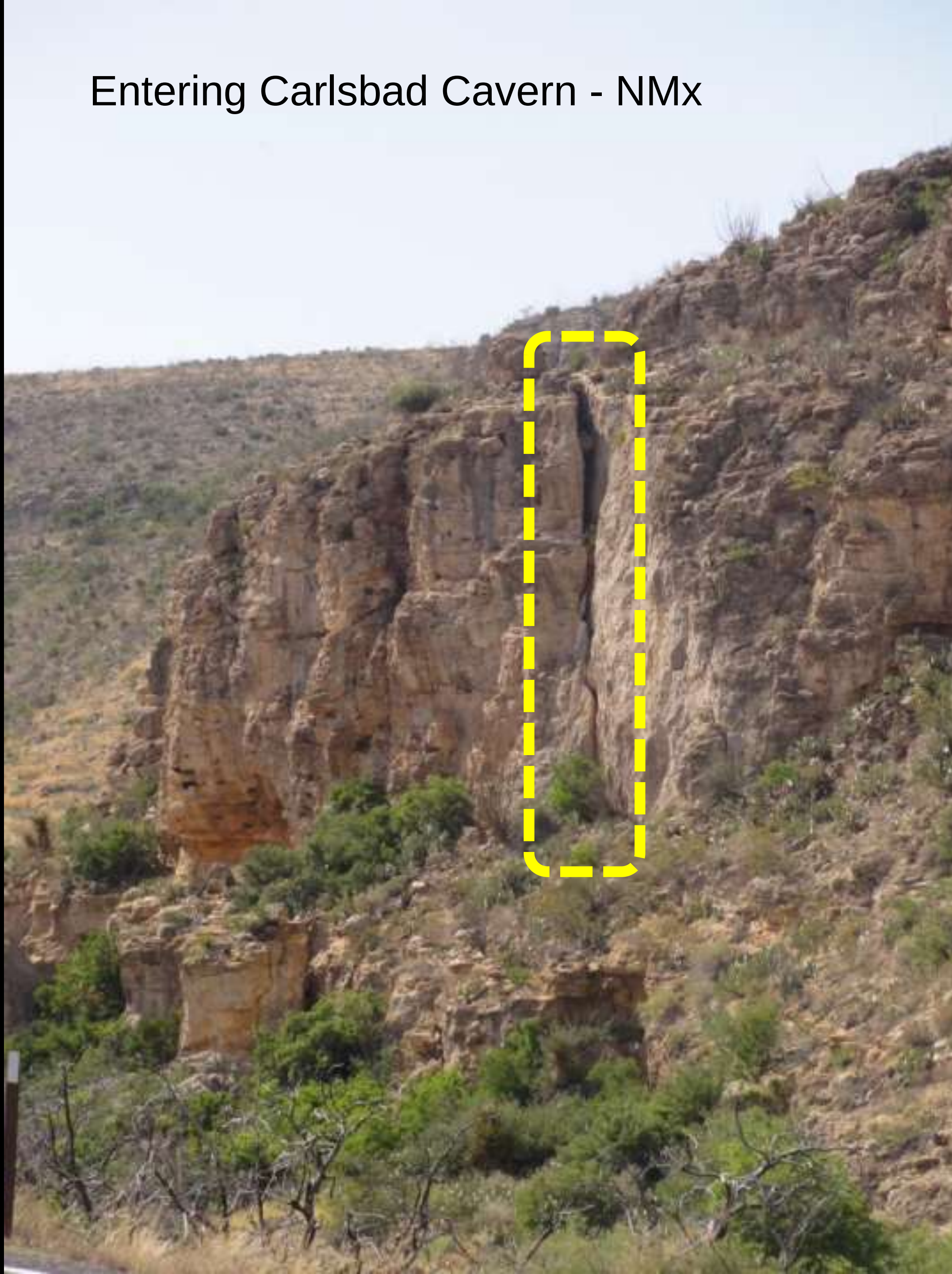
Bakun-Mazor et al. (2011)

Grand Canyon Skywalk



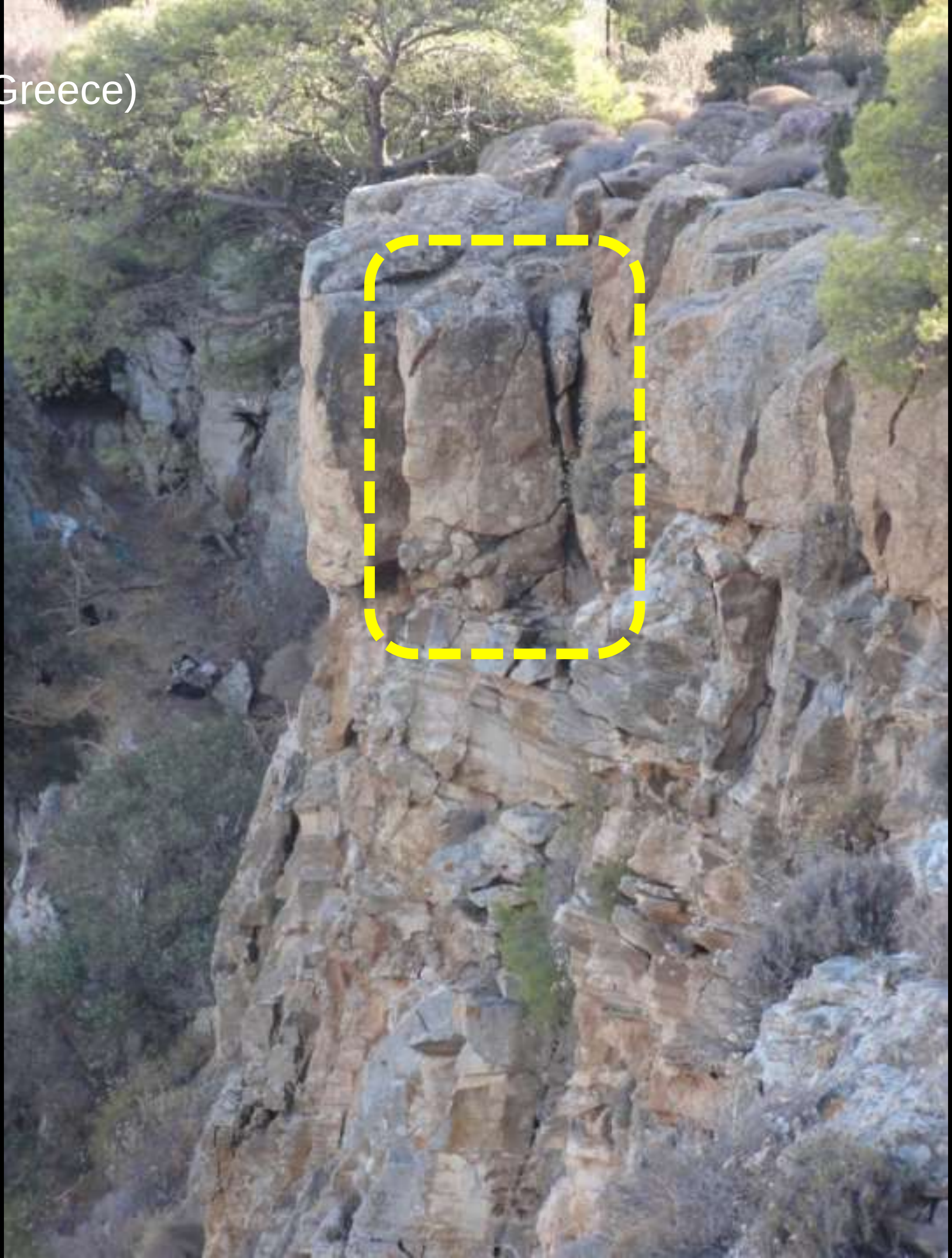
Eric Sakowski

Entering Carlsbad Cavern - NMx

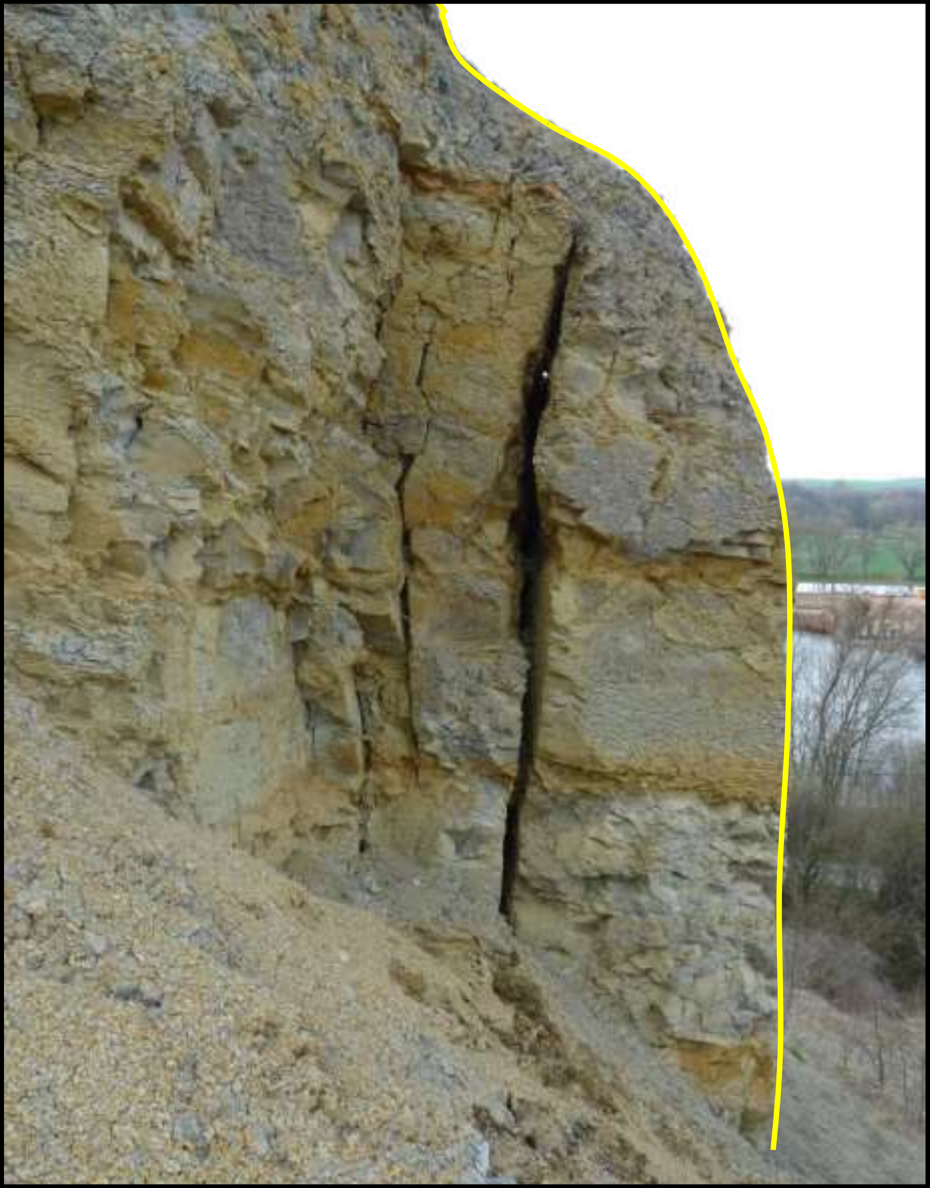


Delphi - Greece

Lavrion (Greece)



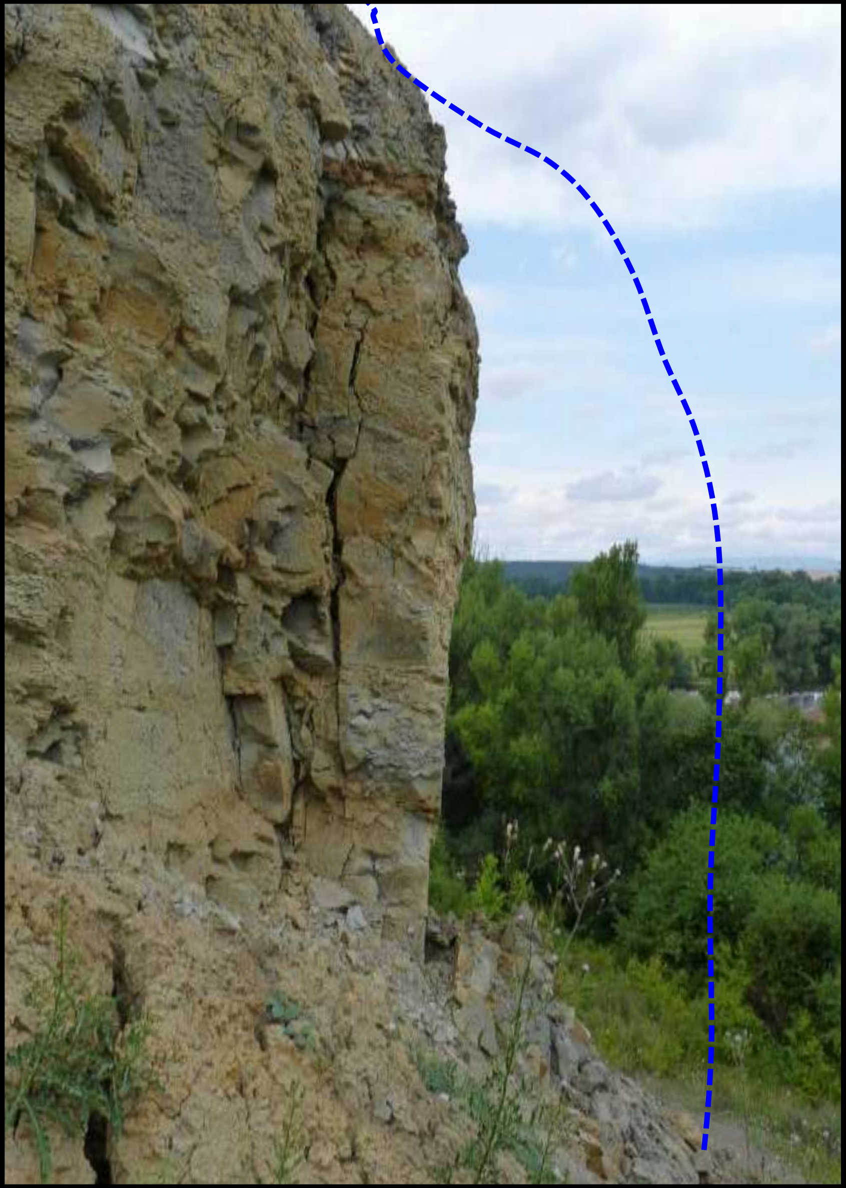
Brezno (Czech Republic)



4/18/2013

Jan.Novotny@arcadis.cz

Brezno (Czech Republic)



7/29/2013

1. Classification
2. Permeability
3. Compressibility
4. Coupling
5. Stiffness: $G_{max} \leftrightarrow G_{tan}$ …Oedometer
6. Shear Strength - Localization
7. Repetitive Loads
8. Properties: Database & IT tool

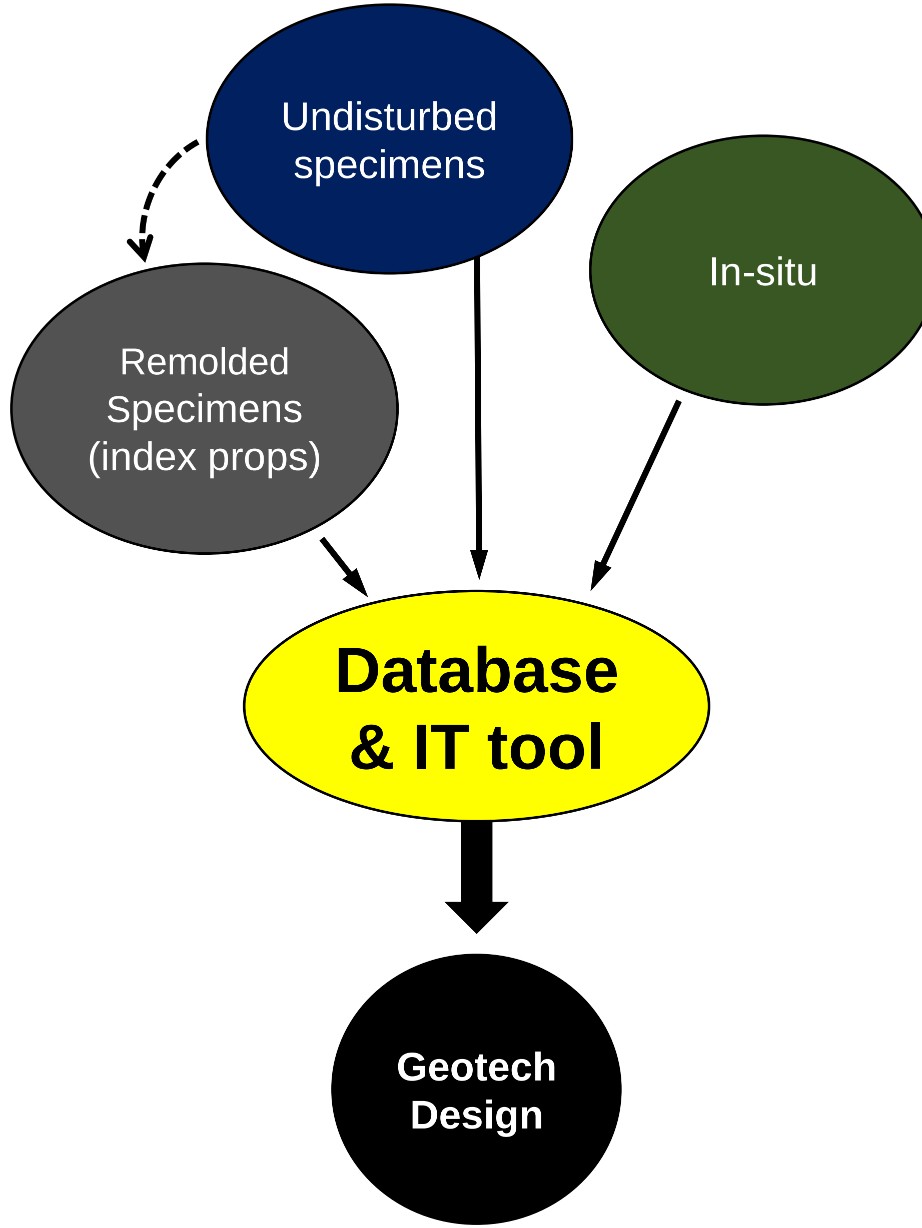
Properties: IT Tool

Soils:

Dr. M. Terzariol
(KAUST)

Fractured rocks:

Dr. L.G. Cruz
(U. Cauca)



Closing Thoughts

Geotech 100 yrs: comprehensive revision + pruning + expansion (starting with classification)

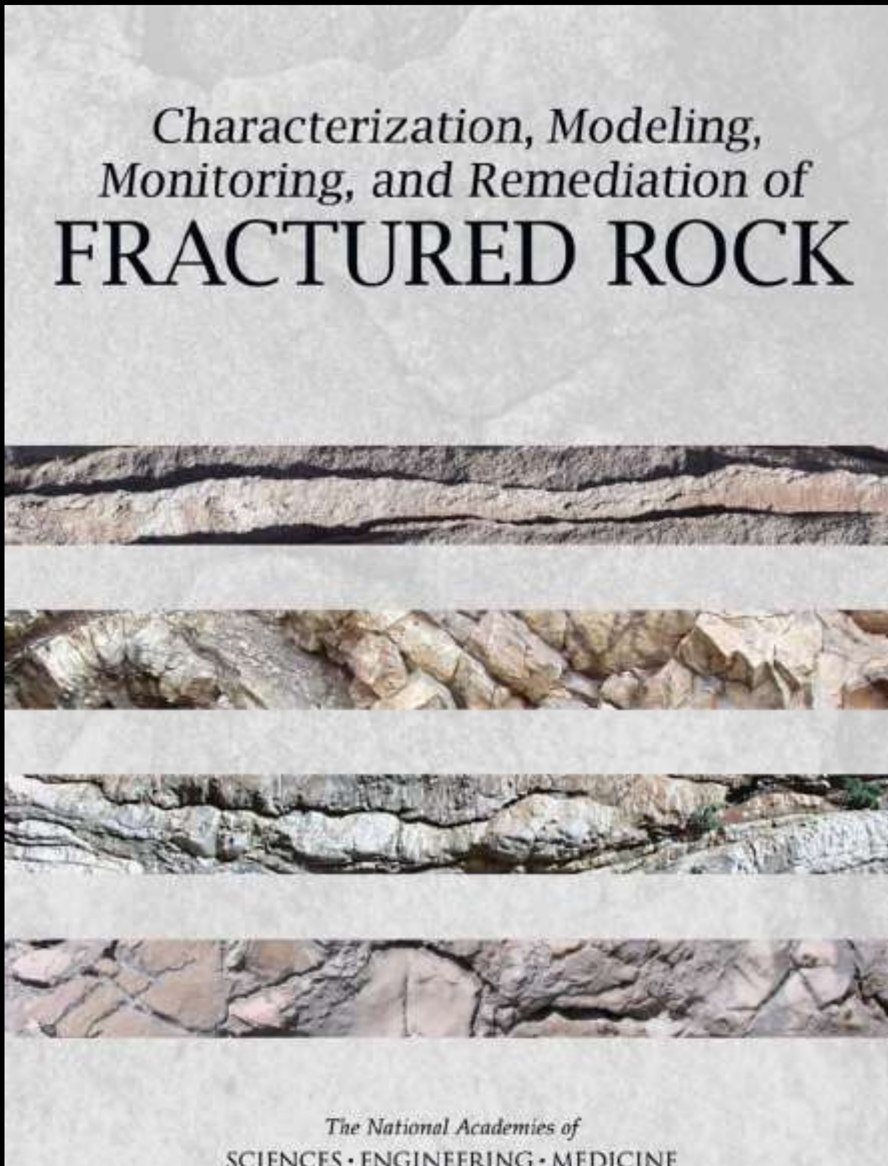
Models & correlations *physics inspired… data driven*
geo-databases: ready for a global community effort

Properties: revolution in experimental methods
boundaries, variability and internal scales
what we want to measure … what we think we measure

Coupled HTCBM: complex … even σ' (the most common HM)

Repetitive loading: ubiquitous … fertile territory for research

Localizations: ubiquitous and problematic



This presentation and support information:

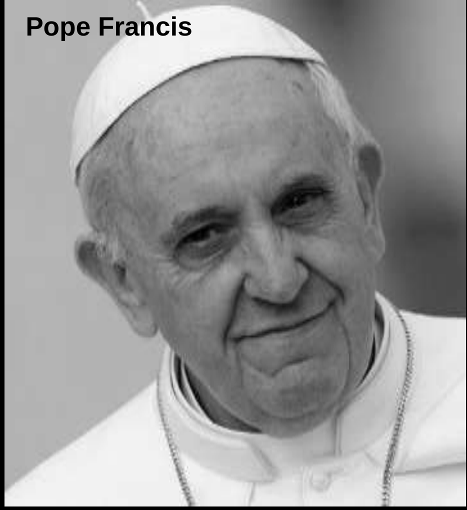
(1)

(2) egel@kaust.edu.sa
or uperc.kaust.edu.sa

Reason for 3 great geo-conferences in Argentina

An invitation to "care for our common home"

how can we -GeoEngineers- contribute?



An invitation to “care for our common home”

how can we -GeoEngineers- contribute?

Soil & rock = terroir (latin)

in Argentina ➔ Malbec, Torrontes…

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Soil & rock = terroir (latin)

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We did <u>not</u> develop TRUBALL (DEM)

we developed GREATBALL !

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It takes two to tango

enjoy wonderful colleagues !

Welcome to Argentina !!

Peck Terzaghi