SYDNEY ICSMGE 2022
A GEOTECHNICAL DISCOVERY DOWN UNDER

Bishop Lecture

The Assessment of Geotechnical Properties in the Information Age

J. Carlos Santamarina
KAUST

Alan W. Bishop (1920-1988)

(1) Mechanical Behavior & Properties

Partially saturated soils (1959+)

Pore pressure generation (1953+)

Shear strength (crushing, stress path effects… 1950+)

Progressive failure (1967+) , Residual strength (1971+)

Creep (1969)

(2) Measurement the devil is in the details Nietzsche

Sampling, sampling effects. Remolded specimens

Field testing (1948+)

Triaxial testing (1950+)

Triaxial test at 7 MPa (1965+)

Pore pressure measurements (1953+)

Specimen size (1969) & compliance effects (1976)

Shear box (1948) Ring shear (1971) **Hollow Cylinder** (1970's)

(3) Engineering driven by practical problems

Earth dams, slopes, excavations - Slices (1954+)

Earth pressure (1957+)

Geomaterials

Sands (1948+) – **Clays** (1953+) – **Rocks** (1966+)

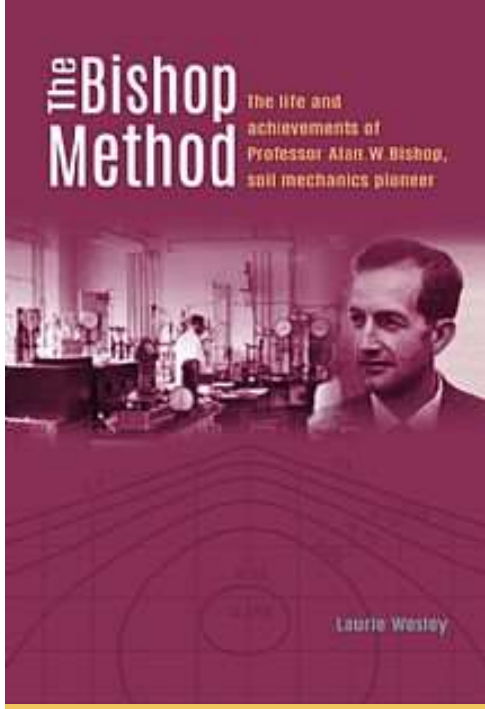
Publications

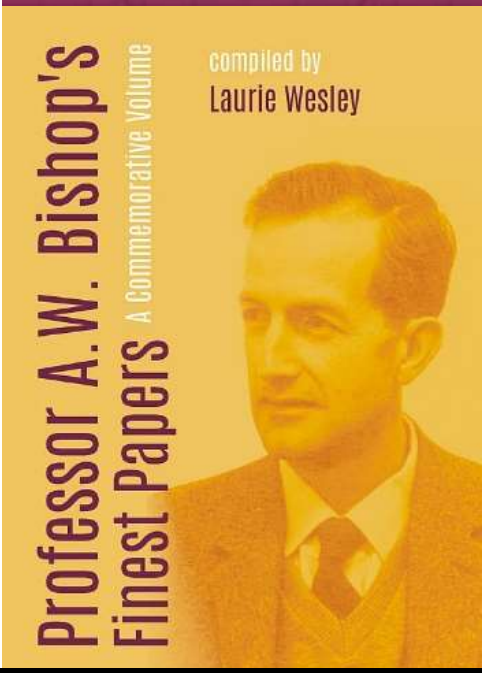
Total: **68 Publications** (1946 and 1981)

Last paper: "Thirty five years of soil testing"
10th ICSMFE Stockholm 1981)

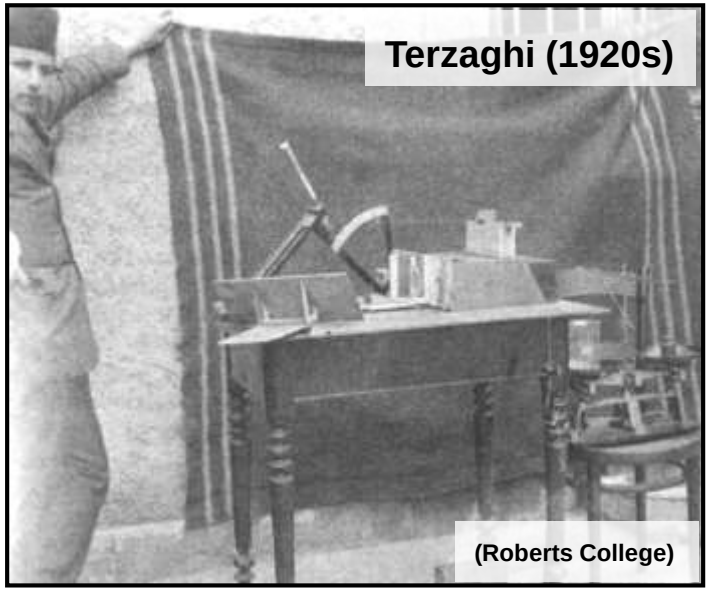
Participation at ICSMFE

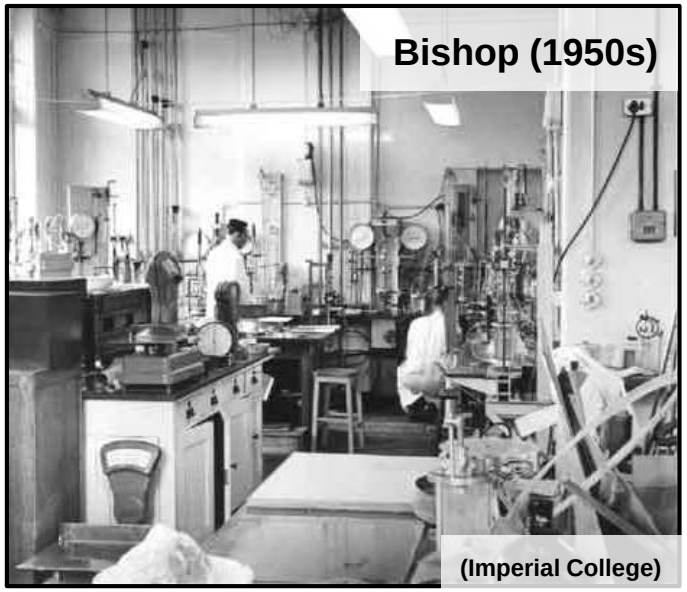
3rd ICSMFE Zurich 1953
4th ICSMFE London 1957
5th ICSMFE Paris 1961
6th ICSMFE Montreal 1965
7th ICSMFE Mexico 1969
8th ICSMFE Moscow 1973
~~9th ICSMFE Tokyo 1977~~
10th ICSMFE Stockholm 1981

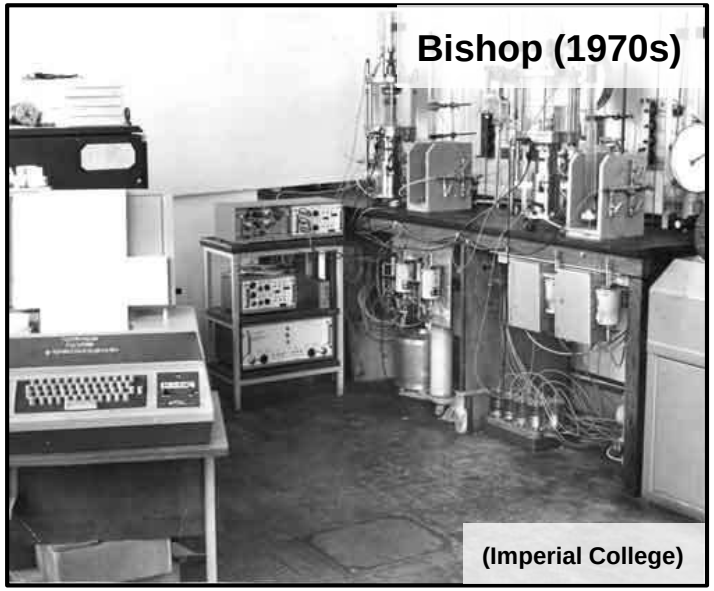




the soil mechanician *the meticulous experimentalist* *the engineer*



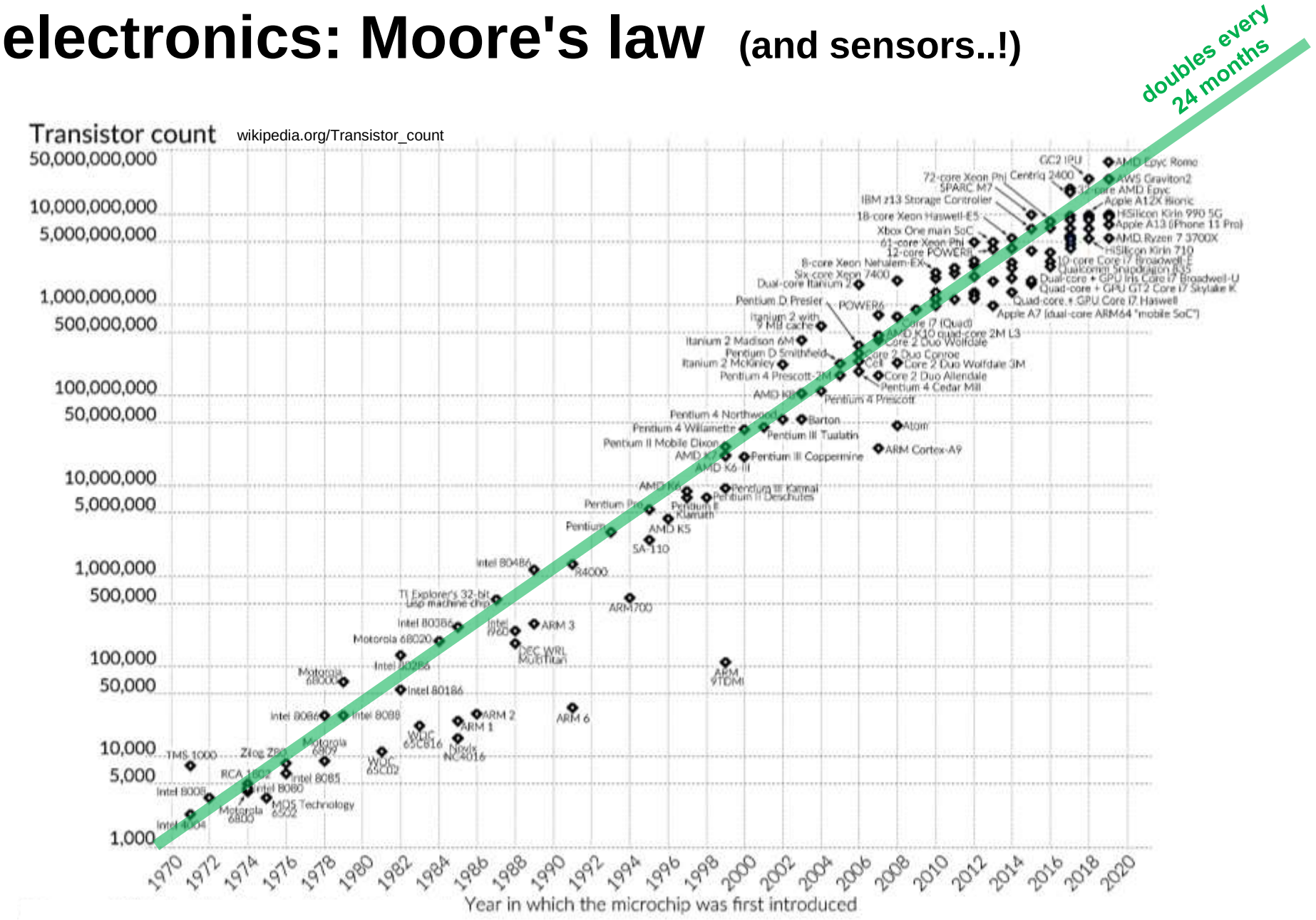




Computer assisted
Multi-sensor
Multi-physics

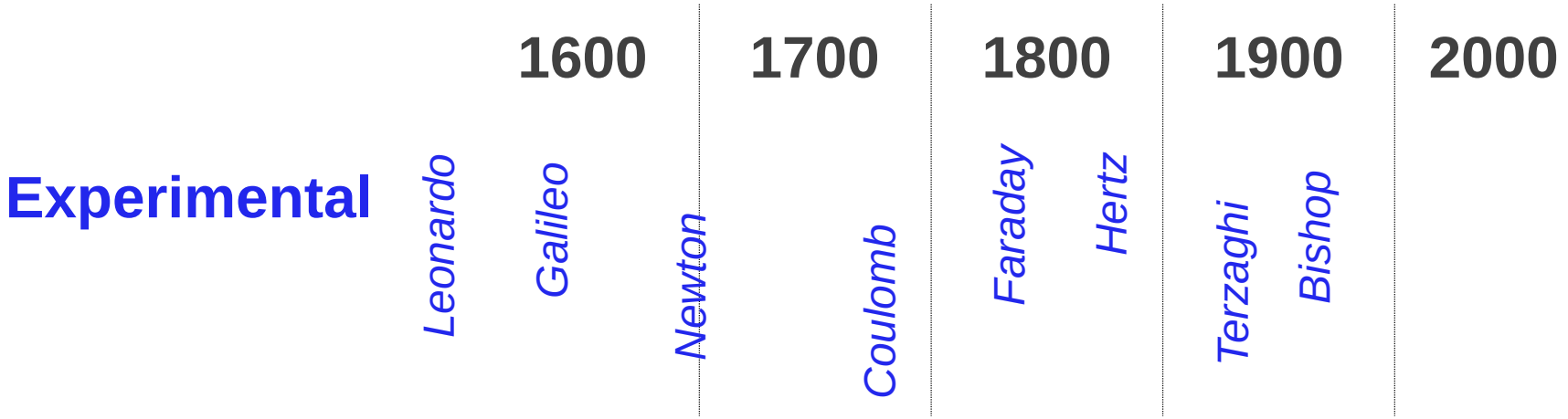
Increased complexity & decreased immediacy

Microelectronics: Moore's law (and sensors..!)

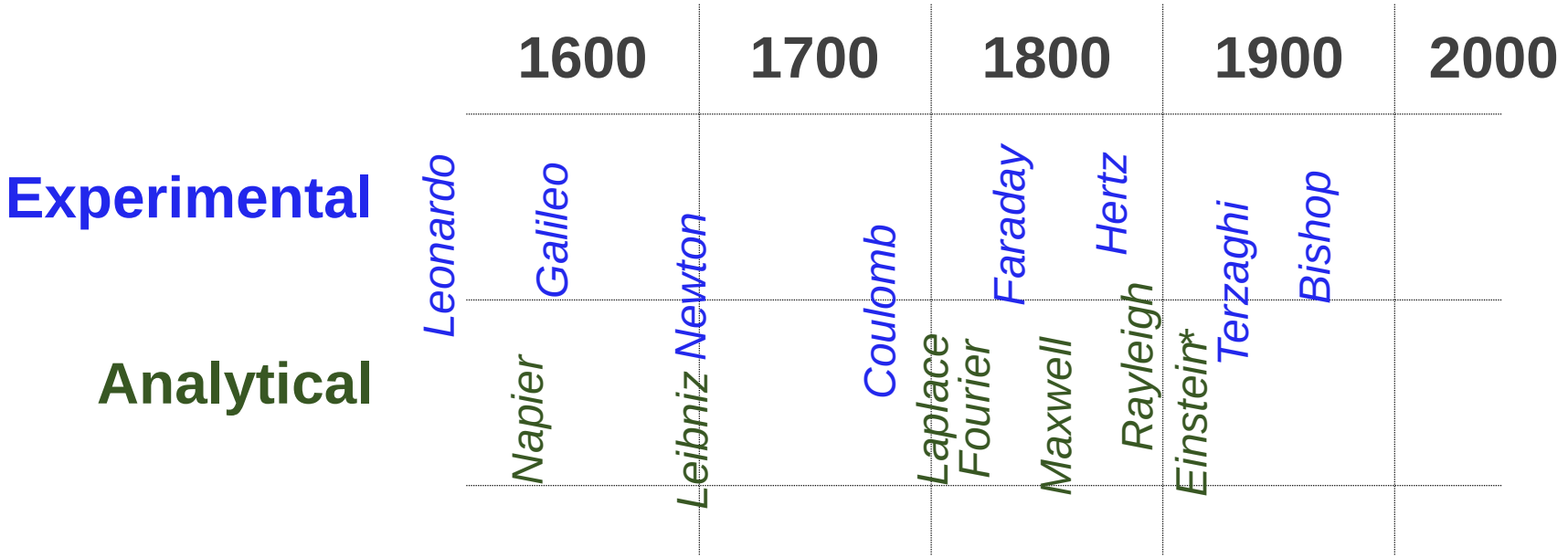


50 million times since Niel Armstrong walked on the moon…!

Knowledge generation

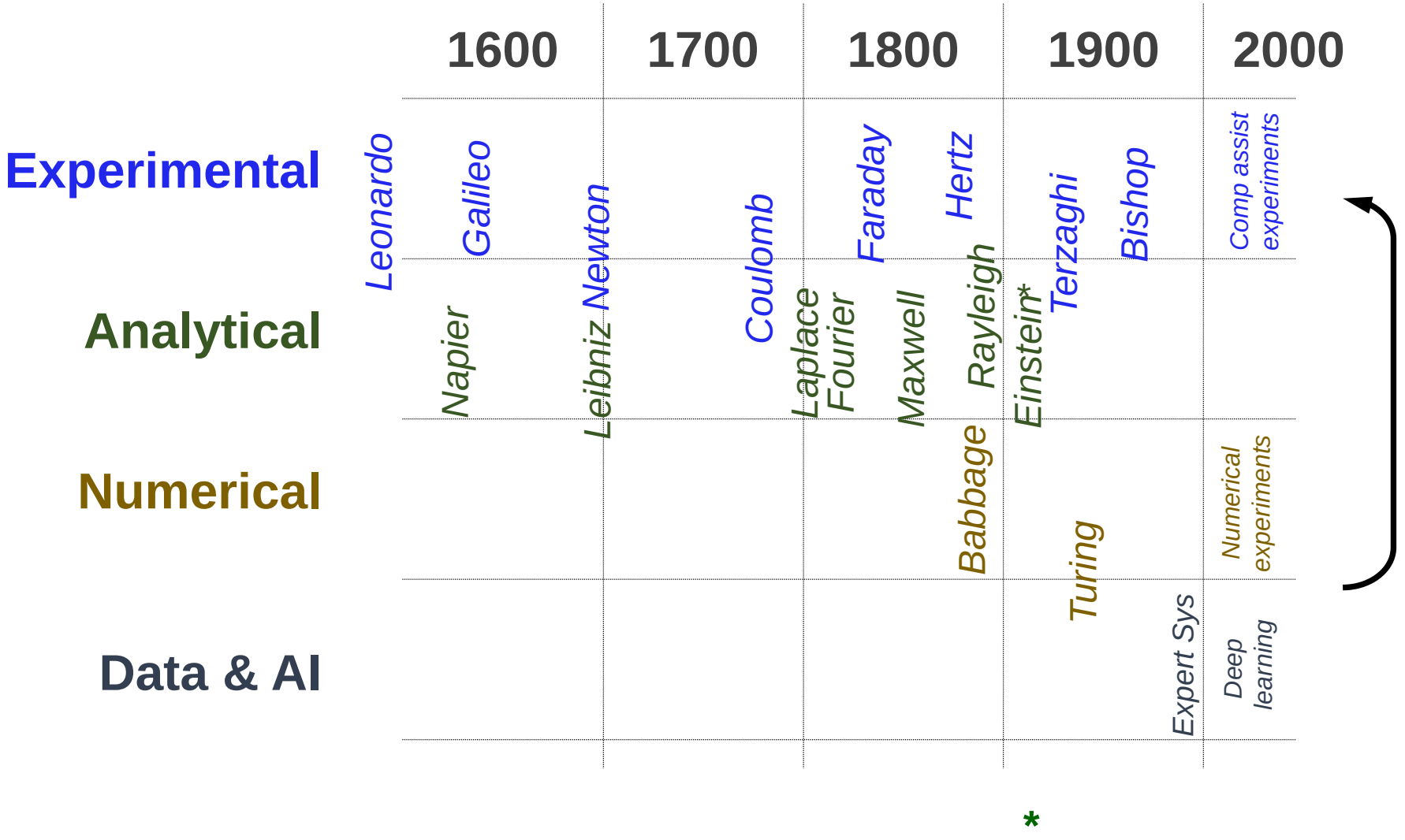


Knowledge generation



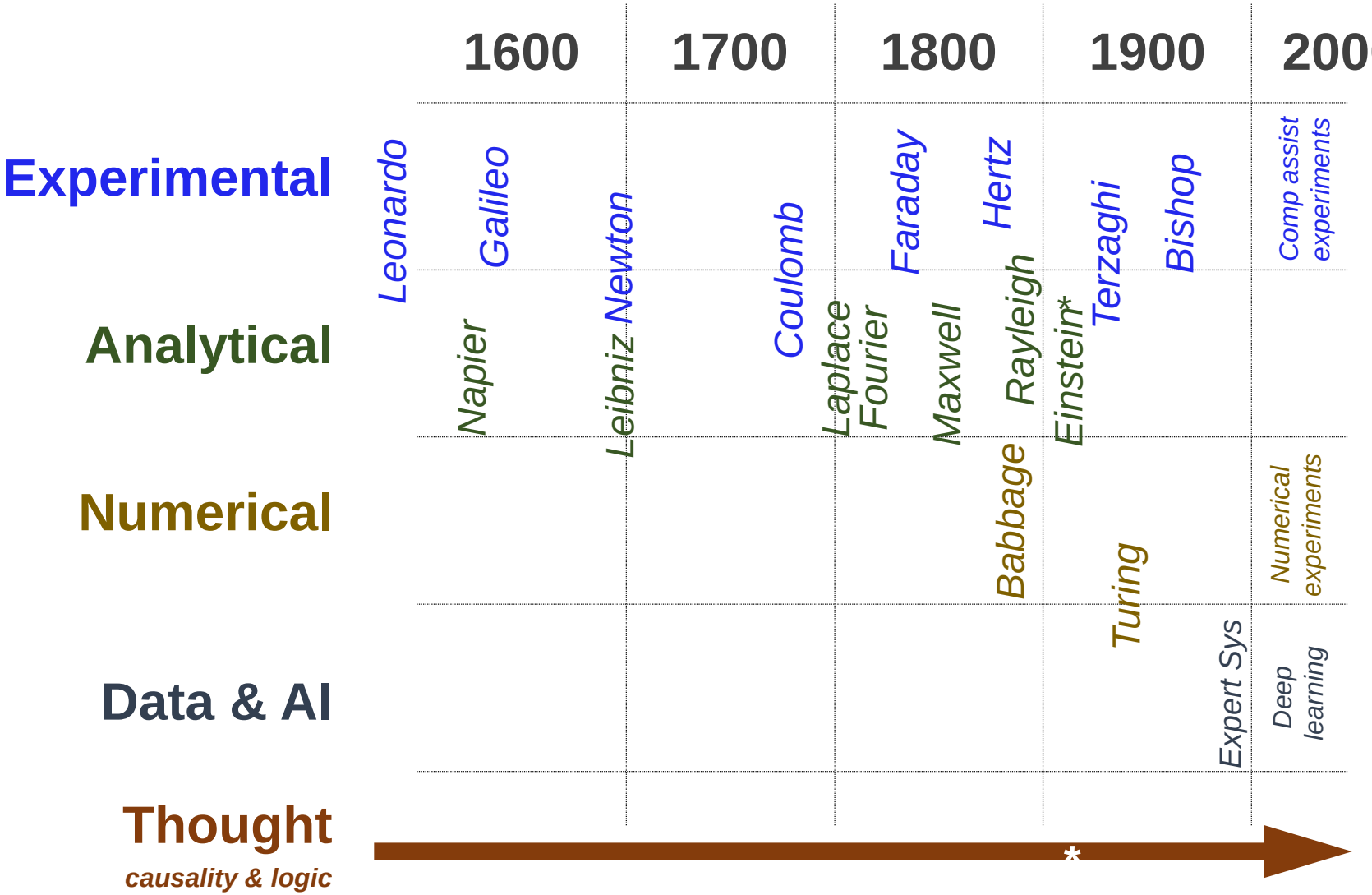
* *thought experiments*

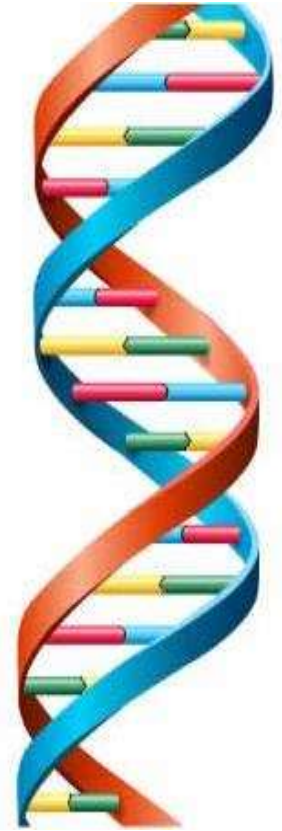
Knowledge generation



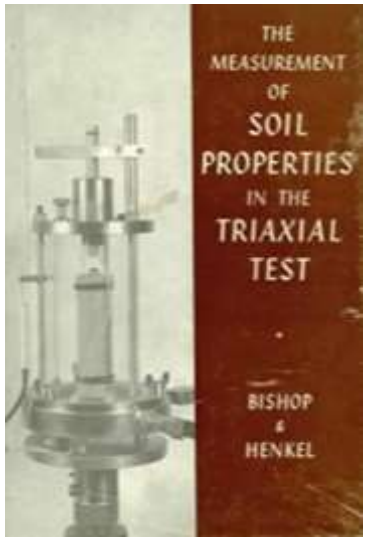
Confluence of technological revolutions *Experimentation: reinvigorated!*

Knowledge generation





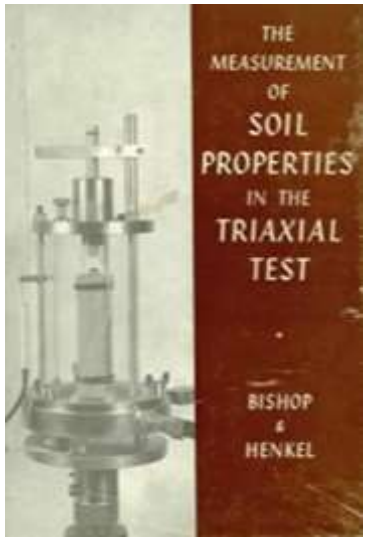
Bishop lectures



1957 - Bishop & Henkel	*THE MEASUREMENT OF SOIL PROPERTIES IN THE TRIAXIAL TEST*
2011 - F. Tatsuoka	Laboratory stress-strain tests for geotechnical engineering research and practice
2013 - R. Jardin	Advanced laboratory testing in research and practice
2015 - H. Di Benedetto	Advanced testing and modelling - Granular materials with/without viscous glue
2017 - D. Muir Wood	Modelling and testing
2019 - J. Koseki	Advanced laboratory testing of geomaterials - Unconventional liquefaction tests
2022 - All of us…	**The assessment of geotechnical properties in the information age**

What has changed in the last 65 years? *What have we gained, lost, forgotten?*

Bishop lectures



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Simple concepts…. how they apply to YOUR lab & field needs ?

What do we measure?

Data ➔ information

Computer-assisted experimentation

“Numerical experiments”… Oxymoron?

Other trends in experimentation

Closing thoughts

What do we measure?

the measurement always alters the measurand

Heisenberg's uncertainty principle

Data ➔ information

Computer-assisted experimentation

"Numerical experiments"… Oxymoron?

Other trends in experimentation

Closing thoughts

What do we measure?

What we want to measure…

What we think we measured…

What we actually measured !!

[anon]

What do we measure?

What we want to measure… processes at zero gravity

What we think we measured… behavior at μ-g

What we actually measured !!

[anon]

$$F = \overbrace{G\frac{M}{r^2}}^{g} m$$

$$g_{ISS} = 0.88\, g_{earth}$$

What do we measure?

What we want to measure…	**processes at zero gravity**
What we think we measured…	**behavior at μ-g**
What we actually measured !!	**response in free fall**

[anon]

$$F = \overbrace{G\frac{M}{r^2}}^{g} m$$

$$g_{ISS} = 0.88\, g_{earth}$$

What do we measure?

What we want to measure… g-effect

What we think we measured… behavior at μ-g

What we actually measured !! response in free fall

[anon]

$$F = \overbrace{G\frac{M}{r^2}}^{g} m$$

$$g_{ISS} = 0.88\, g_{earth}$$

What we want to measure… temperature

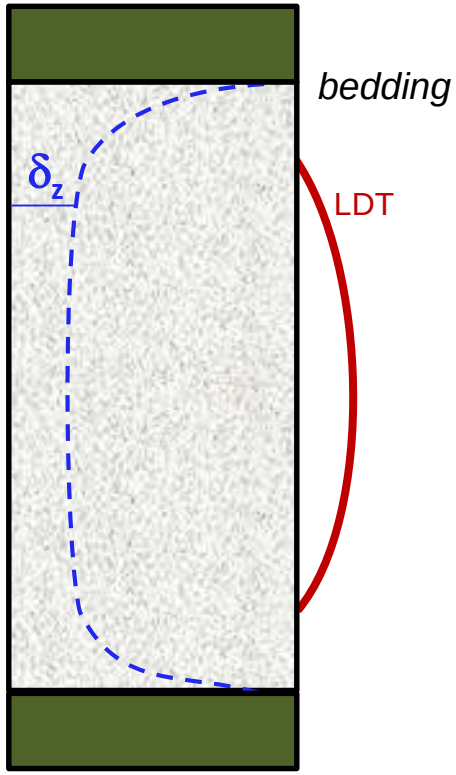
What we think we measured… $T_{ceramic} < T_{carpet}$

What we actually measured !! $D_{ceramic} > D_{carpet}$

[anon]

What do we measure? Boundary effects & relative stiffness

Triaxial



Oedometer

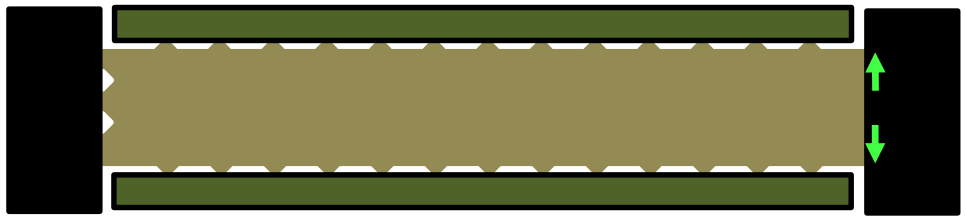
sampling effects

sediment-ring gap

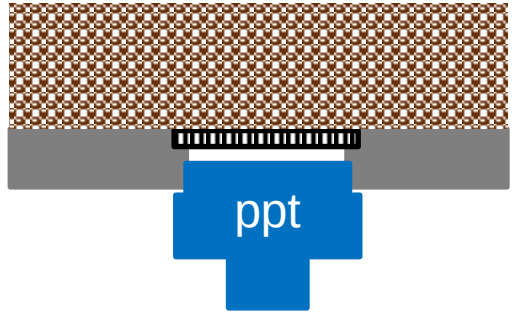
cap seating effects

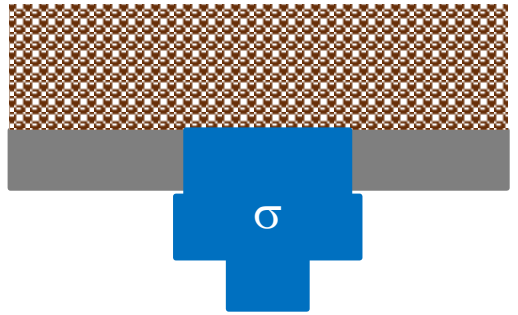
side friction f(h/D)

k= f(z) & m_v=f(z)



Sensor installation

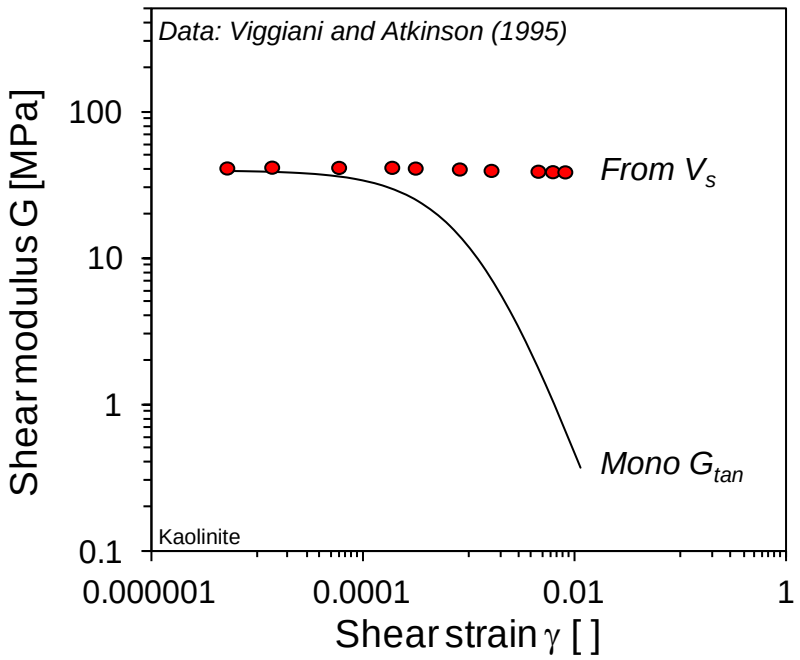




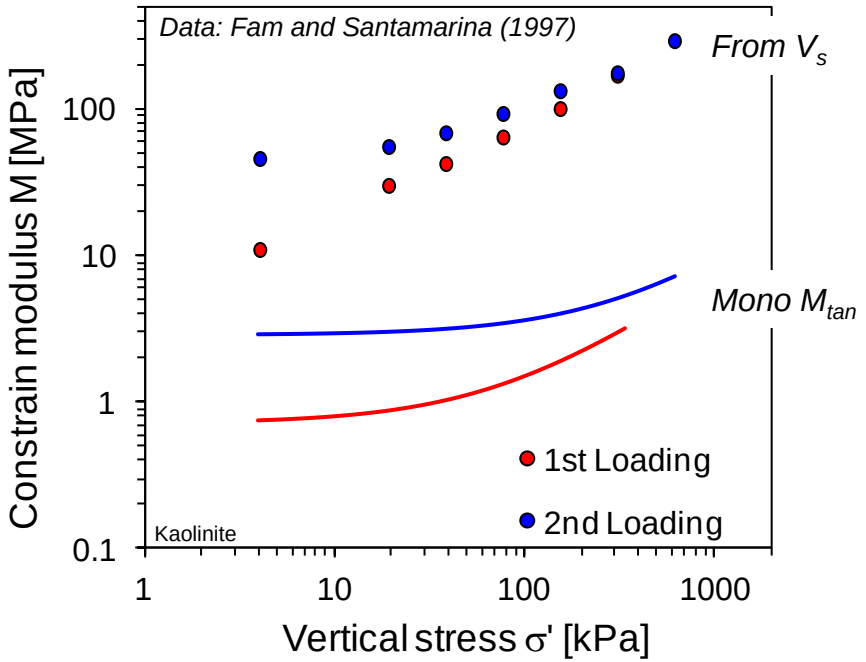
local vs. global drainage *boundary effects* *measurement=integral* *relative stiffness*

What do we measure? Tangent stiffness E_{mono} -vs- E_{prop}

AC Triaxial Test

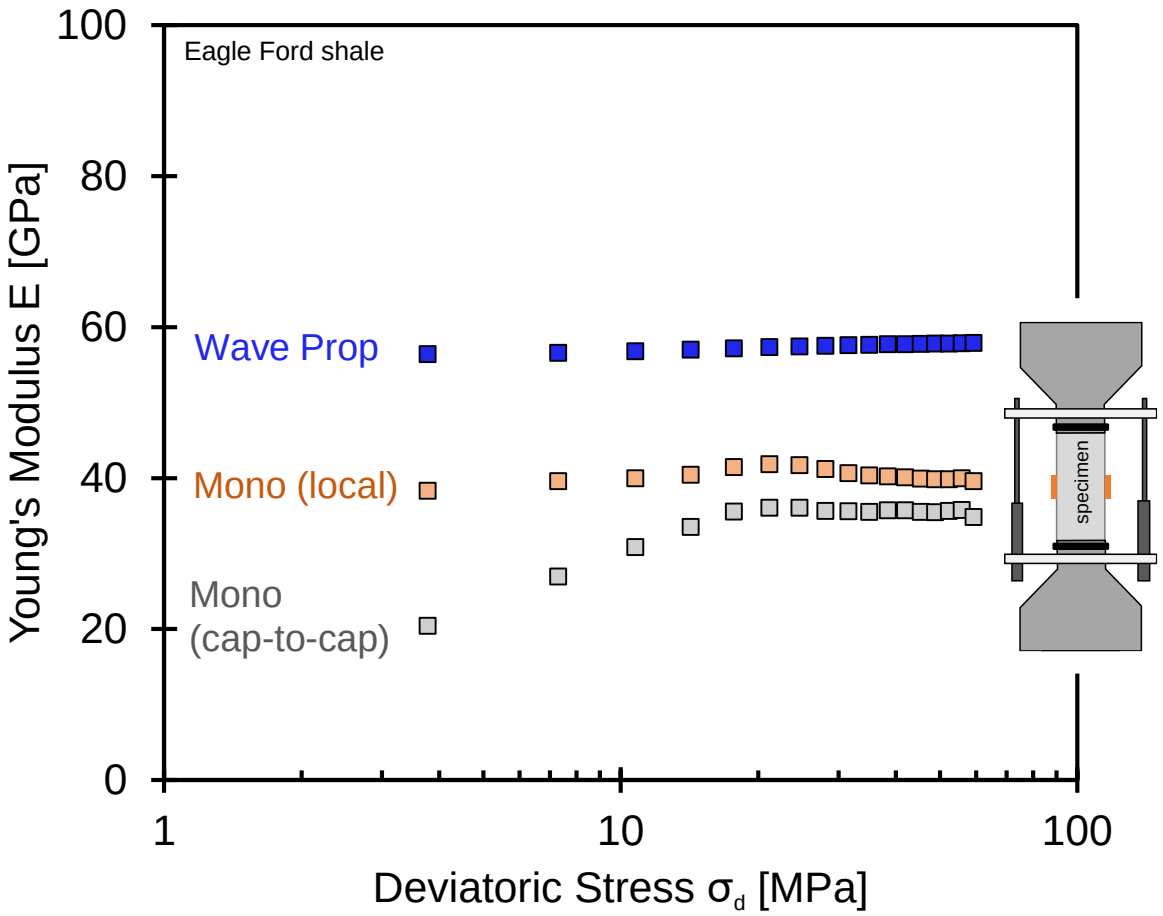


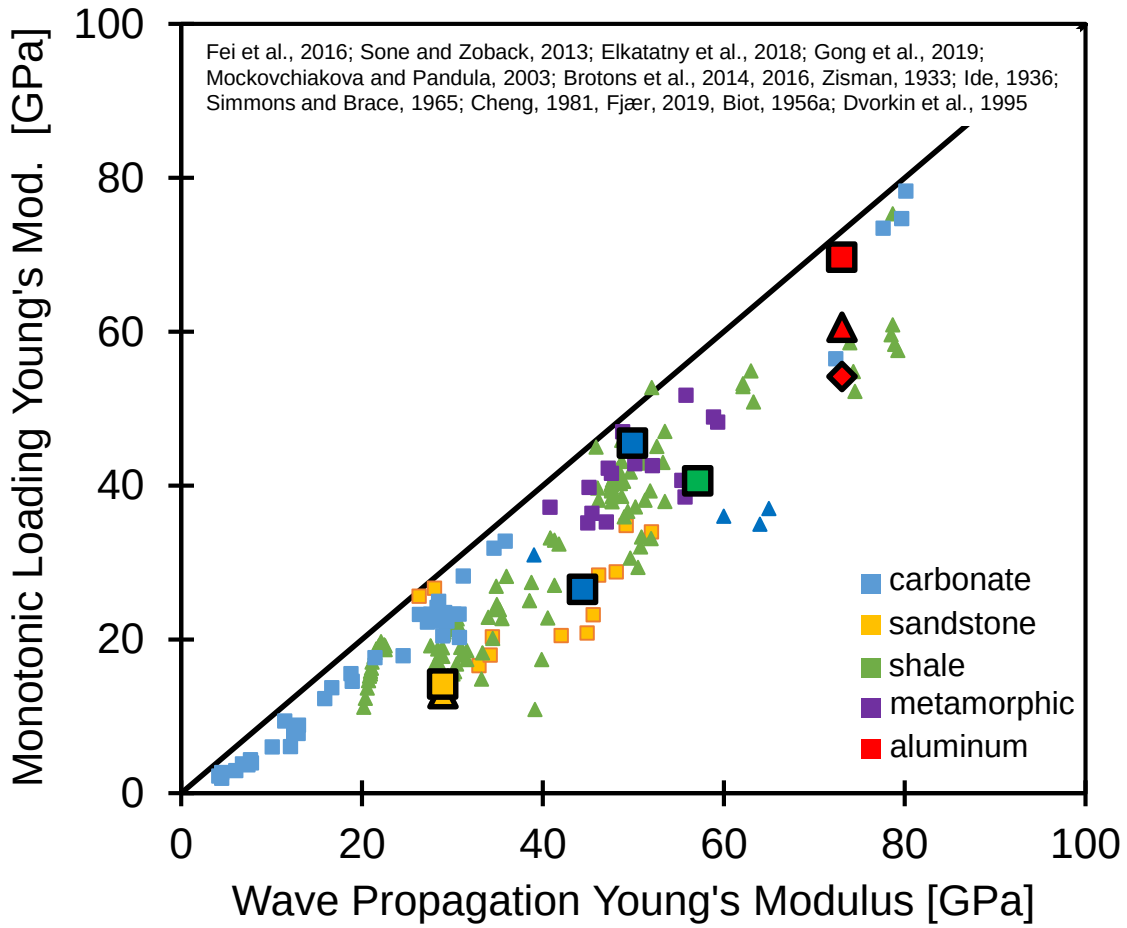
1D Consolidation



Wave propagation: field assessment of stiffness ➔ diagenetic effects without sampling perturbation

What do we measure? Tangent stiffness E_{mono} -vs- E_{prop}



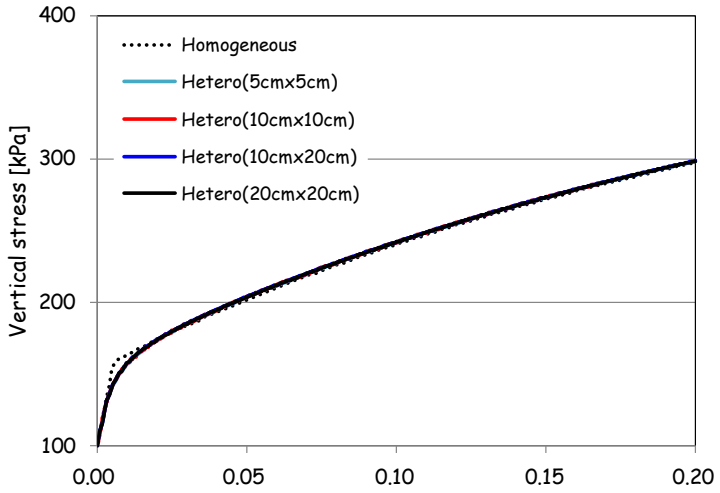


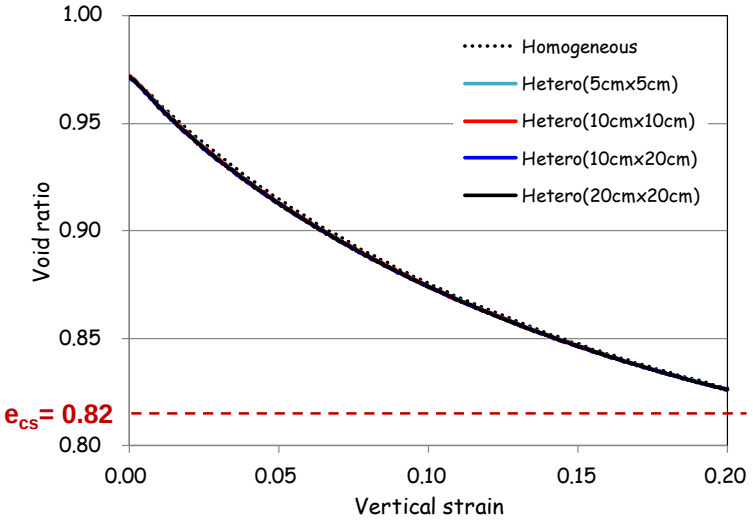
A. Perbawa 2021

What do we measure? Rate effects, stop&creep, λ/L? *Assessment of "state" vs. assessment of "state change"...*

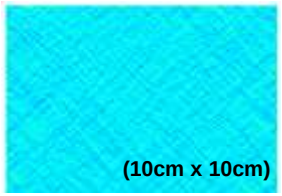
What do we measure?

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

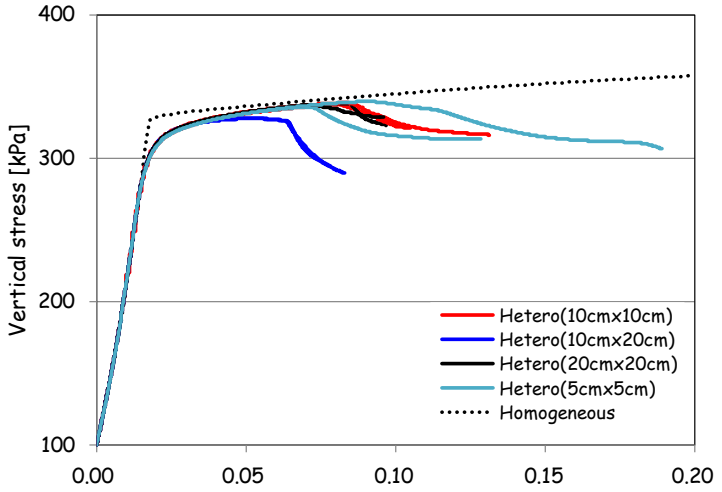


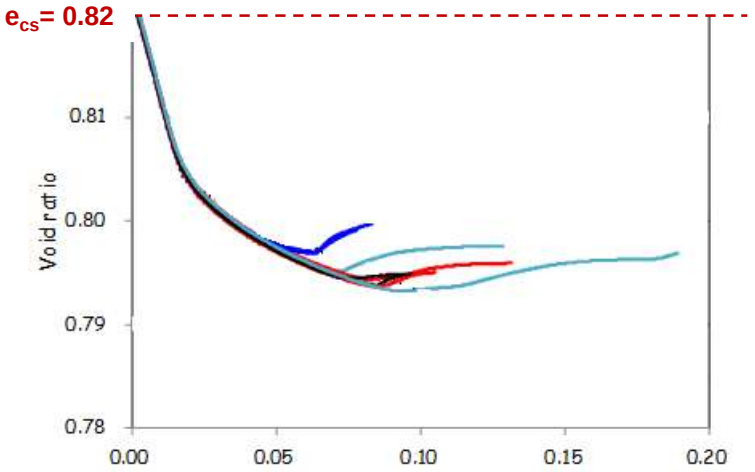


δ-fields @ ε_z=20%

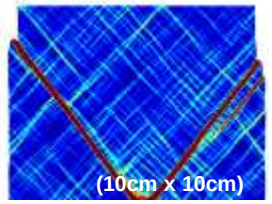


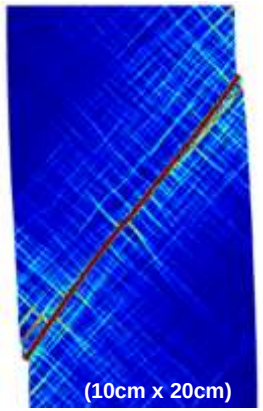
***At Critical State**:* rnd(e)=0.77-0.87 **Note: e_{cs}= 0.82**

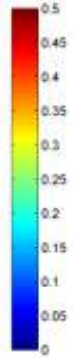




δ-fields @ end of test





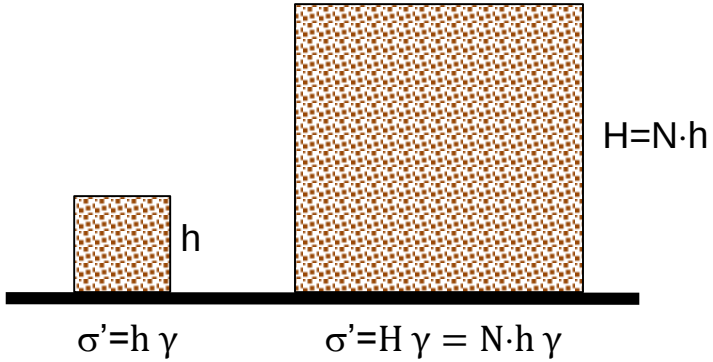


H. Shin – Ulsan Univ.

Critical state = statistical equilibrium ➔ requires strains >> triaxial strains

Scales – Dimensionless ratios

Similarity (Galileo, 1564-1642)
A giant made of the same proportions and material as an ordinary man would crush under his own weight



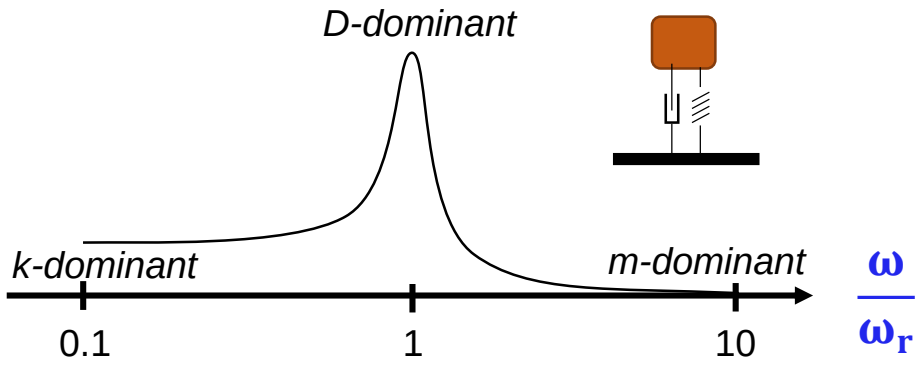
π theorem (E. Buckingham 1867-1940 – Soil Physicist)
A physical equation in terms of n-dimensional variables can be expressed as an equation of n-r dimensionless parameters where r is the number of dimensions involved.

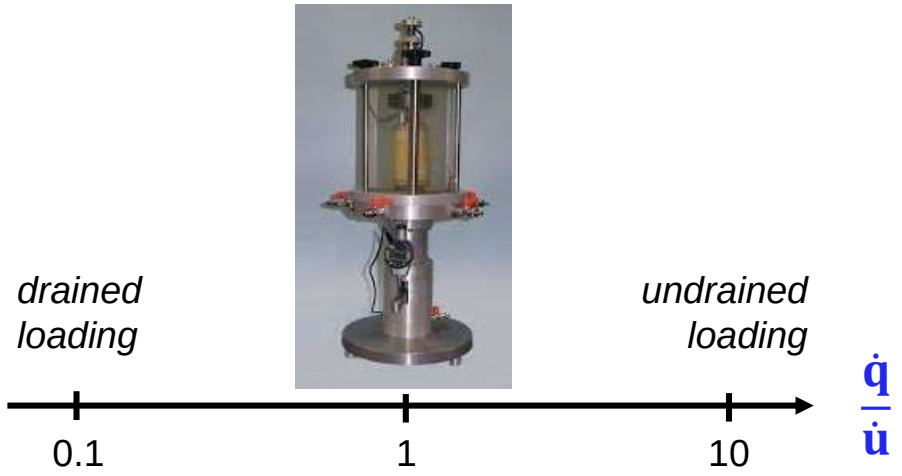
$$f(v_1, v_2, \ldots v_n)$$

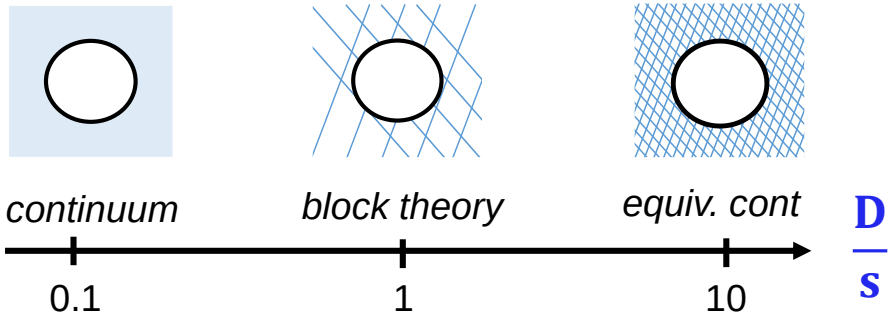
$$\mathrm{F}(\pi_1, \pi_2, \ldots \pi_{n-r})$$

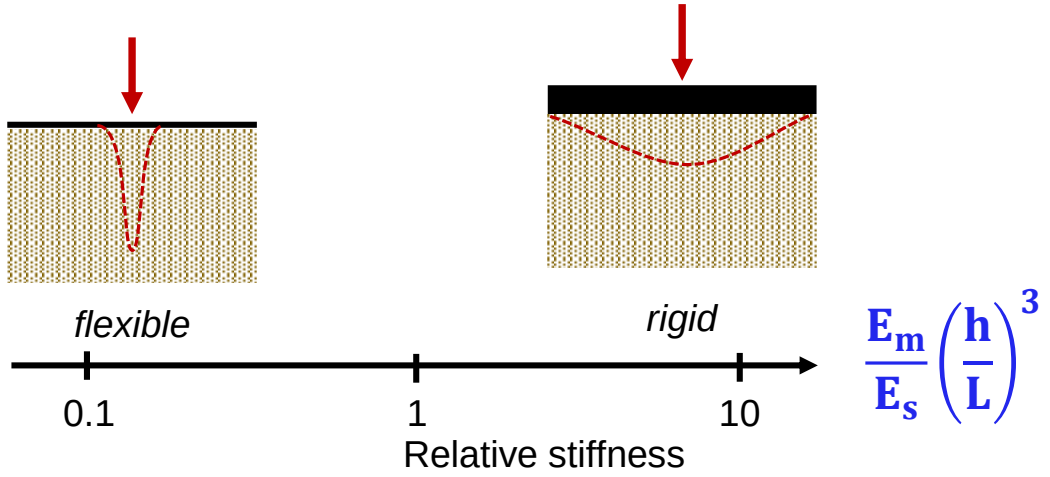
Galileo ➔ centrifuge modeling

π-regime: Dominant conditions





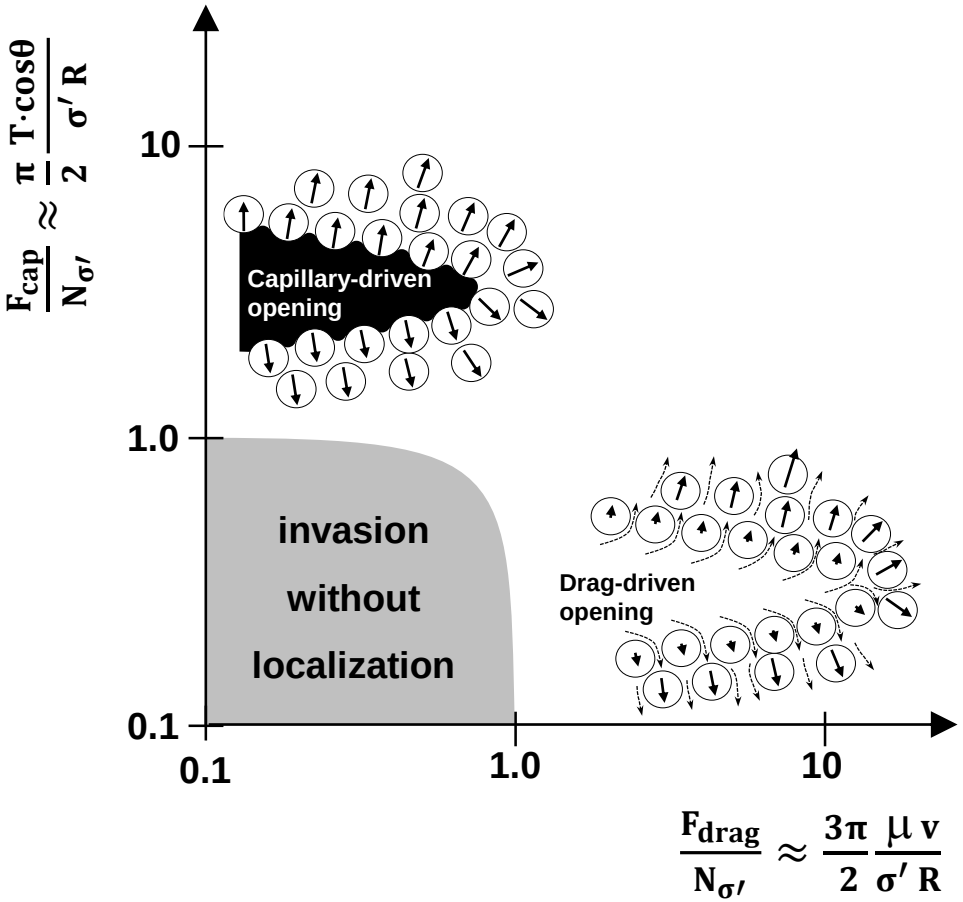




Characterization must be in the relevant π-domain

π-regime: Dominant conditions

HM-Coupling instabilities



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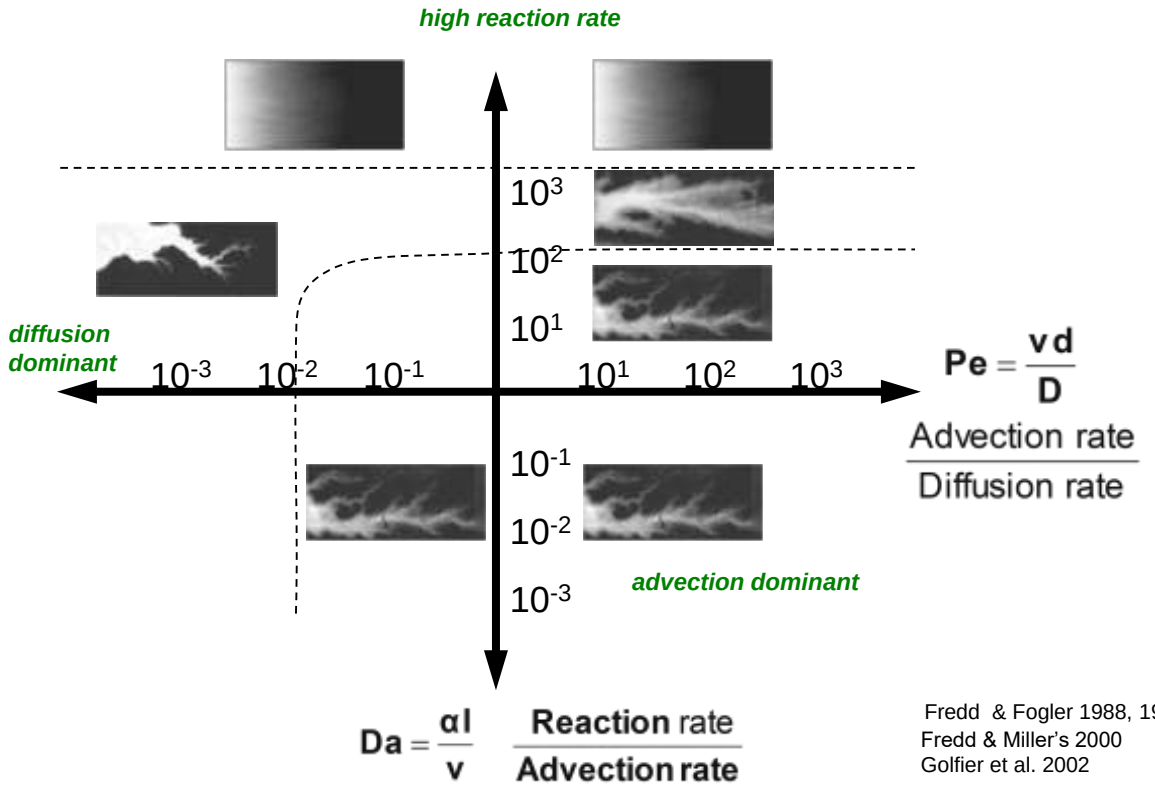
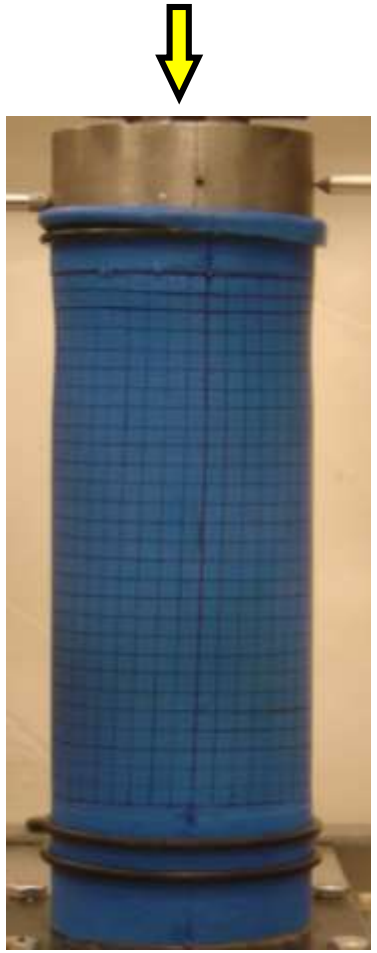


Fredd & Fogler 1988, 1998
Fredd & Miller's 2000
Golfier et al. 2002

Characterization must be in the relevant π-domain

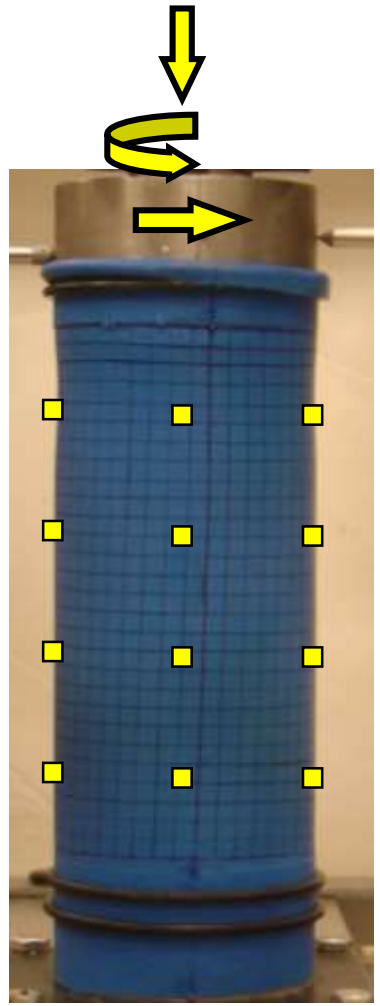
Paradigm shift in experimentation

	Old Paradigm:
	<u>Specimen=Element</u>
Approach	many simple tests
Boundaries	simplest possible
Measurements	very few
Interpretation	simple fitting
Information per test	very limited
Number of tests	many



Paradigm shift in experimentation

	Old Paradigm:	New Paradigm
	Specimen=Element	**Specimen=System**
Approach	many simple tests	a few, information-rich tests
Boundaries	simplest possible	complex
Measurements	very few	many (x,y,z,t) multisensory
Interpretation	simple fitting	model-based inversion
Information per test	very limited	as much as needed
Number of tests	many	just ~one



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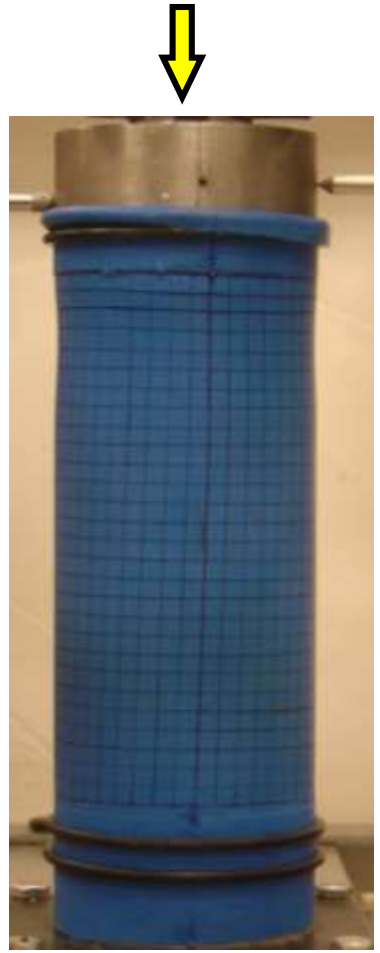
More radical?	many tests	NO constitutive model !!

Andrade @ Caltech



The future is no longer [quite] what it used to be *(Valery 1937)*

What do we measure?

Data ➔ information

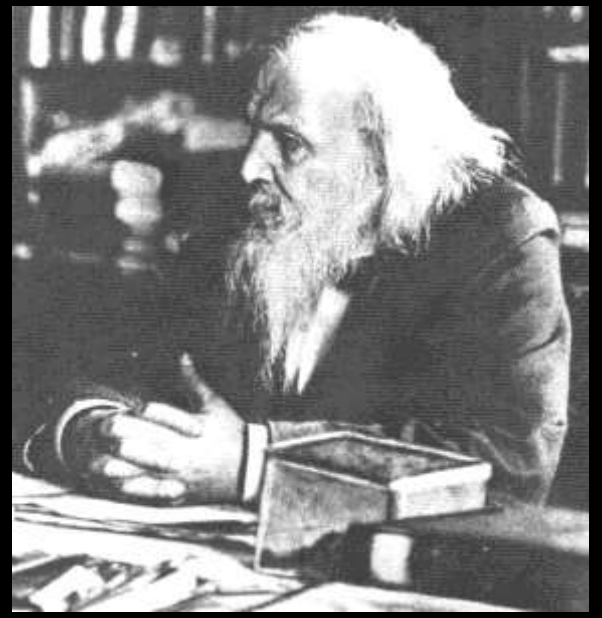
Computer-assisted experimentation

“Numerical experiments”… Oxymoron?

Other trends in experimentation

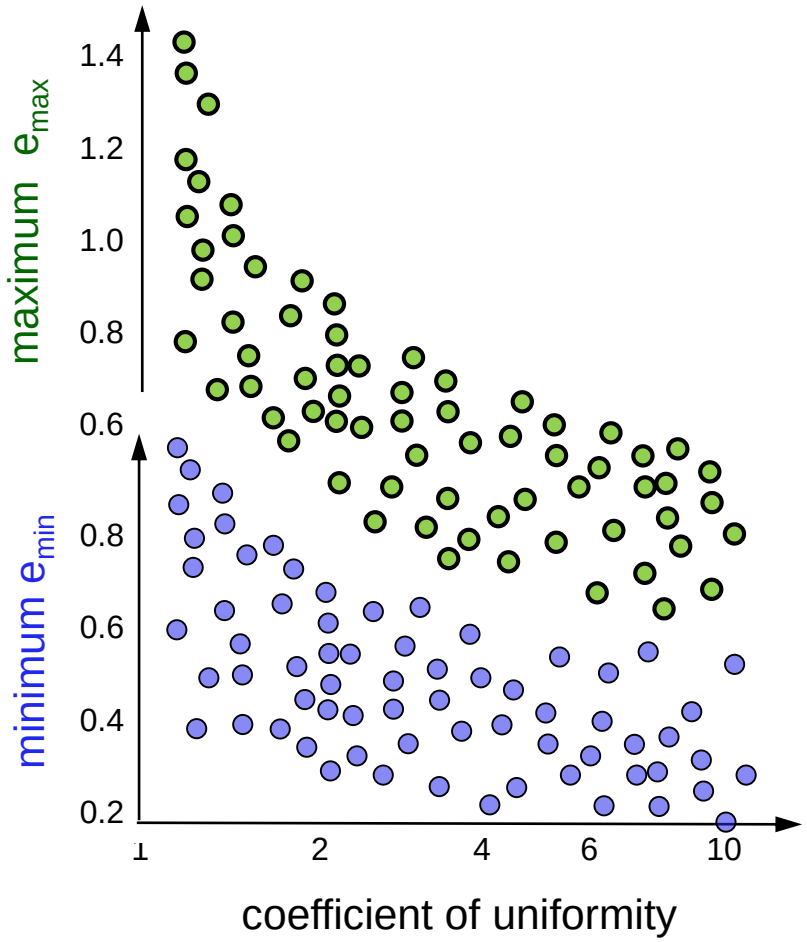
Closing thoughts

Mendeleev (1860's)



Bronowski

Databases: To identify the n^{th} control variable



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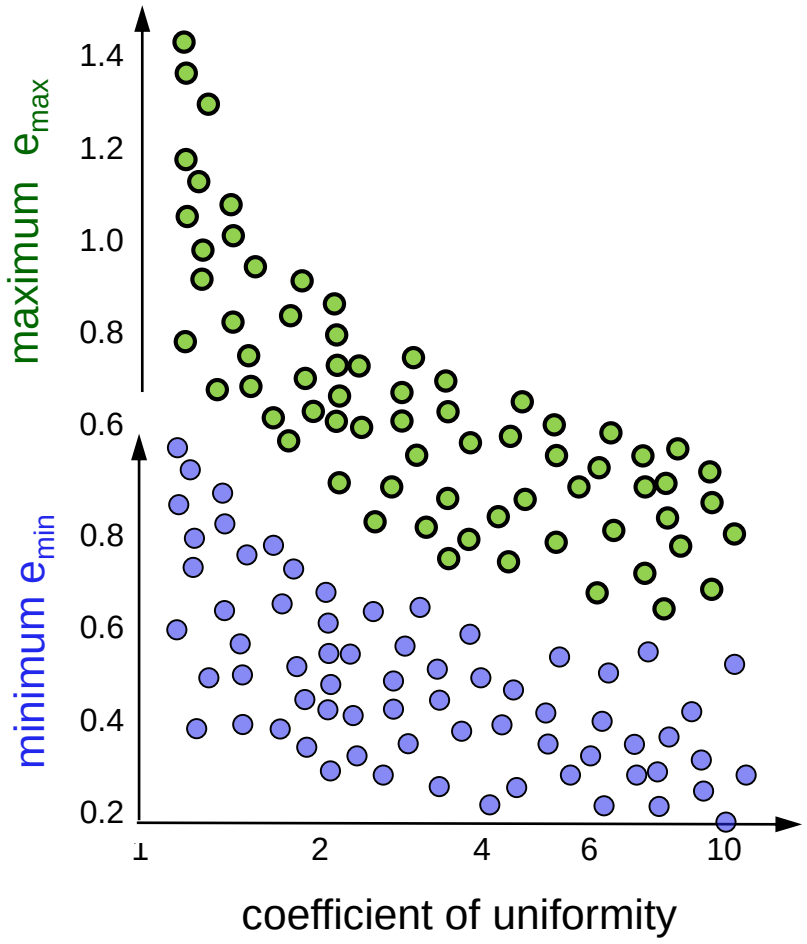
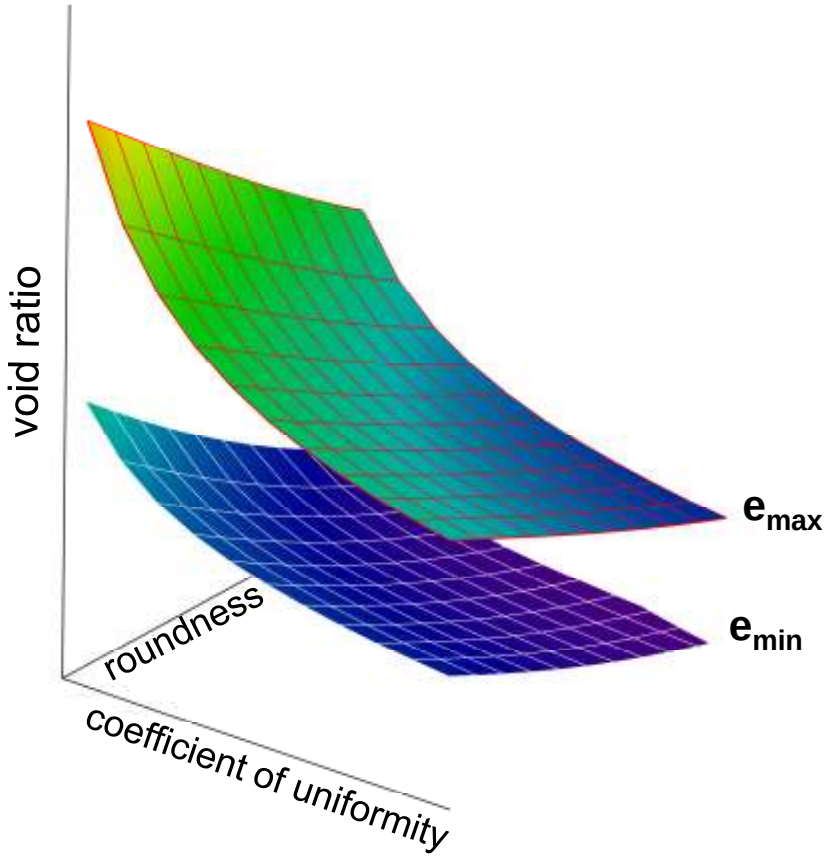
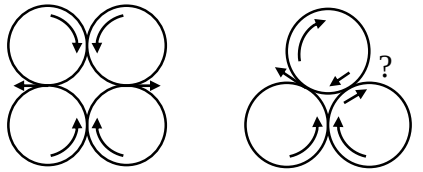


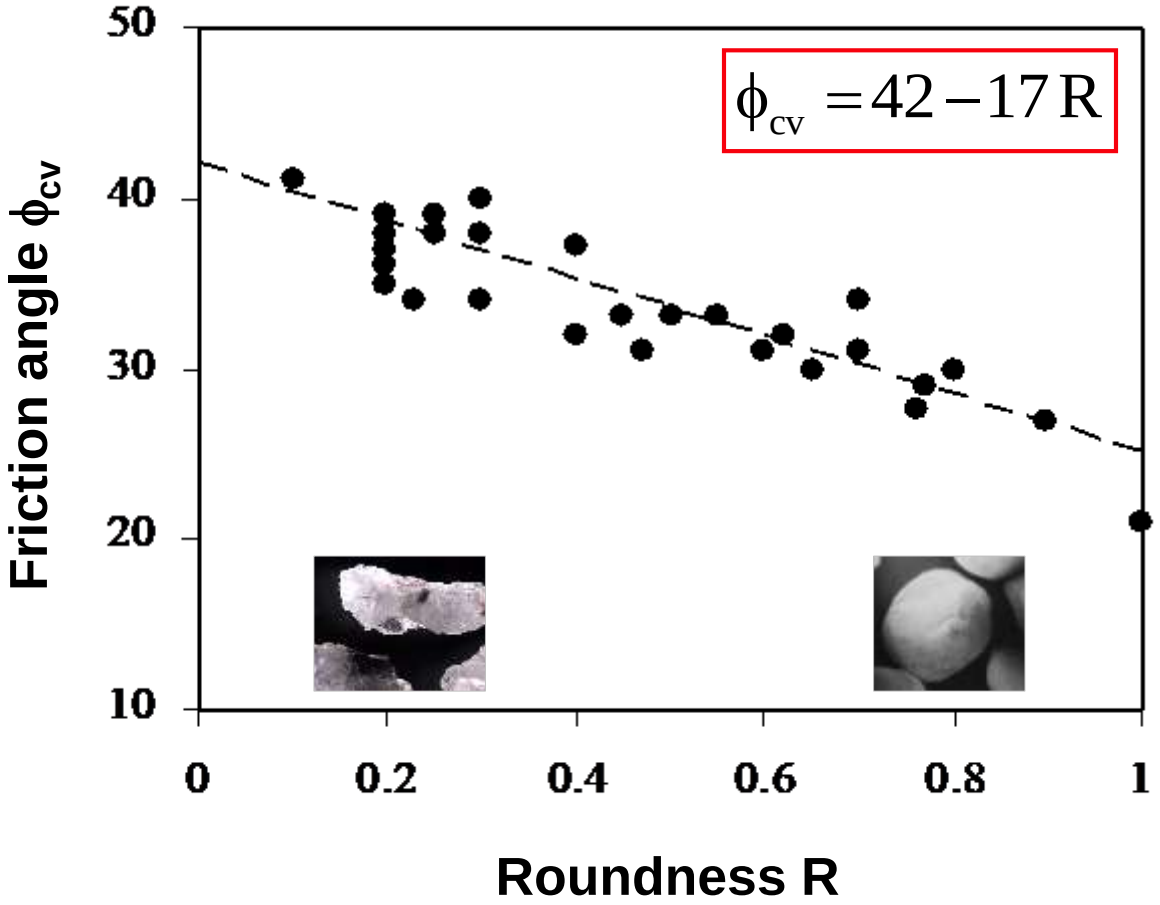


Databases: To explore causal relations

rotational frustration (e↑)

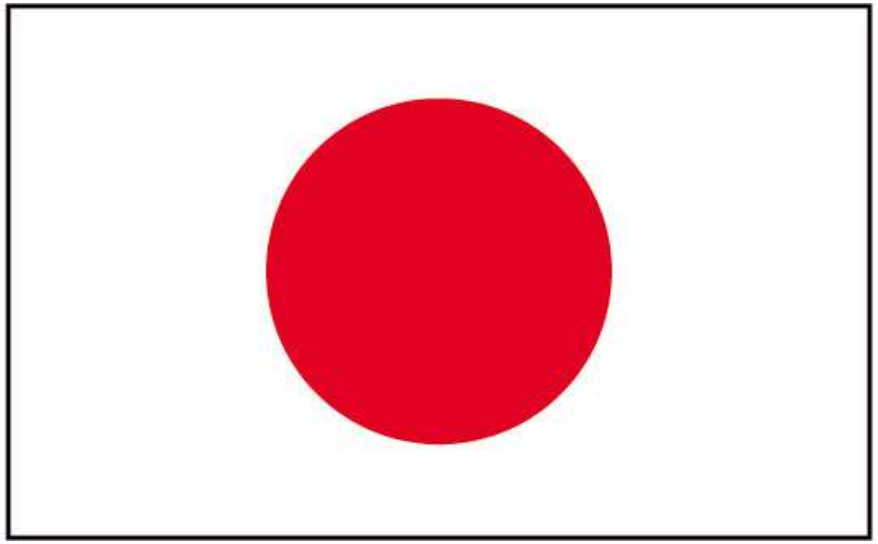
vs. chain collapse (e↓)



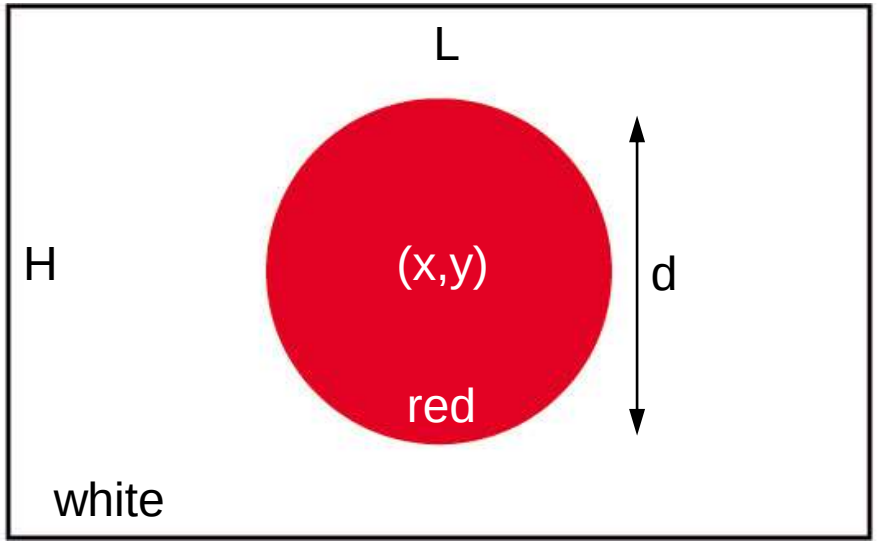


Information *needed* < Information *sought*

100 MP
(10^8 pixels !)



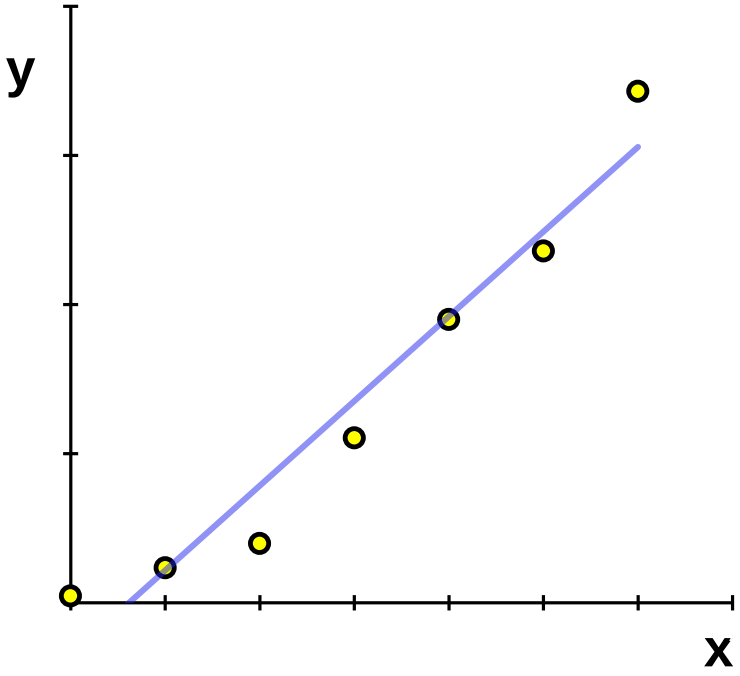
7 parameters



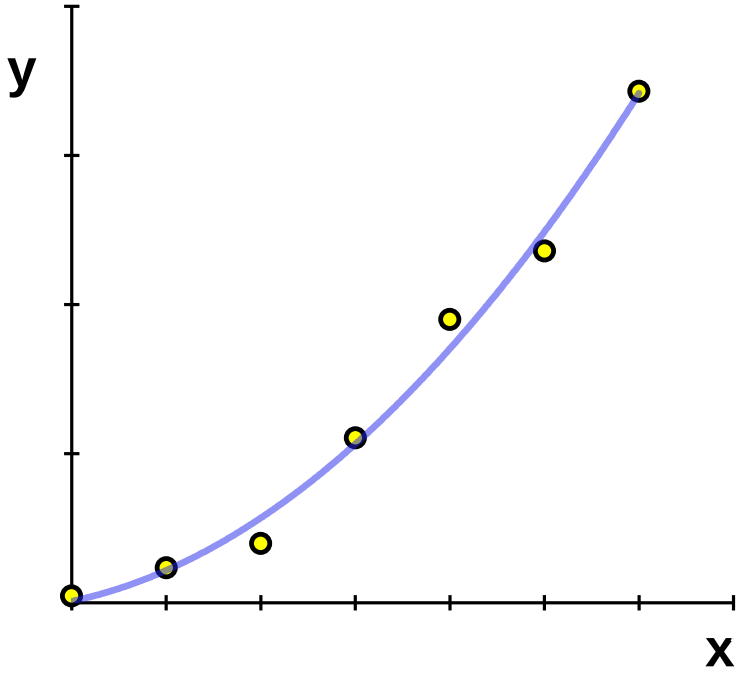
Paul Signac 1909 - Chateau des Papes, Avignon

Ockham's Razor: *Prefer model with fewer parameters*

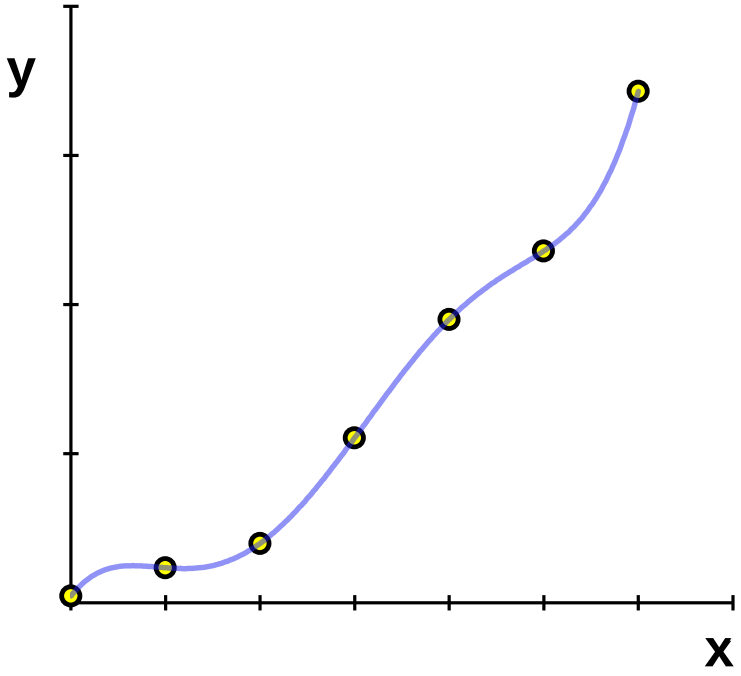
Friar William of Ockham
(1287–1347)



$y = a + bx$



$y = a + bx + cx^2$

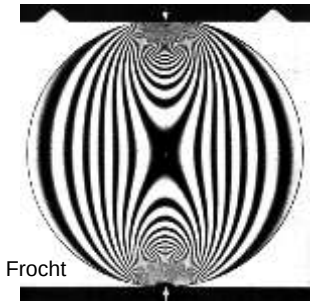


n-1 polynomial

We tend to adopt overparameterized models *Deep learning? Huge-n* *Physics-inspired models…!*

Physics-inspired… data driven: Small strain stiffness f(σ')

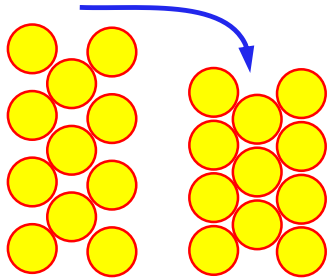
Contact deformation


Frocht

Hertz $V_s = \alpha \left(\frac{\sigma'_{mean}}{kPa} \right)^{\beta}$

Note: NO f(e)

Fabric change



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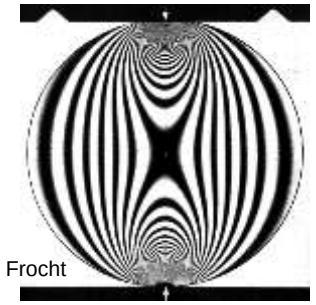

Hertz

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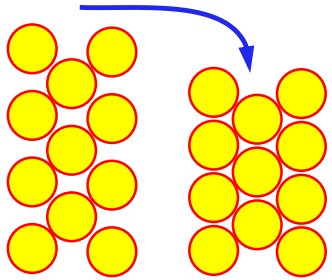

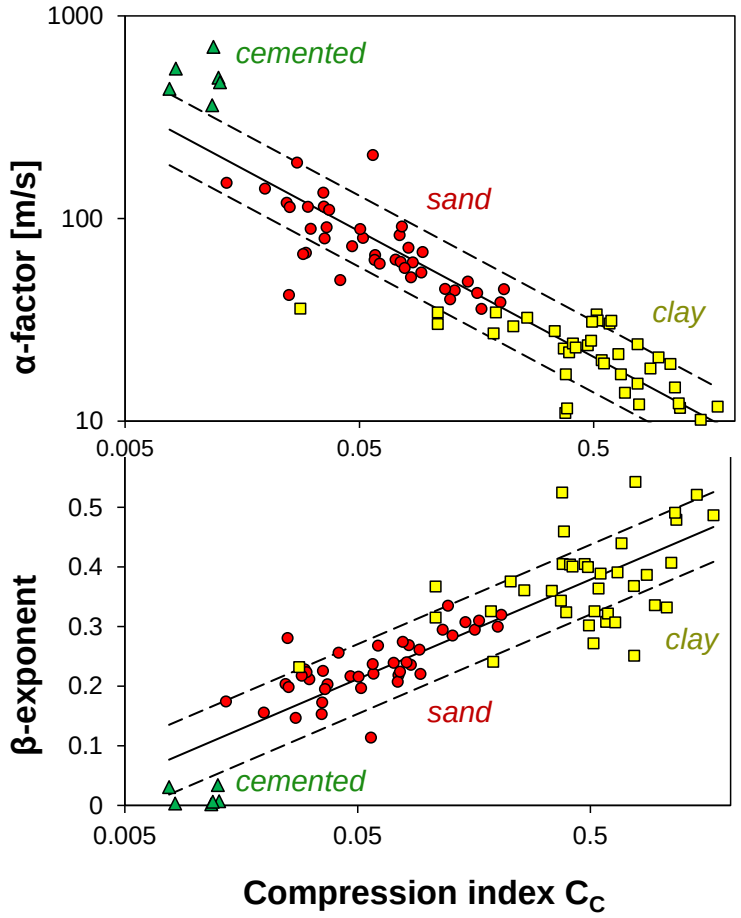

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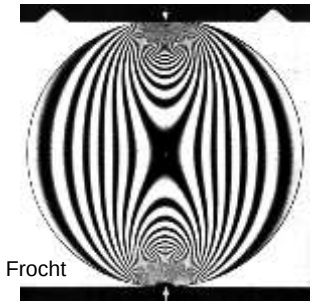

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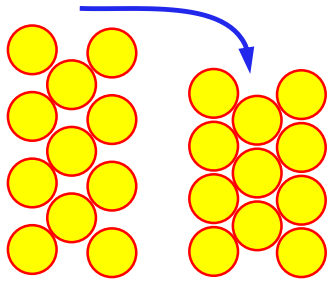
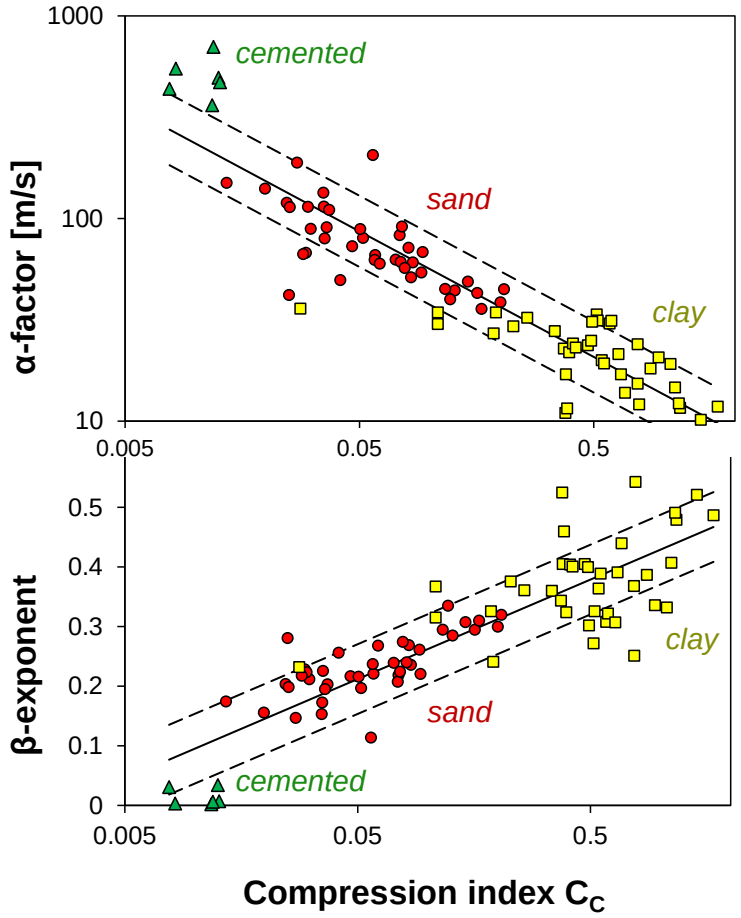
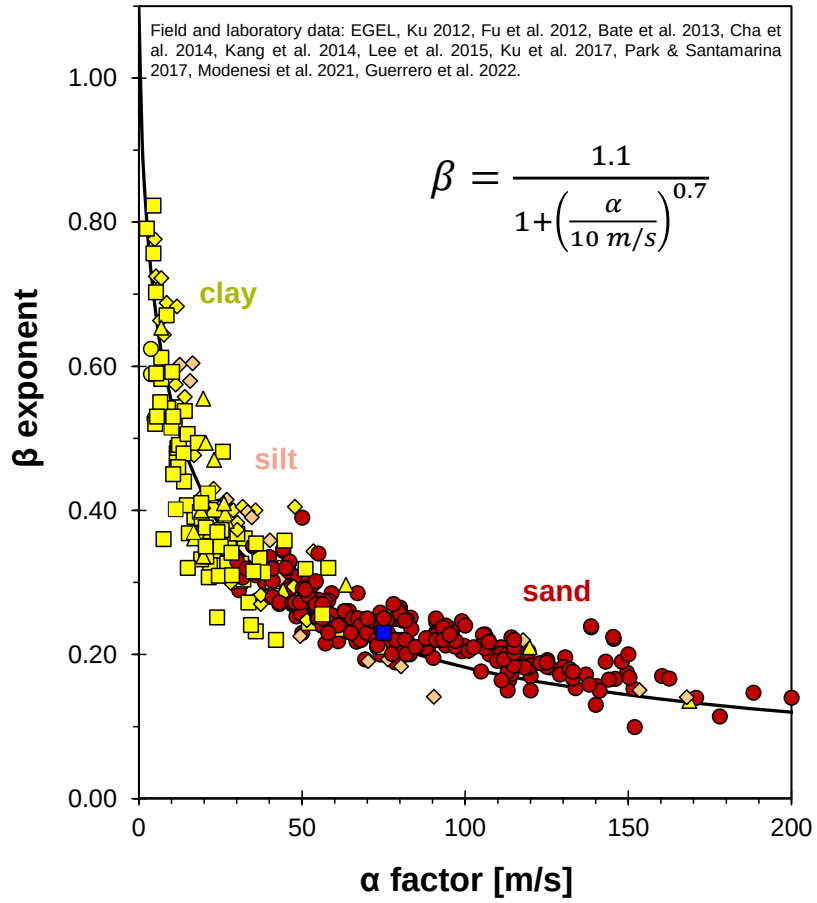
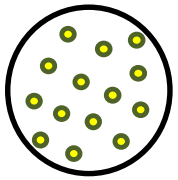






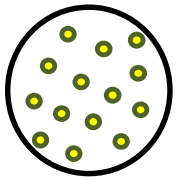
Physics-inspired… data driven: Compressibility



Power	From gas to soil **P·V=const**	$e = e_H + (e_L - e_H)\left(\frac{\sigma' + \sigma_c'}{\sigma_c'}\right)^{-\beta}$	Hansen (1969) Butterfield (1979) Juárez-Badillo (1981) Houlsby & Wroth, (1991) Pestana & Whittle (1995) Bauer (1996)
Exponent.	Gompertz function	$e = e_H + (e_L - e_H) \cdot \exp^{-(\sigma'/\sigma_c')^{\beta}}$	Cargill (1984 – β=1) Gregory et al. (2006)

Wide stress range: seek asymptotically correct models

Physics-inspired… data driven: Compressibility



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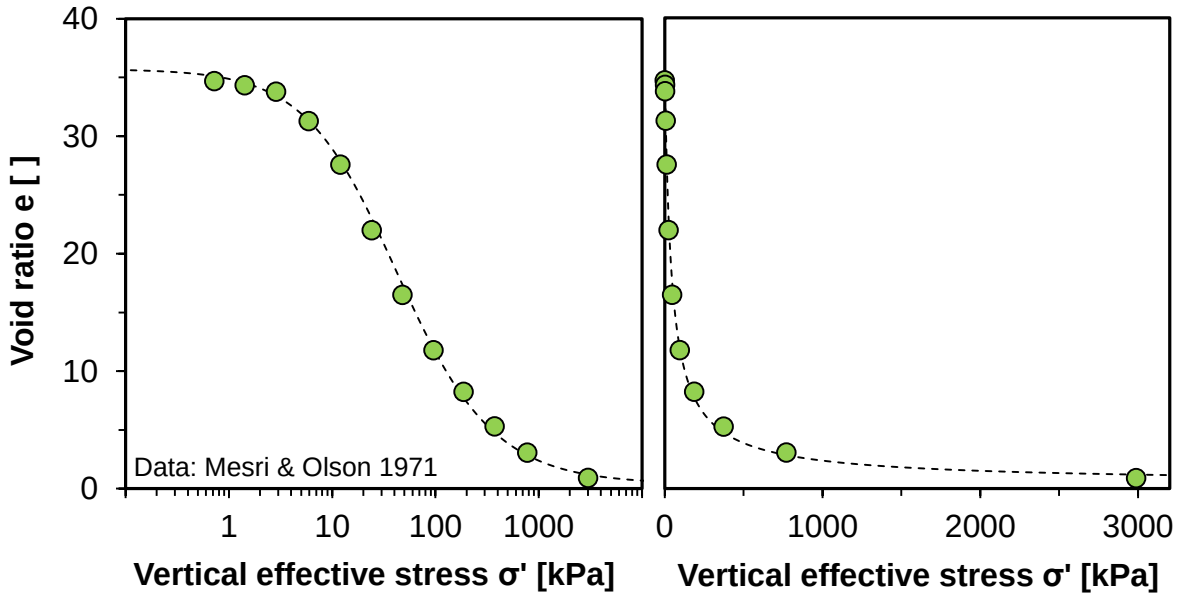
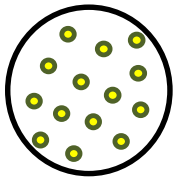


Wide stress range: seek asymptotically correct models

Physics-inspired… data driven: Compressibility



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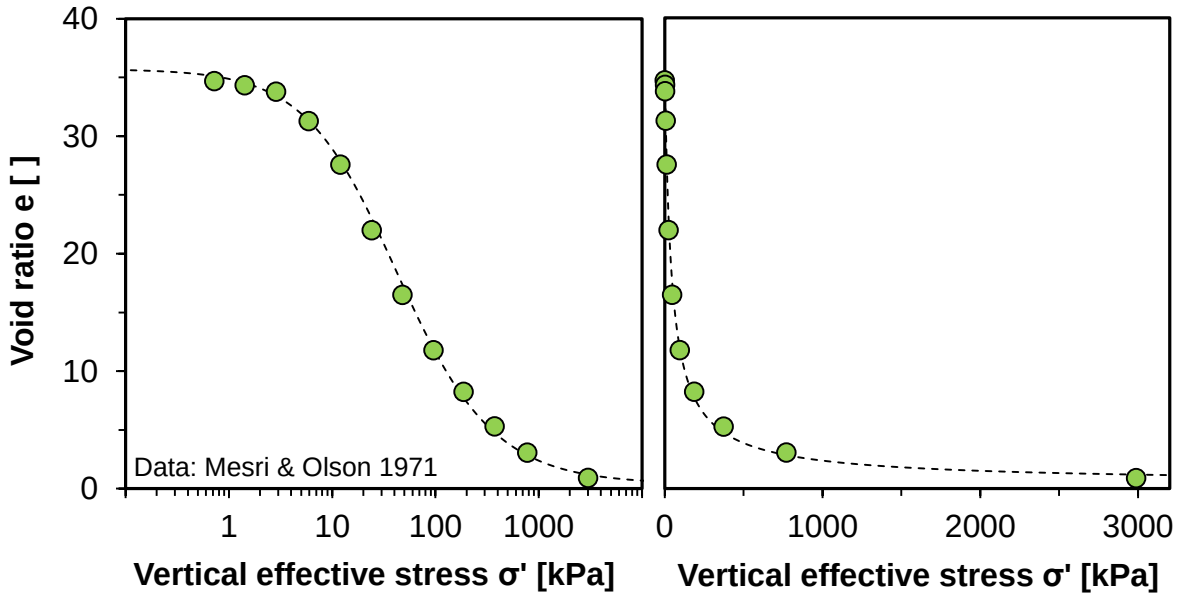
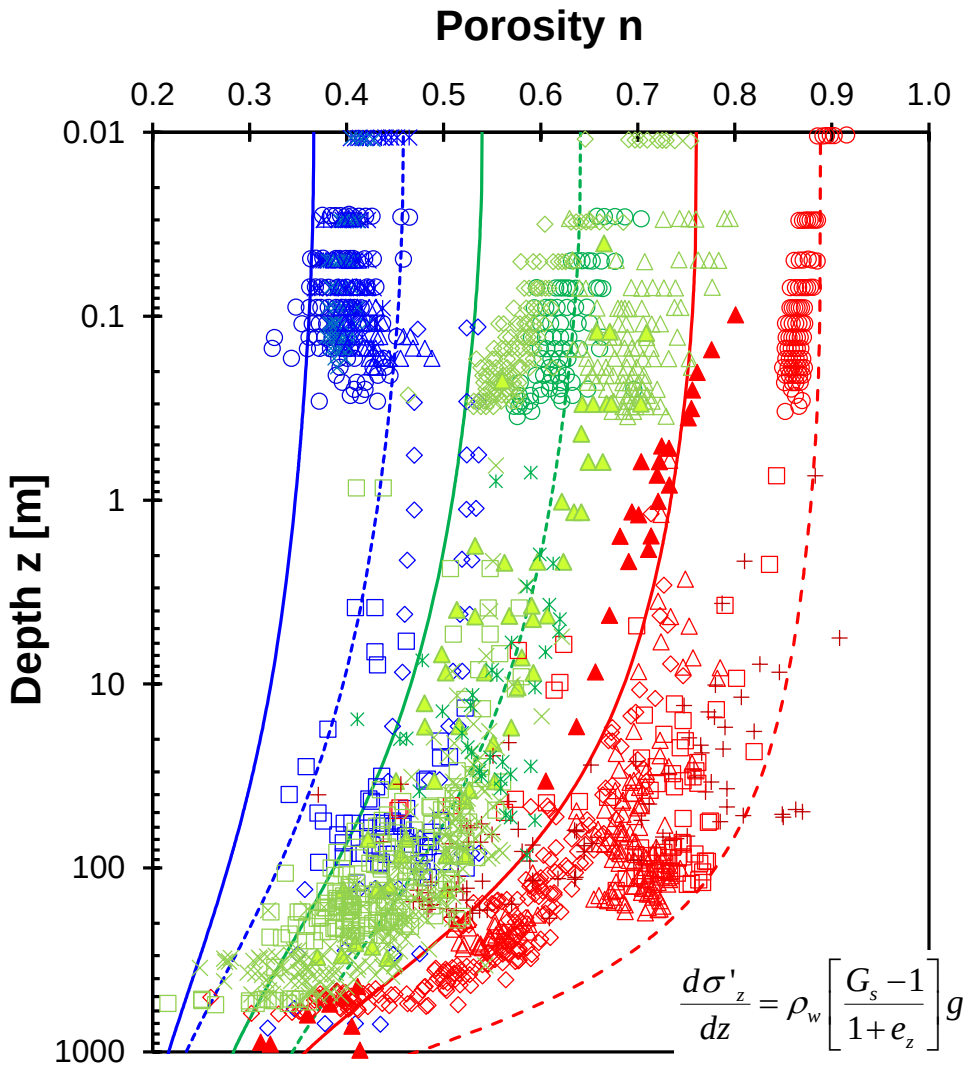
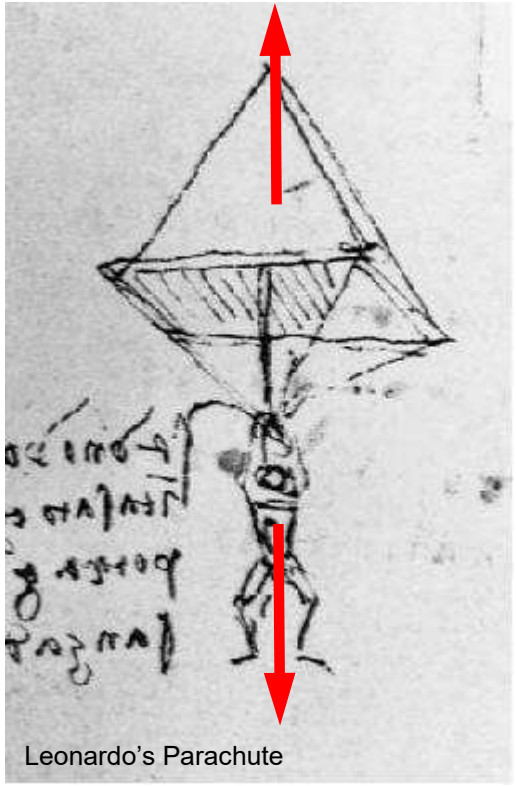




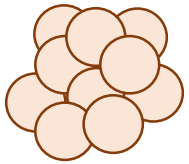
Data: Briggs (1994), Jackson et al. (1996), Richardson and Briggs (1993), Goldhammer (1997), Carter et al. (1999), Feary et al. (2000), D'Hondt et al. (2003), Kominz et al. (2011).

Wide stress range: seek asymptotically correct models

Physics-inspired… data driven: Hydraulic conductivity

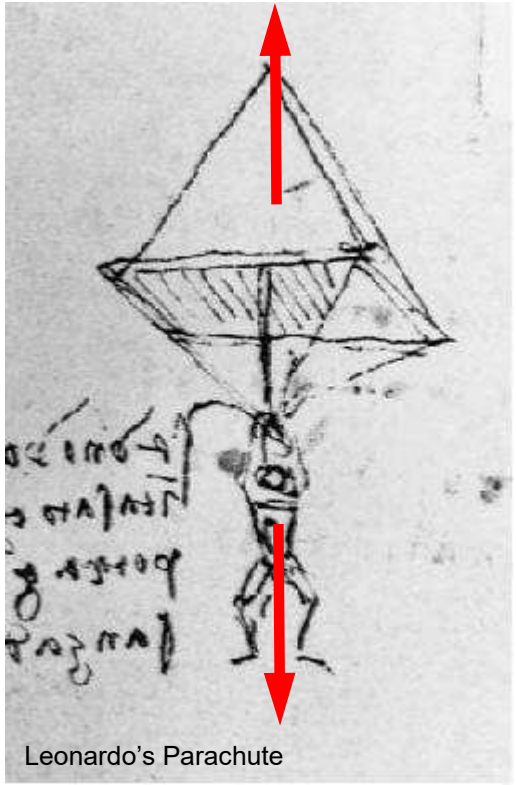


Leonardo's Parachute



Hagen–Poiseuille

Physics-inspired… data driven: Hydraulic conductivity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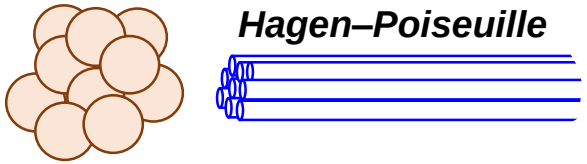
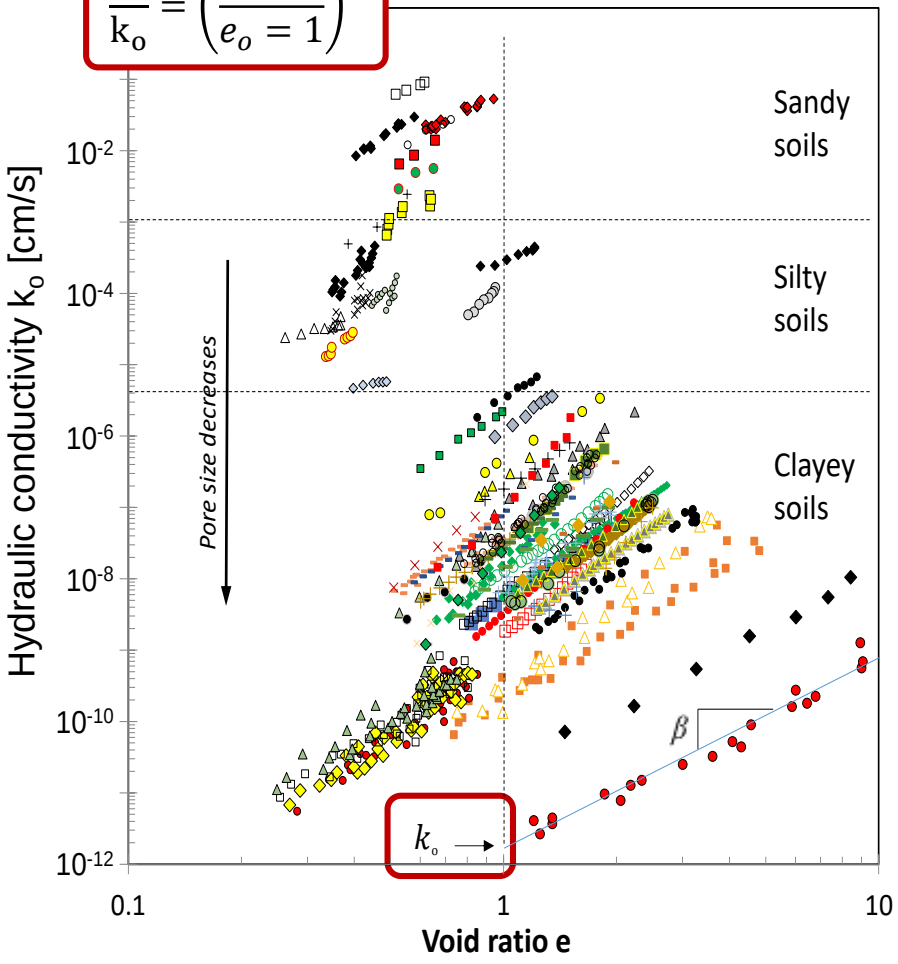
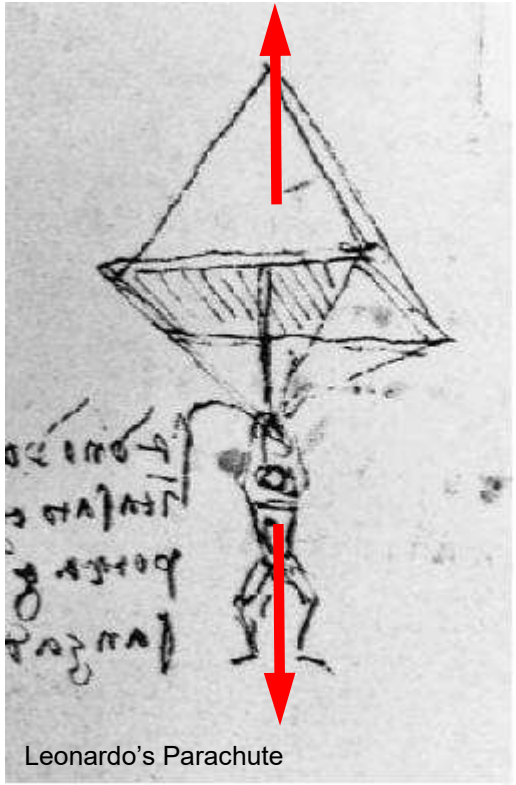
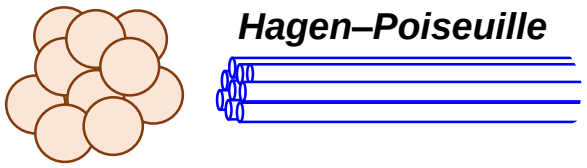


$$\frac{k}{k_o} = \left(\frac{e}{e_o = 1}\right)^{\beta}$$



Physics-inspired… data driven: Hydraulic conductivity


Leonardo's Parachute



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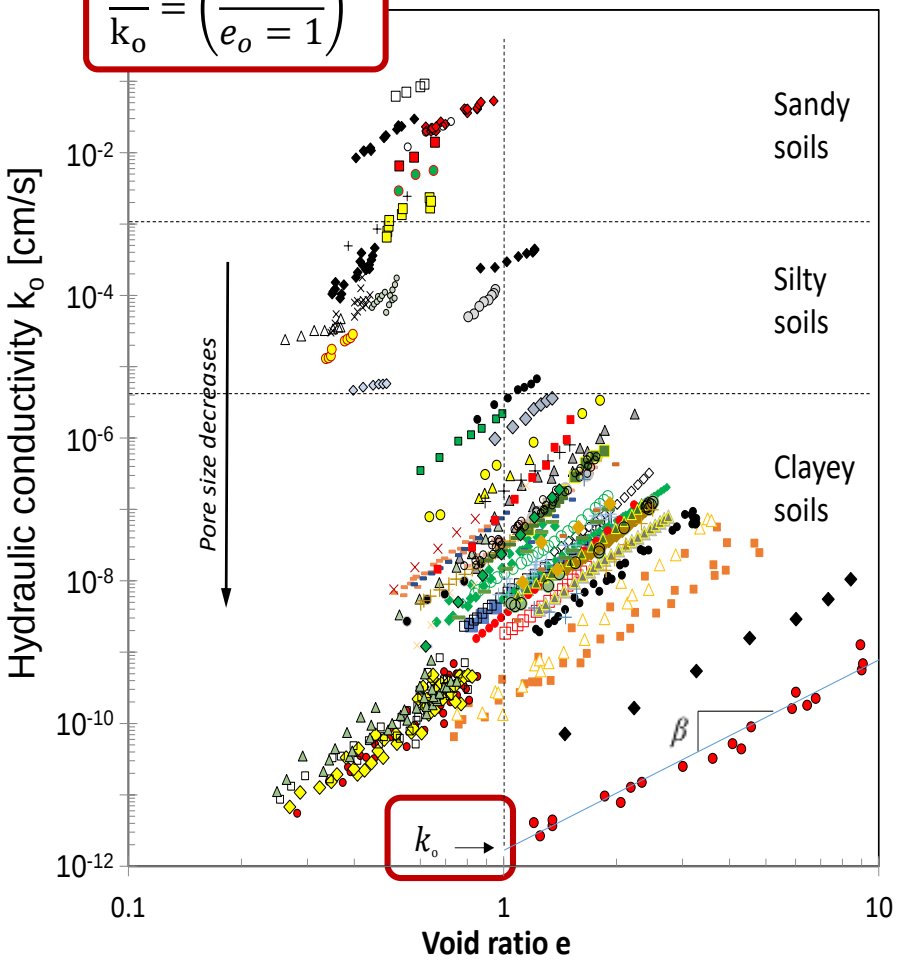
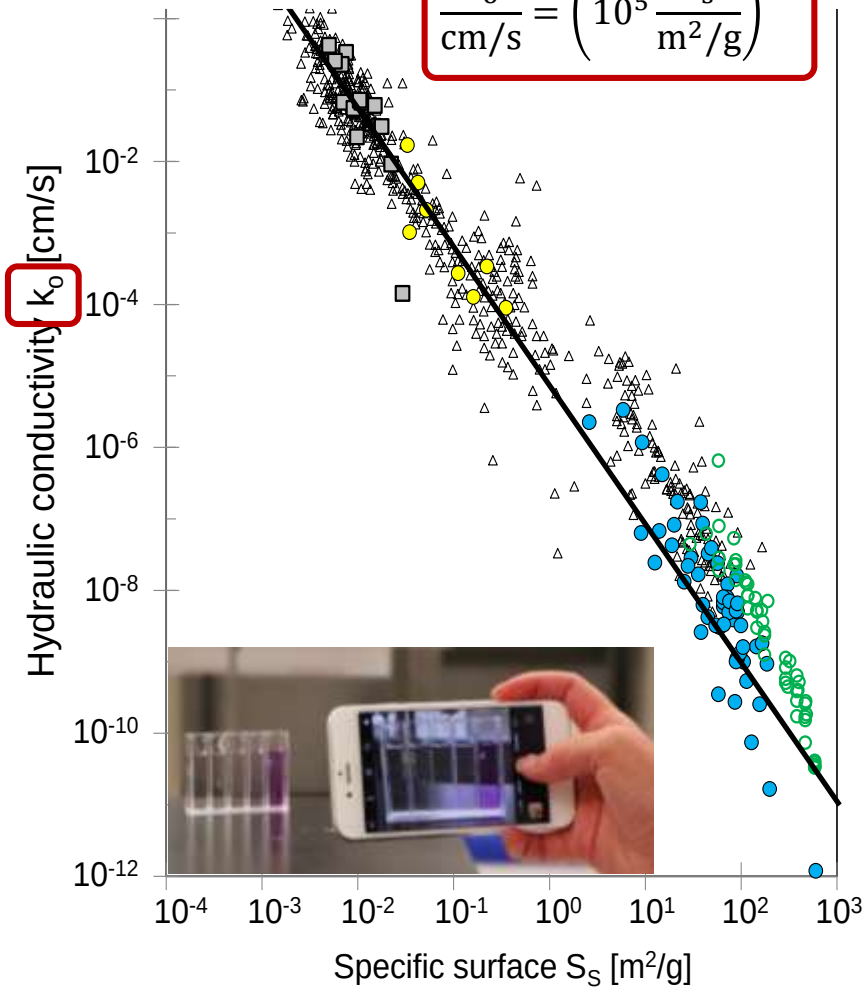


$$\frac{k_o}{cm/s} = \left(10^5 \frac{S_s}{m^2/g}\right)^{-1}$$



What do we measure?

Data ➔ information

Computer-assisted experimentation

“Numerical experiments”… Oxymoron?

Other trends in experimentation

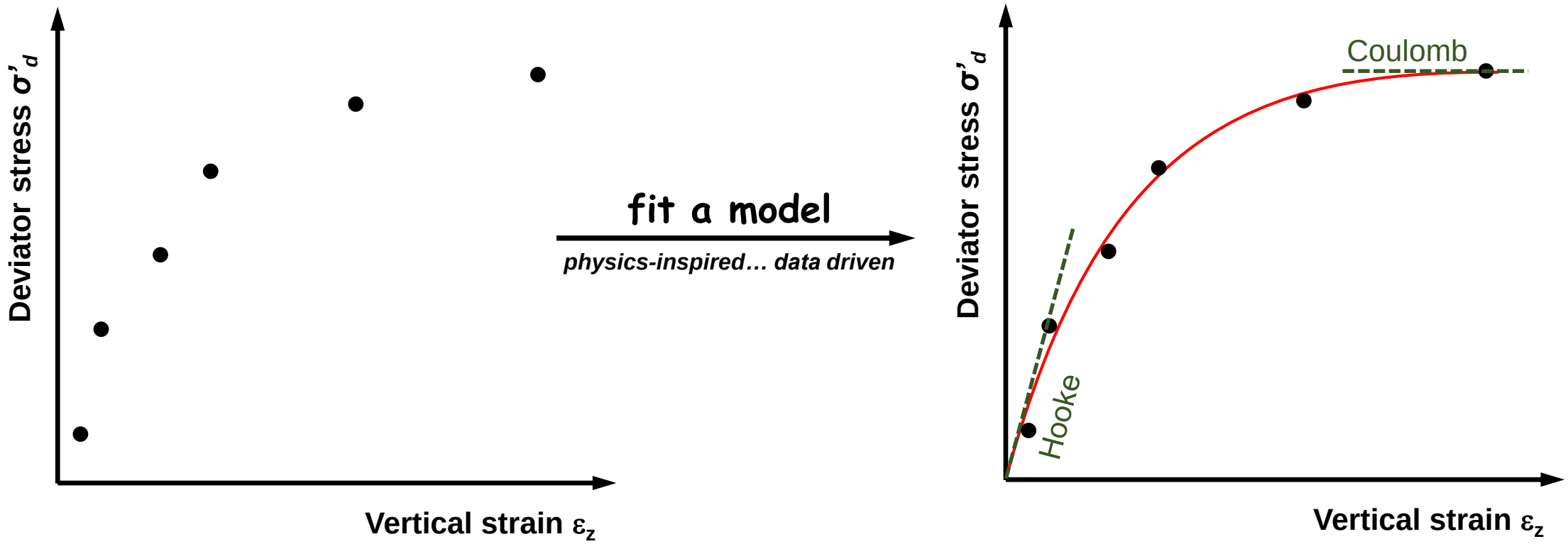
Closing thoughts

Execution

Interpretation, modeling, inversion

Inversion: Regression

Least Squares

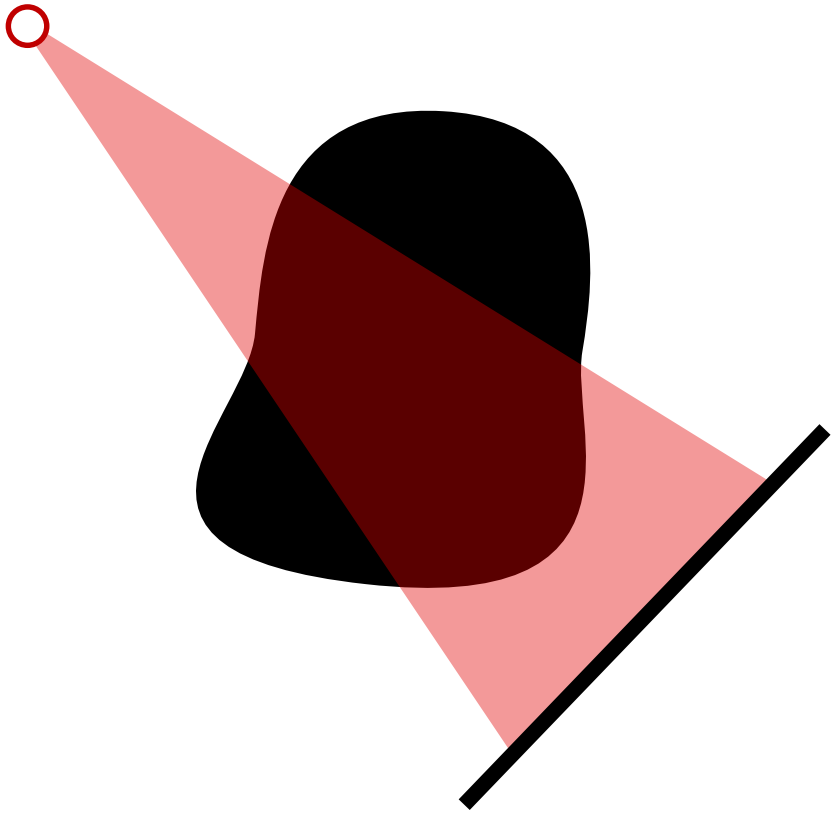


Model = abstraction of reality ➔ uncertain

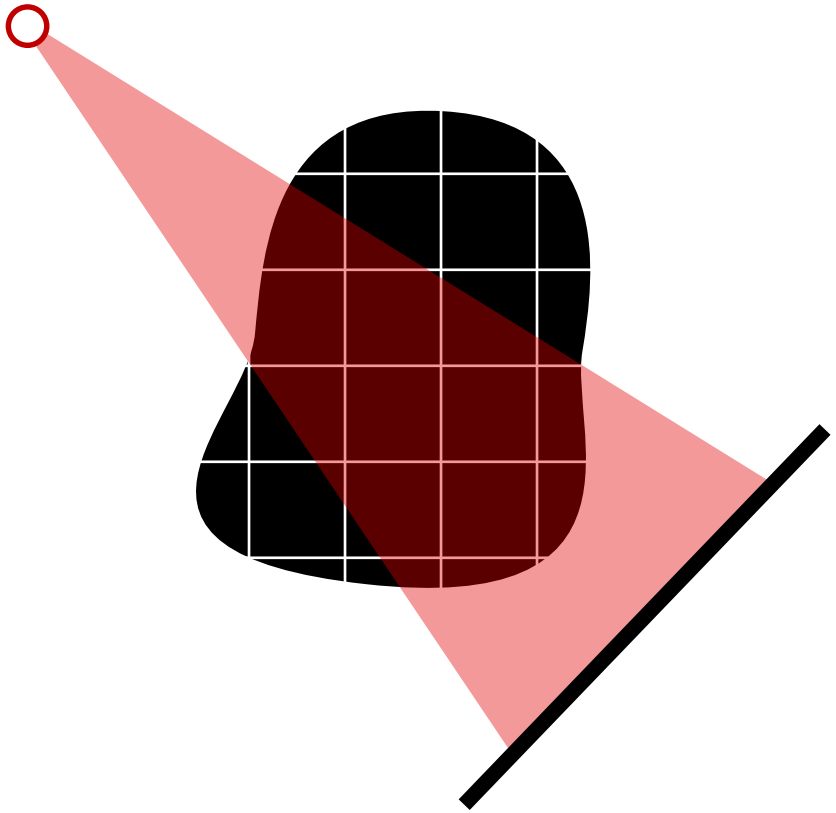
"Soil property" = a model parameter

Inversion: Tomography

Inversion: Tomography



Inversion: Tomography



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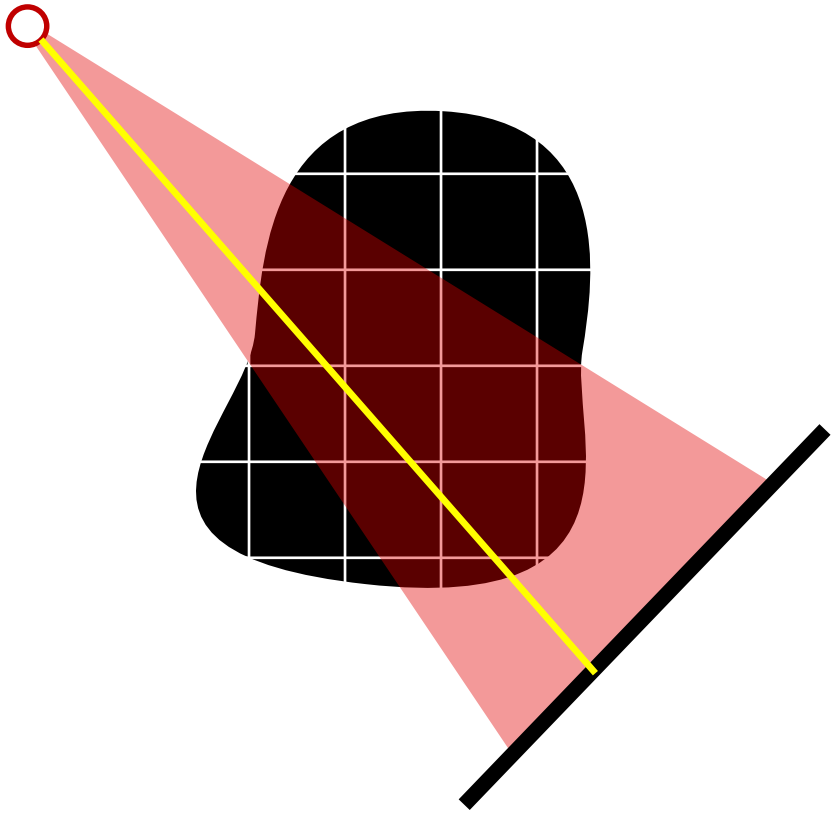
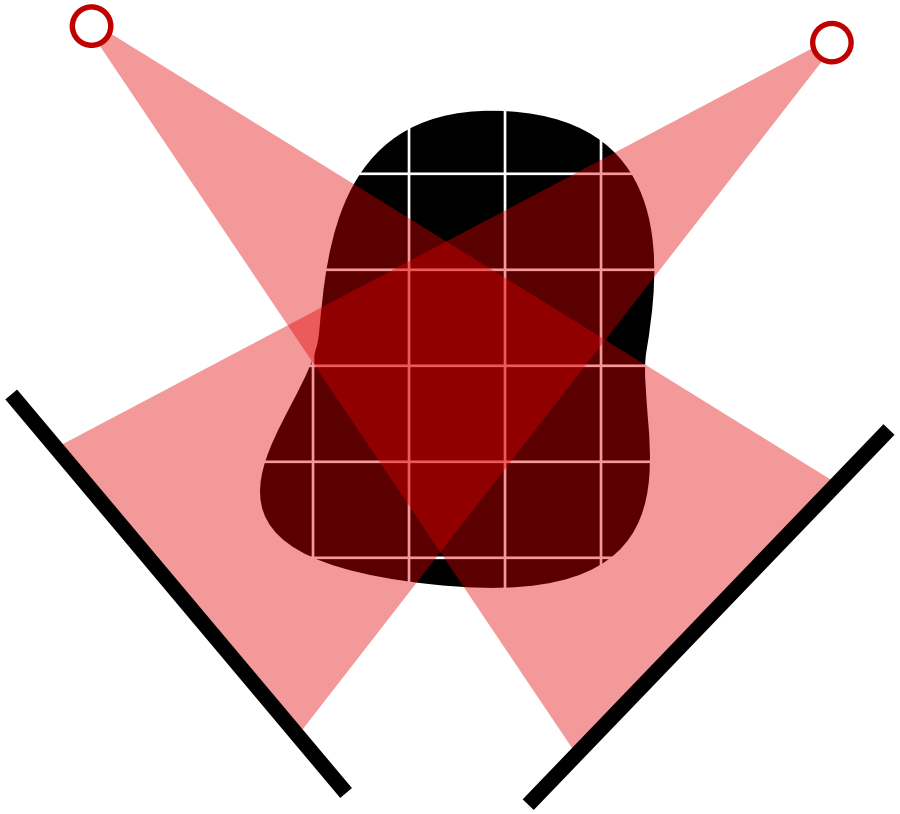


$$A_i = \ell_{i,1}\alpha_1 + \ell_{i,2}\alpha_2 + \cdots + \ell_{i,N}\alpha_N$$

Inversion: Tomography



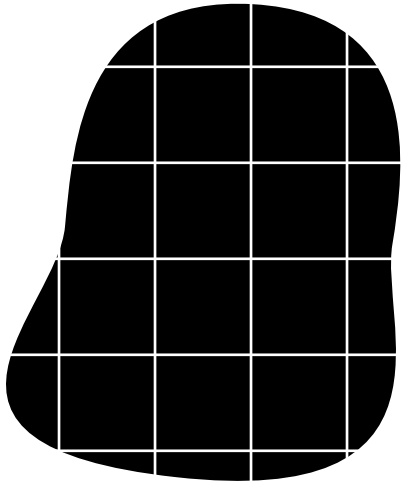
$$A_i = \ell_{i,1}\alpha_1 + \ell_{i,2}\alpha_2 + \cdots + \ell_{i,N}\alpha_N$$

$$\begin{bmatrix} A_1 \\ \dots \\ A_m \end{bmatrix} = \underbrace{\begin{bmatrix} \ell_{1,1} & \dots & \ell_{1,N} \\ \dots & \dots & \dots \\ \ell_{m,1} & \dots & \ell_{m,N} \end{bmatrix}}_{\text{imposed model (known)}} \begin{bmatrix} \alpha_1 \\ \dots \\ \alpha_N \end{bmatrix}$$

measured — imposed model (known) — want

Inversion: Tomography

Least Squares



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$$\mathbf{A} = \mathbf{L}\boldsymbol{\alpha}$$

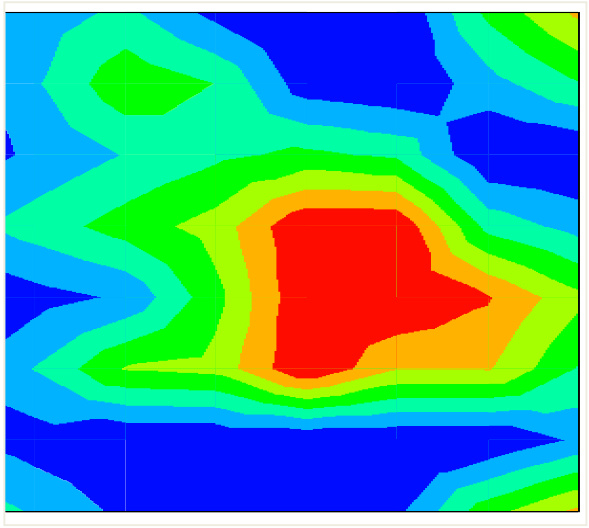
Least square

$$\boldsymbol{\alpha} = \left(\mathbf{L}^T\mathbf{L}\right)^{-1}\mathbf{L}^T\mathbf{A}$$

Cannot invert?

Inversion: Tomography

Least Squares



$$A_i = \ell_{i,1}\alpha_1 + \ell_{i,2}\alpha_2 + \cdots + \ell_{i,N}\alpha_N$$

$$\begin{bmatrix} A_1 \\ \cdots \\ A_m \end{bmatrix} = \begin{bmatrix} \ell_{1,1} & \cdots & \ell_{1,N} \\ \cdots & \cdots & \cdots \\ \ell_{m,1} & \cdots & \ell_{m,N} \end{bmatrix} \begin{bmatrix} \alpha_1 \\ \cdots \\ \alpha_N \end{bmatrix}$$

$$\mathbf{A} = \mathbf{L}\ \boldsymbol{\alpha}$$

$$\boldsymbol{\alpha} = \left(\mathbf{L}^T\mathbf{L}\right)^{-1}\mathbf{L}^T\mathbf{A}$$

$$\boldsymbol{\alpha} = \left(\mathbf{L}^T\mathbf{L} + \delta\,\mathbf{I}\right)^{-1}\mathbf{L}^T\mathbf{A}$$

Increase the main diagonal!

what you get..!!

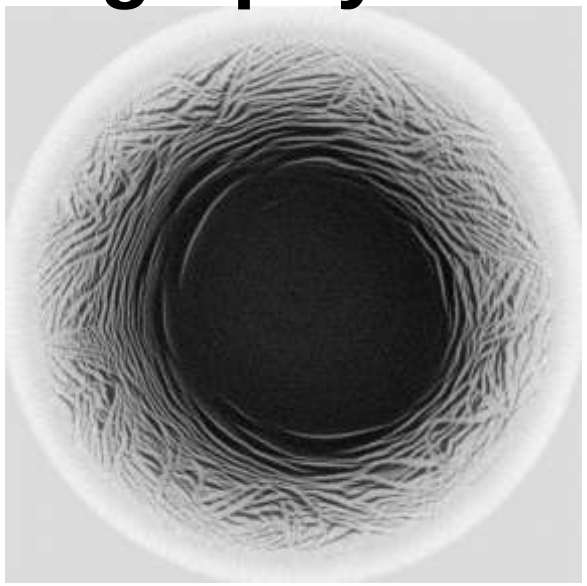
selected model assumptions test design

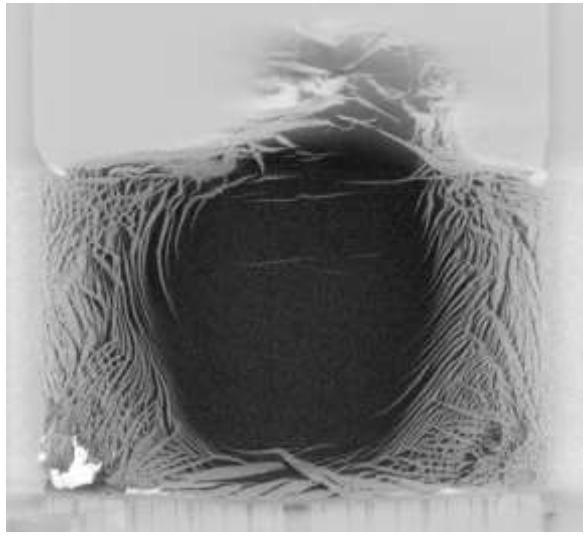
what you measure

Caution: overparameterized model

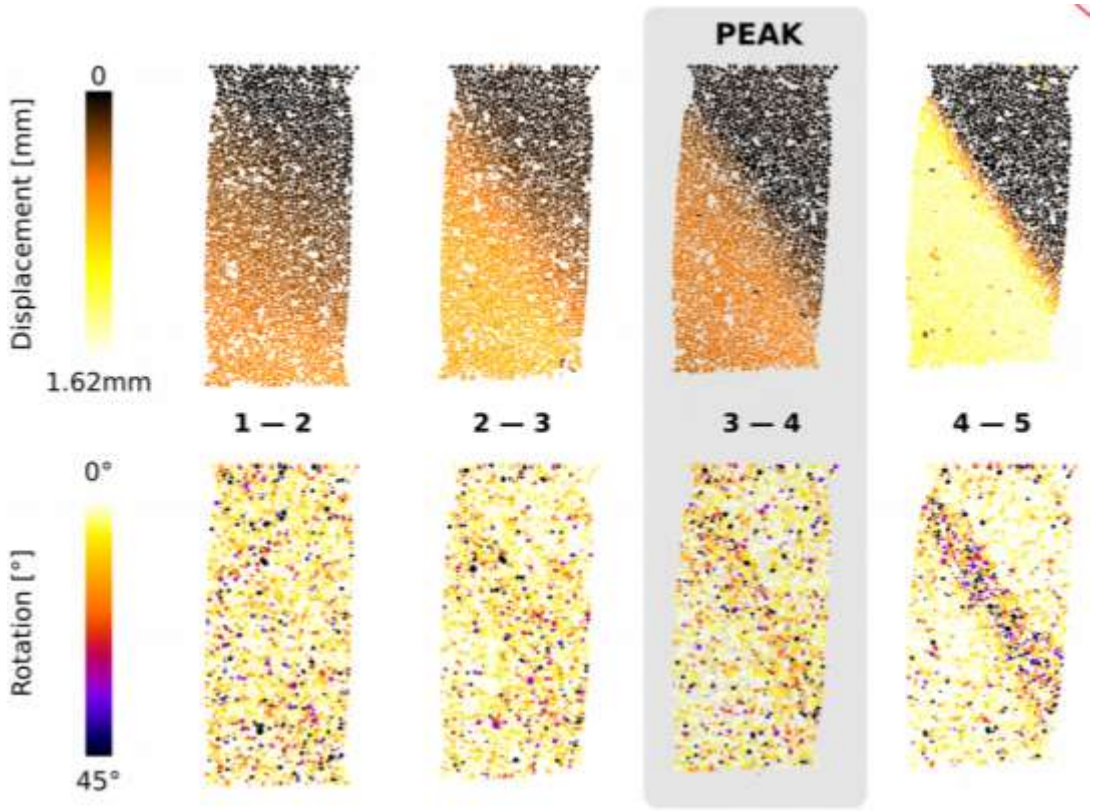
Design experiments for "invertibility"

X-ray Tomography





Viggiani et al. 2015



Ando et al. 2012

Lots of great data + good physical model ➔ amazing results

What do we measure?

Data ➔ information

Computer-assisted experimentation

“Numerical experiments”… Oxymoron?

To gain unprecedented insight

Unfeasible experiment

Process lacks characteristic scale

Inherently multi-scale

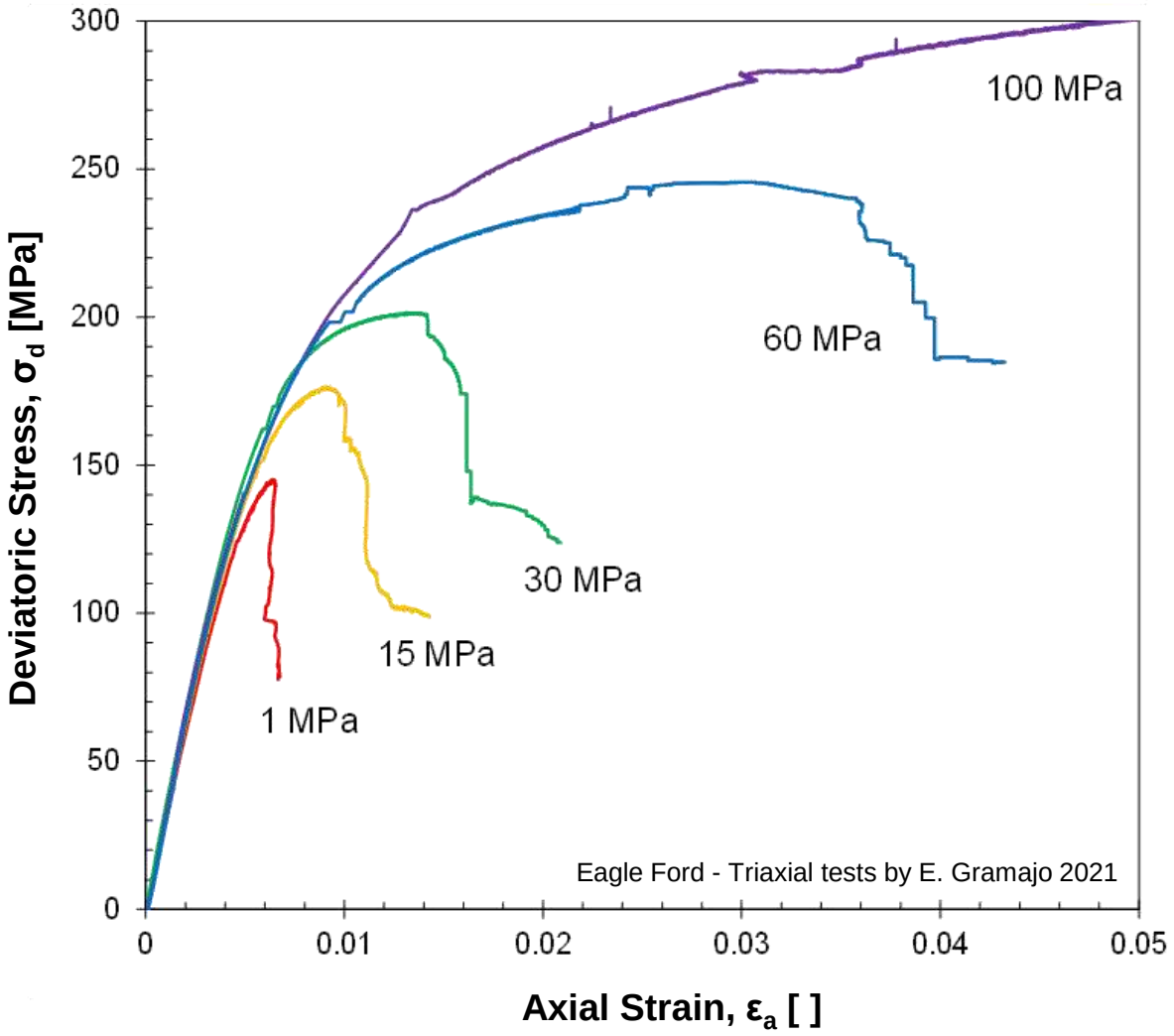
Other trends in experimentation

Closing thoughts

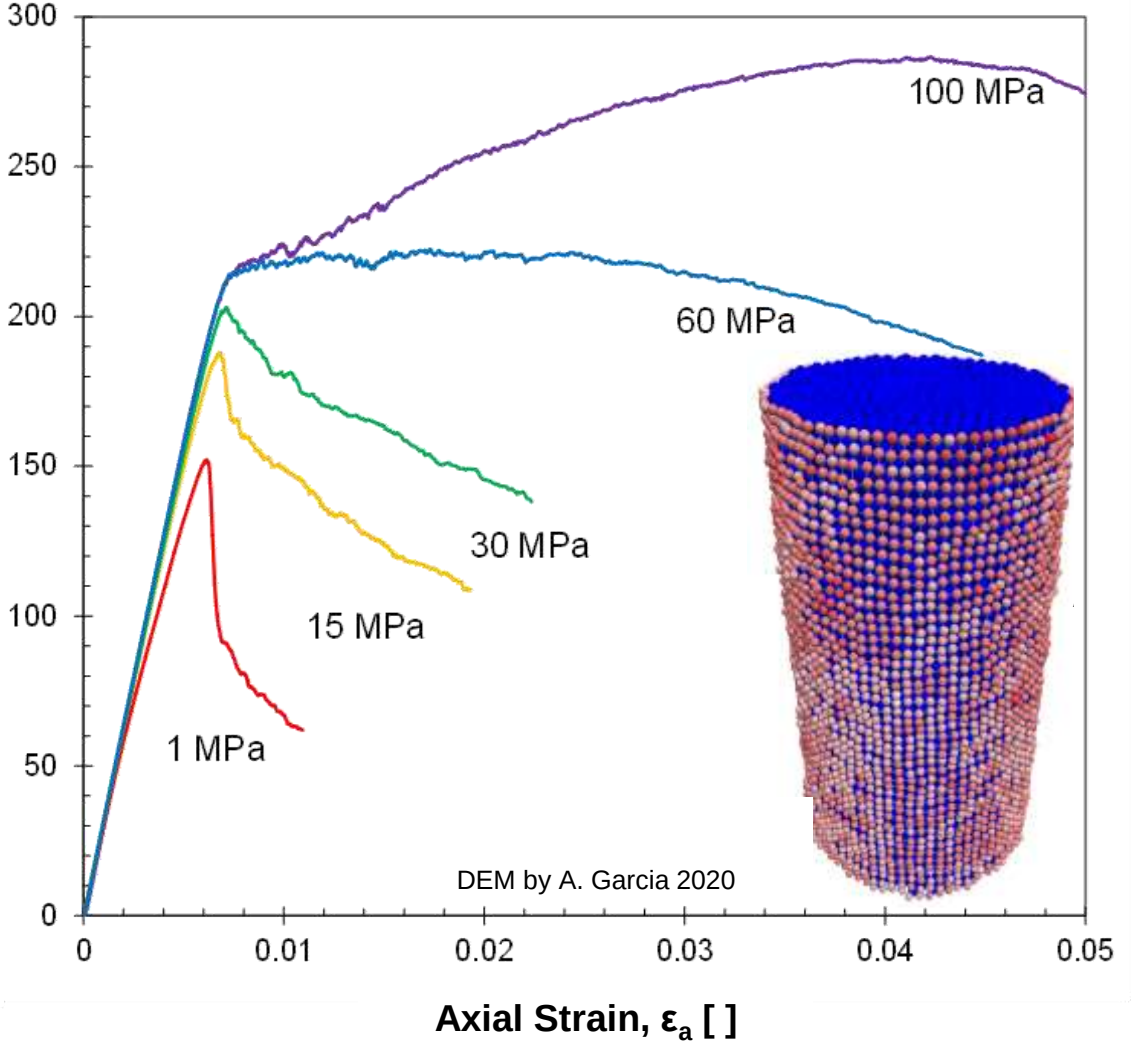
To gain unprecedented insight

Rock stress-strain response: digital rock analogue

Experimental Data



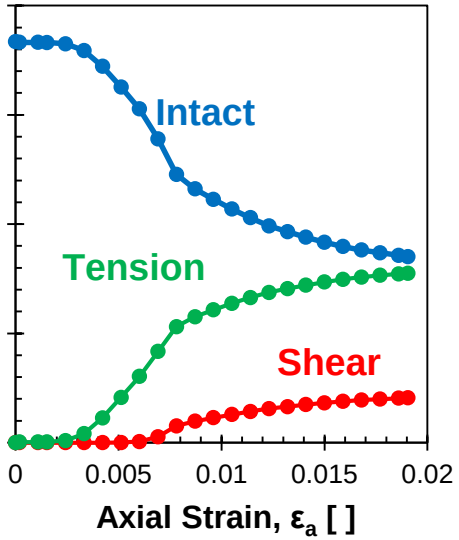
Digital Rock Analogue

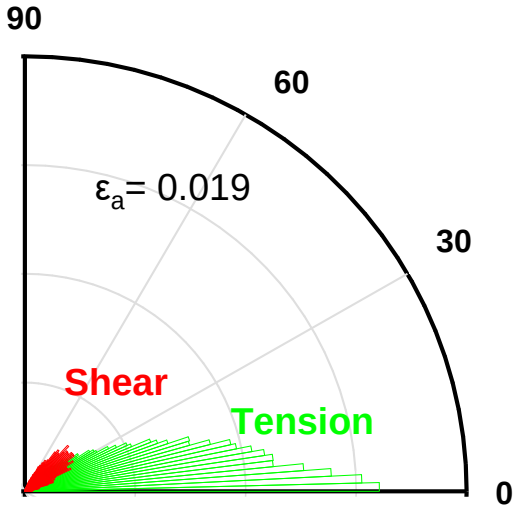


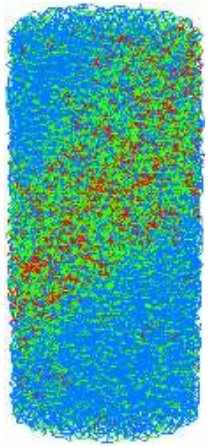
To gain unprecedented insight

brittle-ductile transition? friction & cohesion? exhumation?

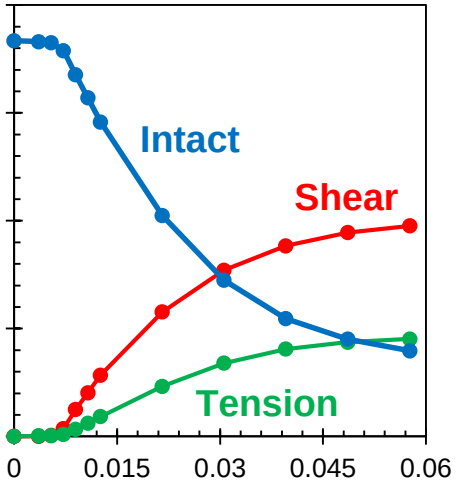
15 MPa

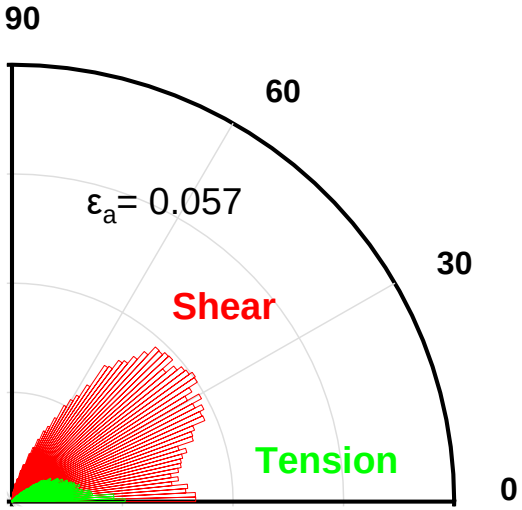


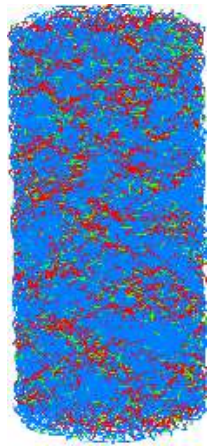




100 MPa







A. Garcia

Just can’t do it…! *hydrate bearing sediments*

Replicate in the lab: takes years

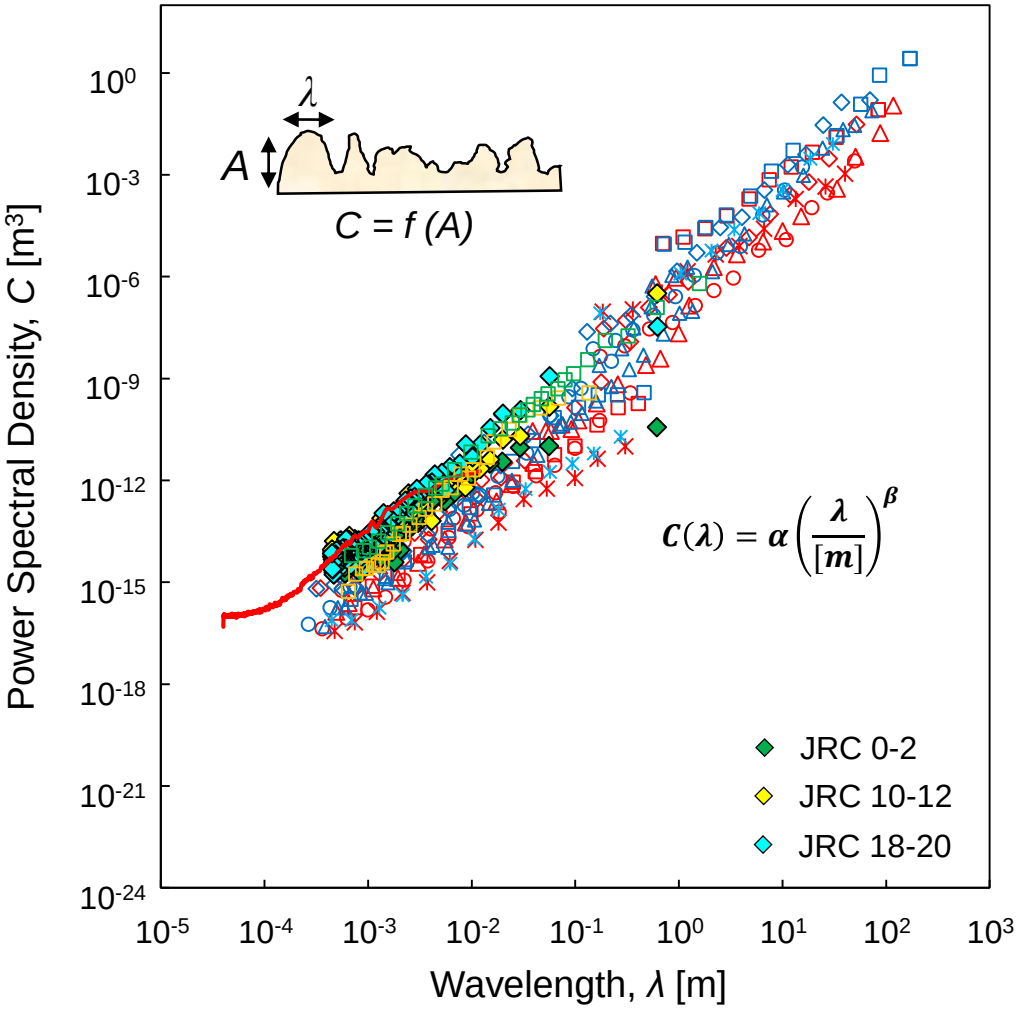
Very difficult to sample
Significant sampling effects

Samples: no REV

Lacks characteristic scale

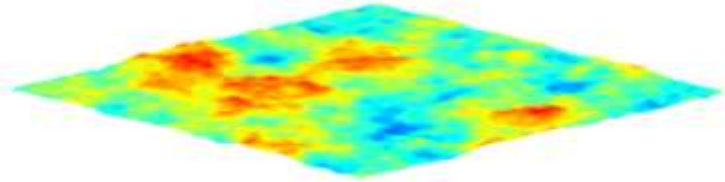
Fractures = fractal topography

Surface roughness



Numerical experiment

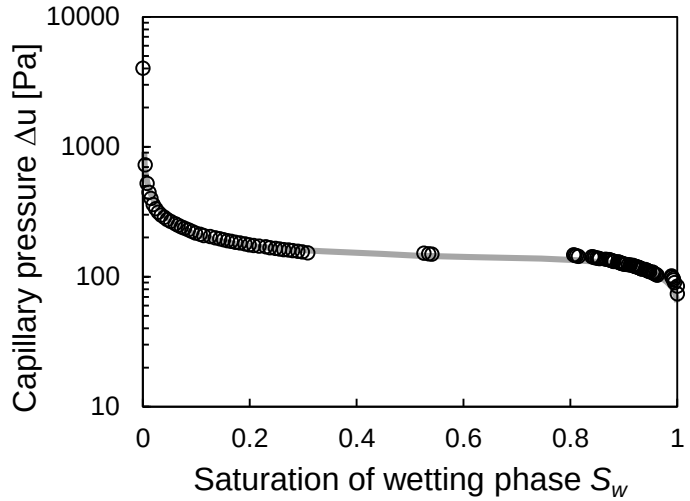
1. Fracture surface



2. Shear displacement

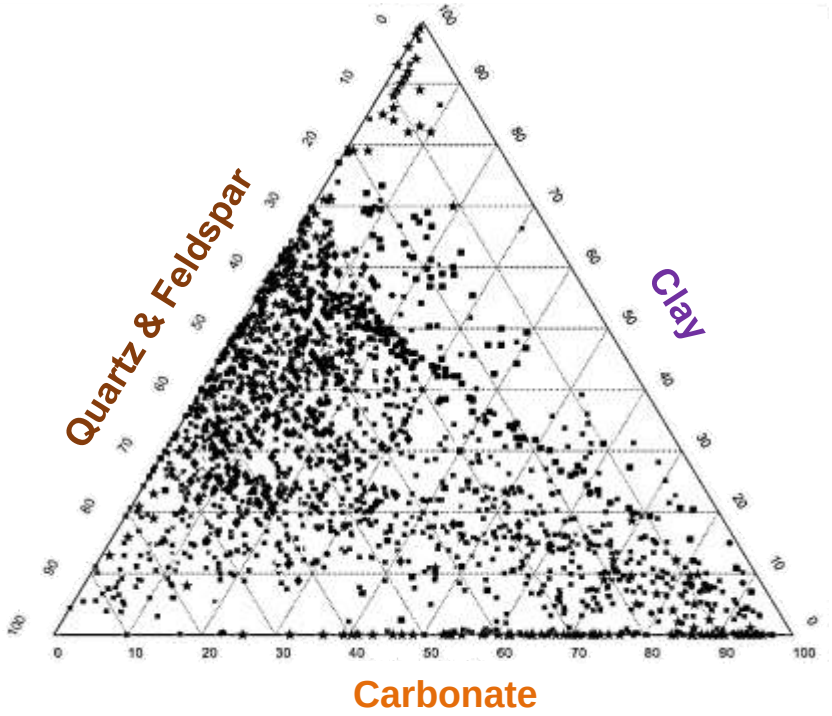
3. Normal stress $A_c = A\frac{\sigma_n}{\sigma_{yield}}$

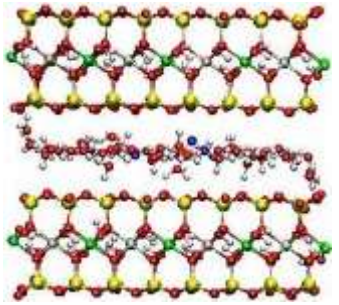
4. Invasion percolation



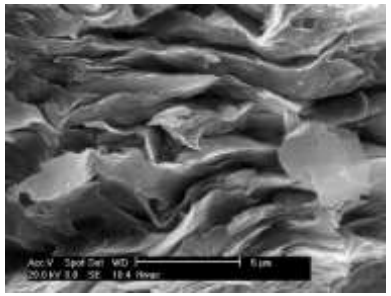
Inherently multi-scale/multi-physics

Shales | *Sedimentary*
Clastic - Fine grained
Fissile

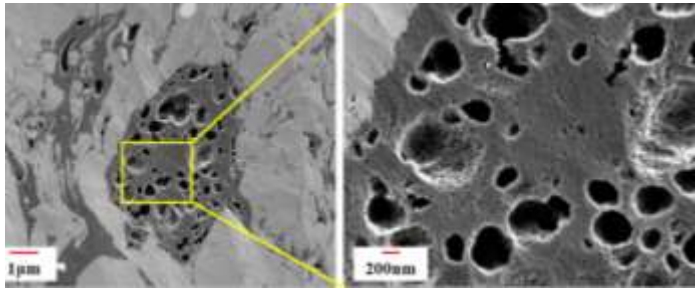




Clay-clay
10^{-9} m (MD)



Flock
10^{-6} m



Kun Zhang et al 2020 Open Sciences

Layer
10^{-2} m
…
Formation
m (FEM)

What do we measure?

Data ➔ information

Computer-assisted experimentation

“Numerical experiments”… Oxymoron?

Other trends in experimentation

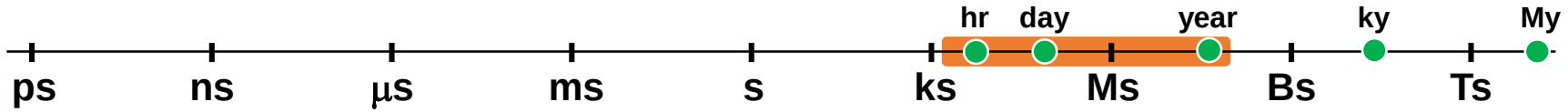
Closing thoughts

Scale broadening
Multiphysics HTCBM coupling
Multiphysics repetitive
Fluid & fluid-mineral focus
Lab-on-a-bench?

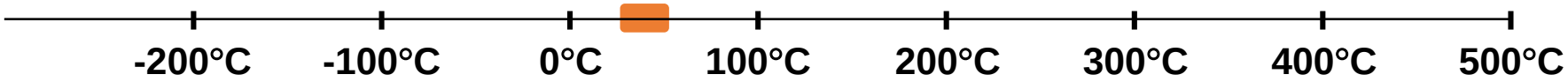
Bishop's geotechnical engineering ... 65 years later

Space: 16 orders

Time: 25 orders

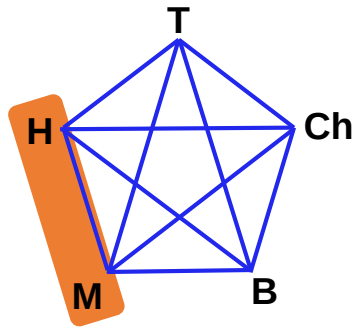


Extreme temperatures

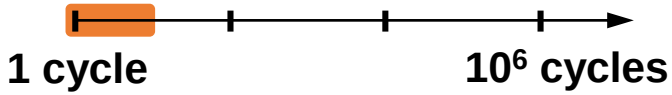


Extreme pressures

Multi-physics



Repetitive loads

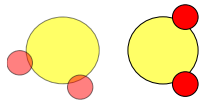


Fluids & fluid-mineral interaction

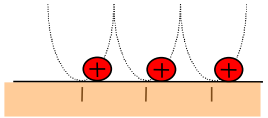
Polarization

Charges (water & ions)

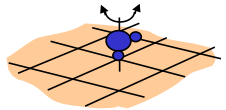
Water Orientation



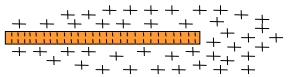
Stern layer



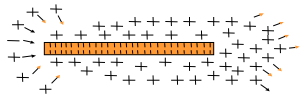
Bound water



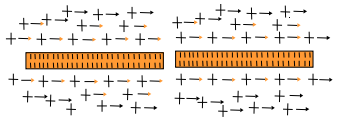
DDL in DI water



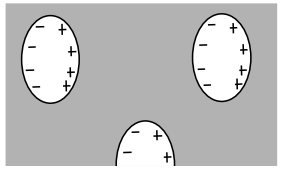
DDL in solution



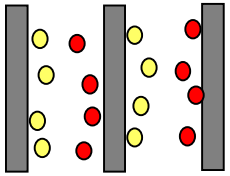
Particle interaction



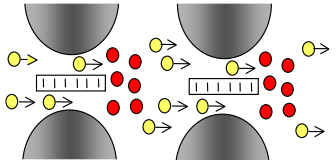
Wagner relaxation



Maxwell relaxation

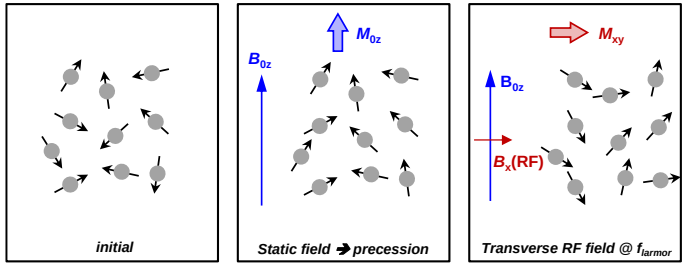


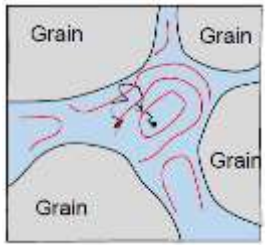
Semi-perm. membrane

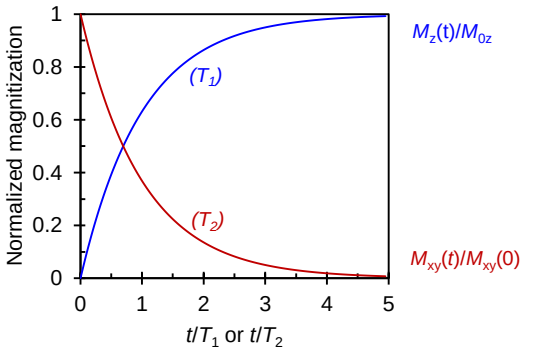


NMR Relaxation

H-atom nucleus





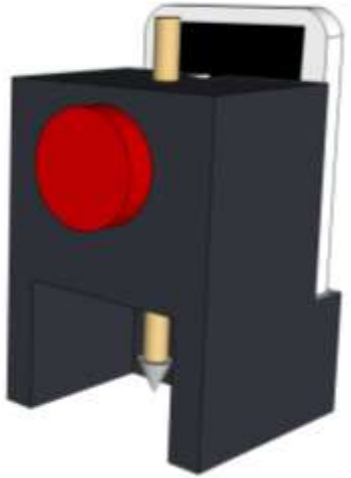


Lab-on-a-bench

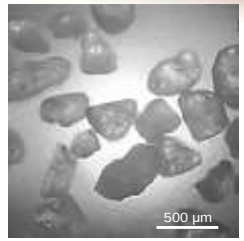
S_s colorimetry

GSD light absorption

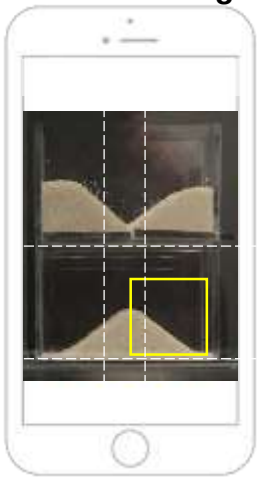
LL cell-caliper



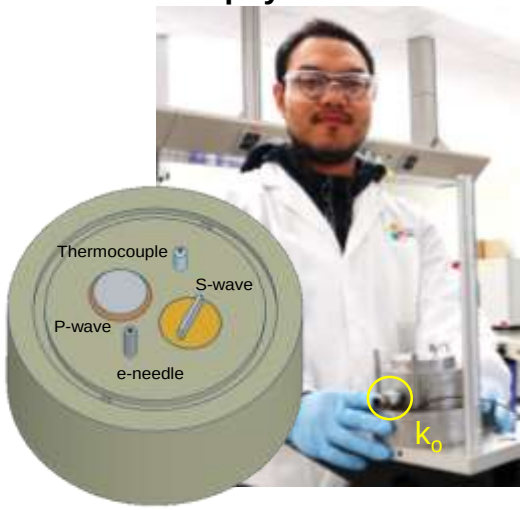
Particle size and shape



CV friction angle

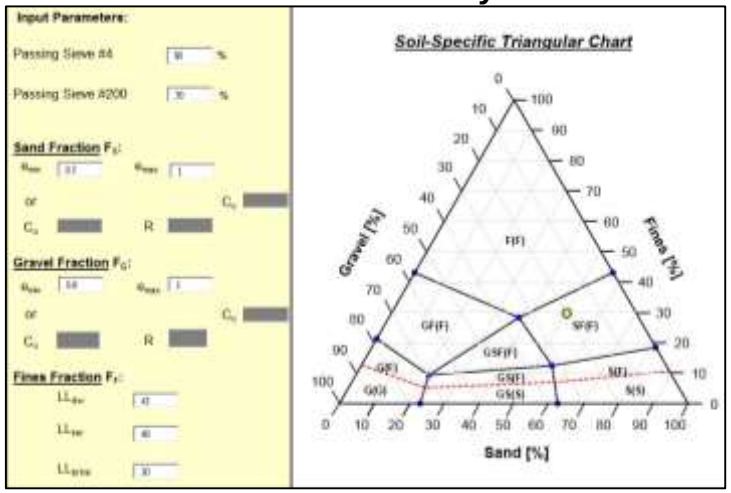


Multi-physics oedometer



Benchtop NMR & permittivity

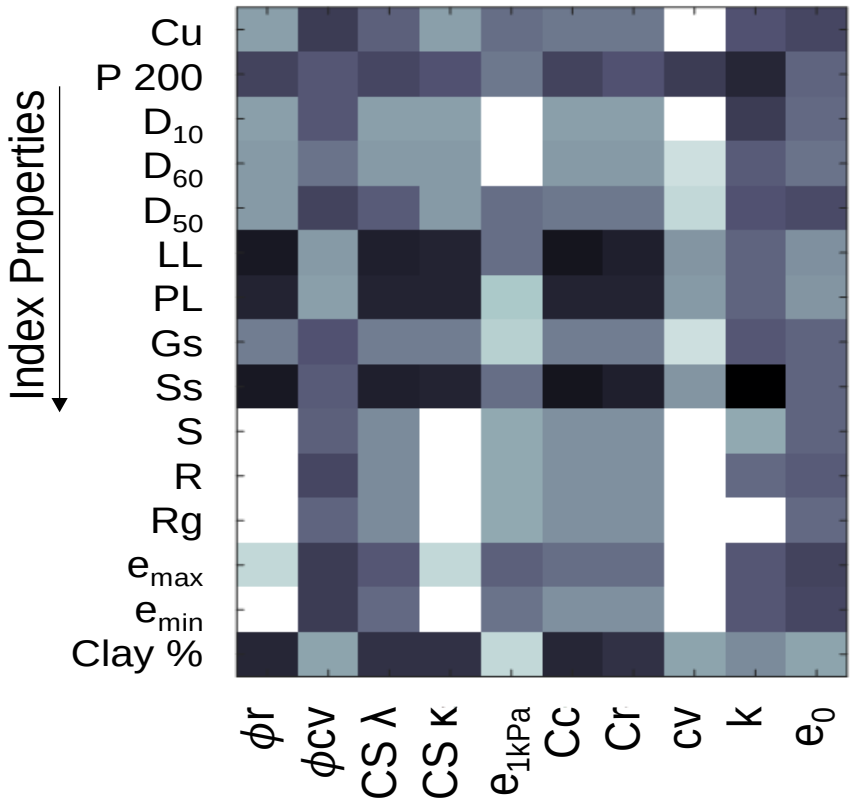
Revised Soil Classification System RSCS



Paradigm shift in soil & rock characterization for engineering purposes

Index properties + database → Engineering properties

NETFLIX



Multi-physics

Self-consistent properties

Predicts uncertainty

Assess cost/benefit of new data

Best engineering ANYwhere

Collective effort (everywhere)

Prototypes available … join the effort!!

What do we measure?

Data ➔ information

Computer-assisted experimentation

“Numerical experiments”… Oxymoron?

Other trends in experimentation

Closing thoughts

Soil mechanician
Meticulous experimentalist
Engineer… practical problems

The last 65 years:

- **information & sensor revolution**
- **marked stretching of geotechnical scales**
- **loss of immediacy during test execution and analysis**

Challenges remain:

- **inherent scaling, sampling & measurement effects**
- **what we want to measure ≠ think we measured ≠ actually measured**

We impose models to data

- **choose an adequate model**
- **overparameterization: slippery road (Ockam's razor)**
- **physics inspired… data driven (asymptotically correct)**
- **information << data (info needed < info sought…)**

How is it that we have so much [data] but know so little?
Noam Chomsky

Trends & paradigm shifts

- **revival of experimentation: new tools and new philosophy ➔ design experiments for invertibility**
- **new protocols to assess THCBM coupled processes (monotonic and repetitive)**
- **numerical experiments: may be needed … add them to the tool box**
- **measurements + databases = towards credible & self-consistent parameters ➔ reliable analyses & design**

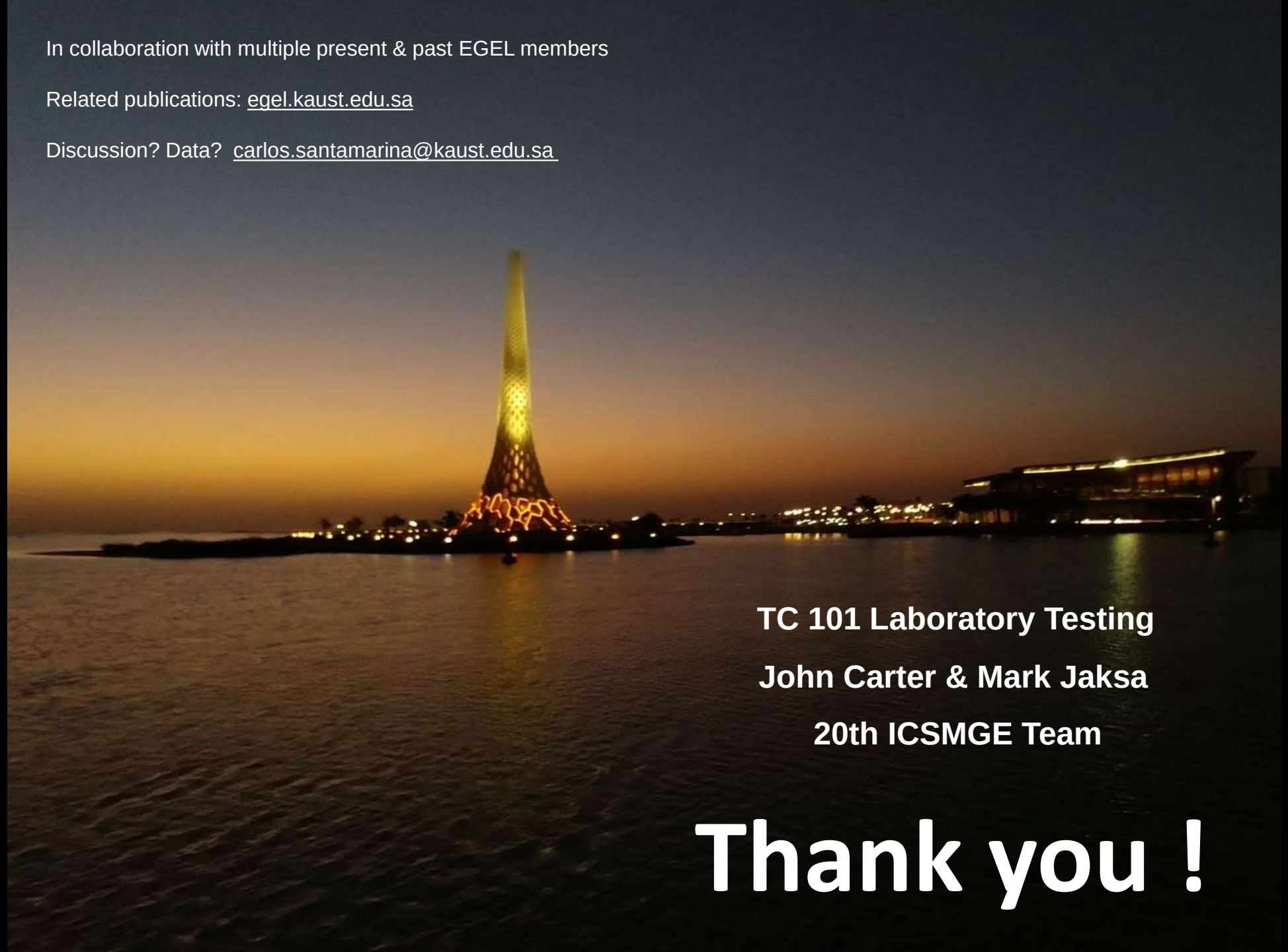
Time to revisit our labs and educational programs … Let's embrace the XXI century !

KAUST

In collaboration with multiple present & past EGEL members

Related publications: egel.kaust.edu.sa

Discussion? Data? carlos.santamarina@kaust.edu.sa



TC 101 Laboratory Testing

John Carter & Mark Jaksa

20th ICSMGE Team

Thank you !