MUSE - Barcelona 2005:

Unsaturated soils: small-to-large

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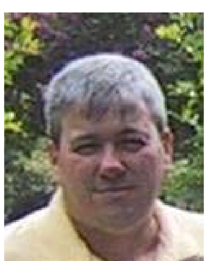
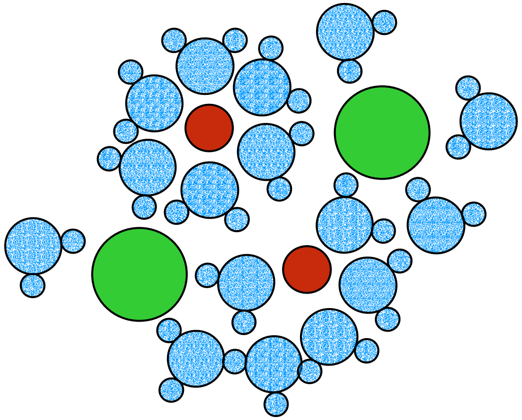


J. Alvarellos
INTEVEP

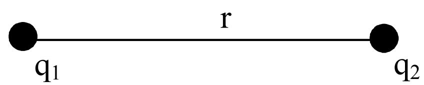
S. Lazcano
Guadalajara

FROM MOLECULES TO WETTING



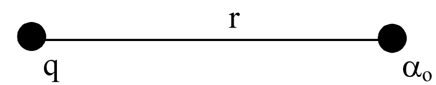
Electrical Forces (ions and molecules)

Ion-to-Ion



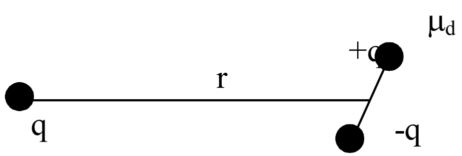
$$F = \frac{1}{4\pi\varepsilon_o\kappa'}\frac{q_1 q_2}{r^2}$$ ***Coulomb's Law***

Ion-to-Polarized Molecule



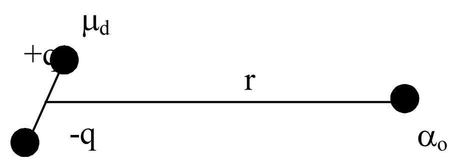
$$F = -\frac{2q^2\alpha_o}{(4\pi\varepsilon_o\kappa')^2 r^5}$$

Ion-to-Dipole



$$F = -\frac{4q^2\mu_d^2}{6(4\pi\varepsilon_o\kappa')^2 kTr^5}$$ ***Free Dipole***

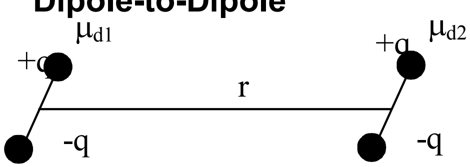
Dipole-to-Polarized Molecule



$$F = -\frac{6\mu_d^2\alpha_o}{(4\pi\varepsilon_o\kappa')^2 r^7}$$ ***Free Dipole***

(Debye)

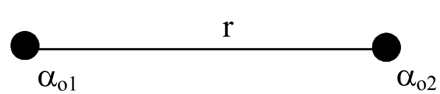
Dipole-to-Dipole



$$F = -\frac{2\mu_{d1}^2\mu_{d2}^2}{(4\pi\varepsilon_o\kappa')^2 kTr^7}$$ ***Free Dipole***

(Keesom)

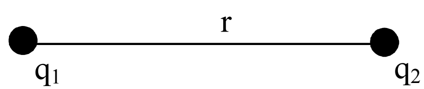
Two Polarized Molecules



$$F = -\frac{9h\nu\alpha_o^2}{2(4\pi\varepsilon_o\kappa')^2 r^7}$$ ***London Disp.***

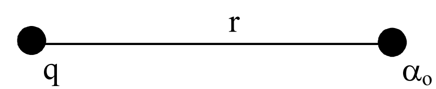
Electrical Forces (ions and molecules)

Ion-to-Ion



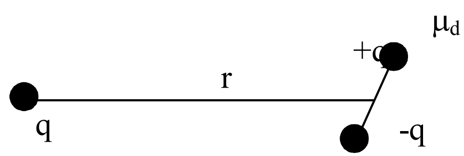
$$F = \frac{1}{4\pi\varepsilon_o \kappa'} \frac{q_1 q_2}{r^2}$$ ***Coulomb's Law***

Ion-to-Polarized Molecule



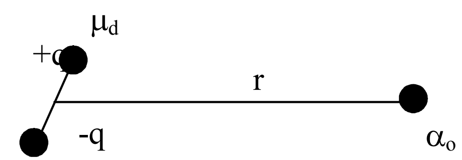
$$F = -\frac{2q^2\alpha_o}{(4\pi\varepsilon_o\kappa')^2 r^5}$$

Ion-to-Dipole



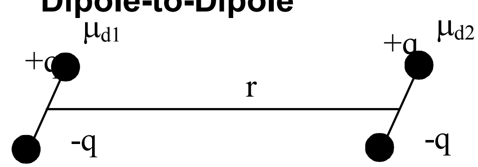
$$F = -\frac{4q^2\mu_d^2}{6(4\pi\varepsilon_o\kappa')^2 kTr^5}$$ ***Free Dipole***

Dipole-to-Polarized Molecule



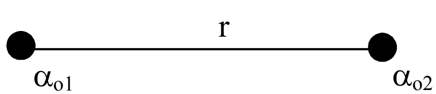
$$F = -\frac{6\mu_d^2\alpha_o}{(4\pi\varepsilon_o\kappa')^2 r^7}$$ ***Free Dipole*** **(Debye)**

Dipole-to-Dipole



$$F = -\frac{2\mu_{d1}^2\mu_{d2}^2}{(4\pi\varepsilon_o\kappa')^2 kTr^7}$$ ***Free Dipole*** **(Keesom)**

Two Polarized Molecules

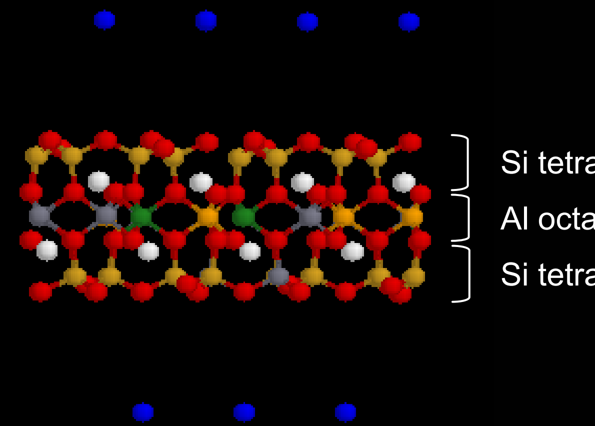


$$F = -\frac{9h\nu\alpha_o^2}{2(4\pi\varepsilon_o\kappa')^2 r^7}$$ ***London Disp.***

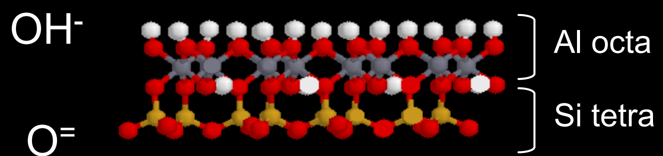
van der Waals

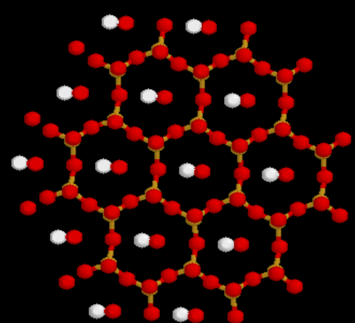
Minerals

montmorillonite

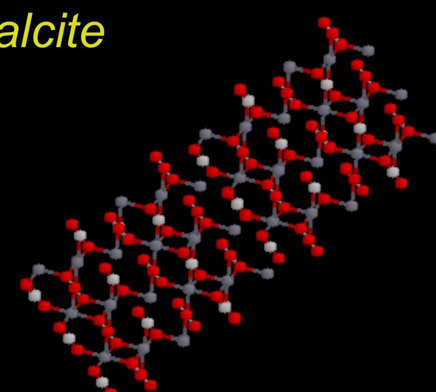


kaolin





calcite



MDL / www.soils.wisc.edu/virtual_museum/index.html

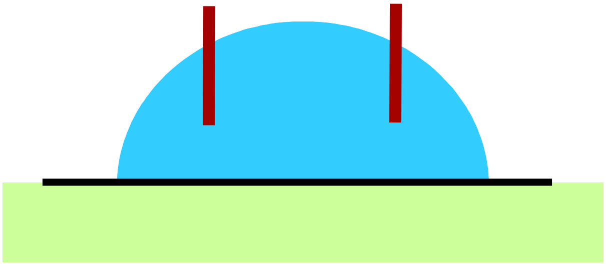
Contact Angle

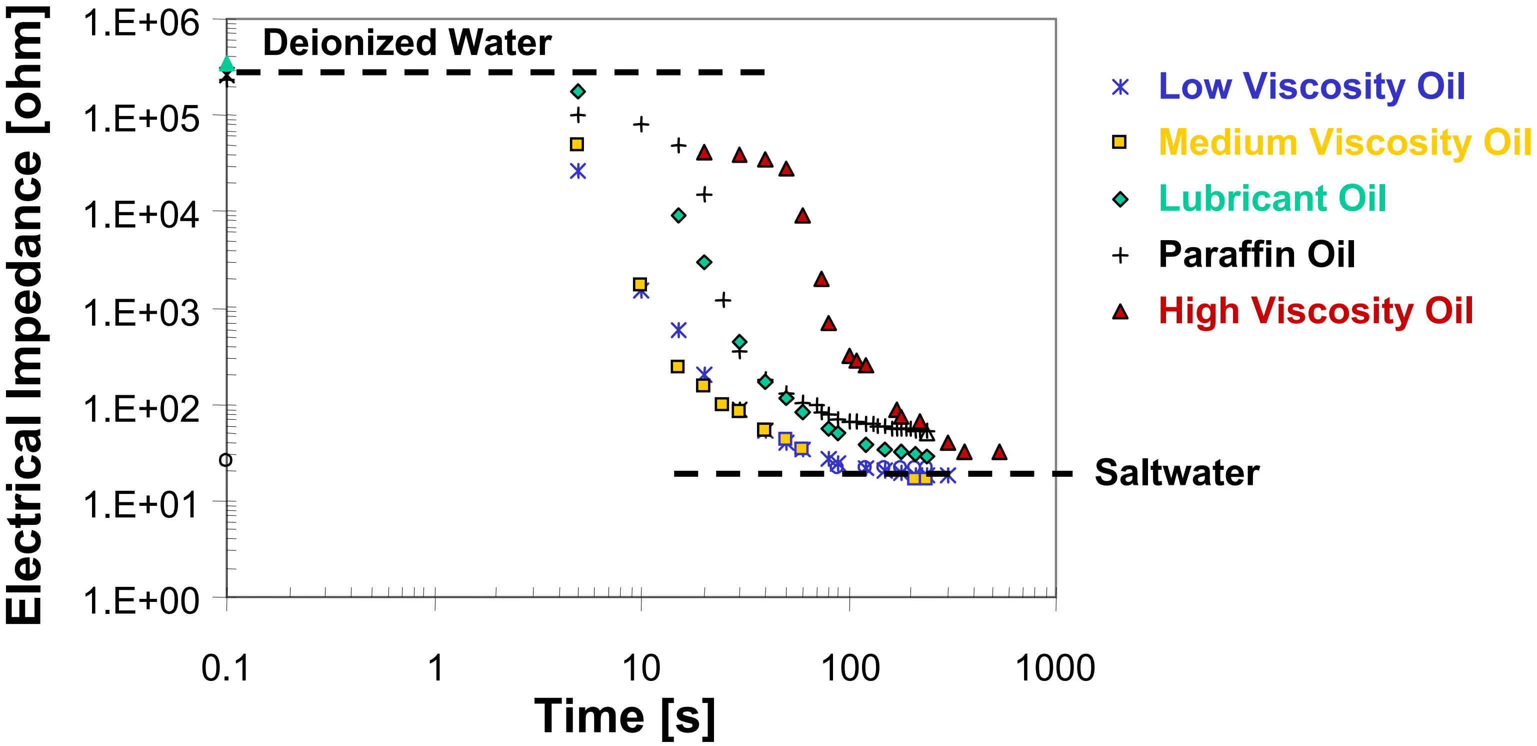
$$\cos\theta = \frac{\sigma_{OS} - \sigma_{WS}}{\sigma_{OW}}$$

(in air)	Water	Paraffin Oil	Silicone Oil	Lubricant Oil	Isopropyl Alcohol
Calcite	49.6 ±7.9	8.8 ±1.8	≈ 0	22.4±2.3	22.9±3.8
Quartz	13.1 ±2.0	≈ 0	≈ 0	7.5±1.4	≈ 0
Biotite	32.6 ±2.9	≈ 0	≈ 0	7.0±1.5	9.5±1.4
Muscovite	16.6 ±3.5	≈ 0	≈ 0	9.9±2.4	≈ 0

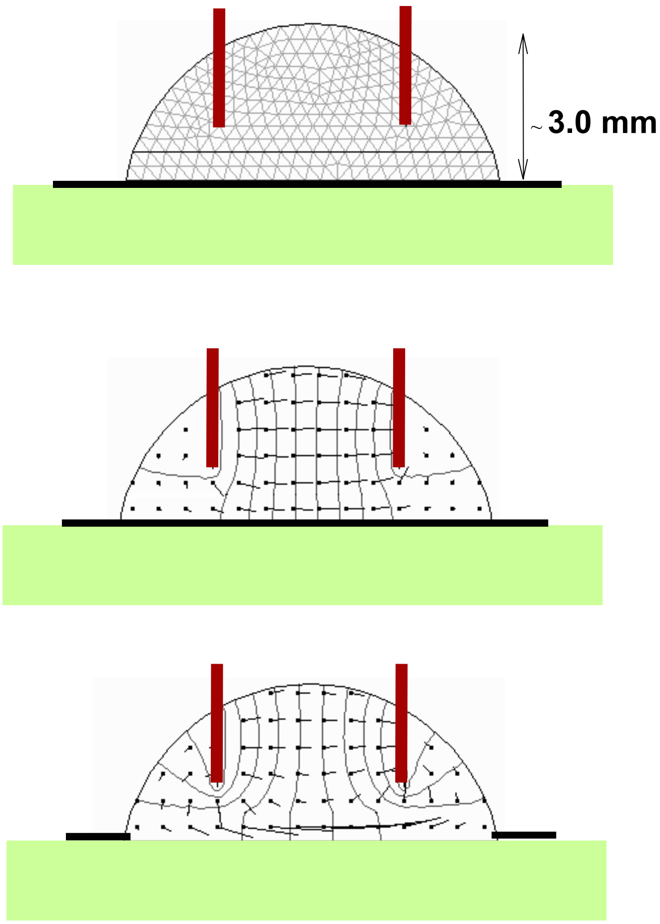
Film Breakage (oil and water)

Time for Film Breakage

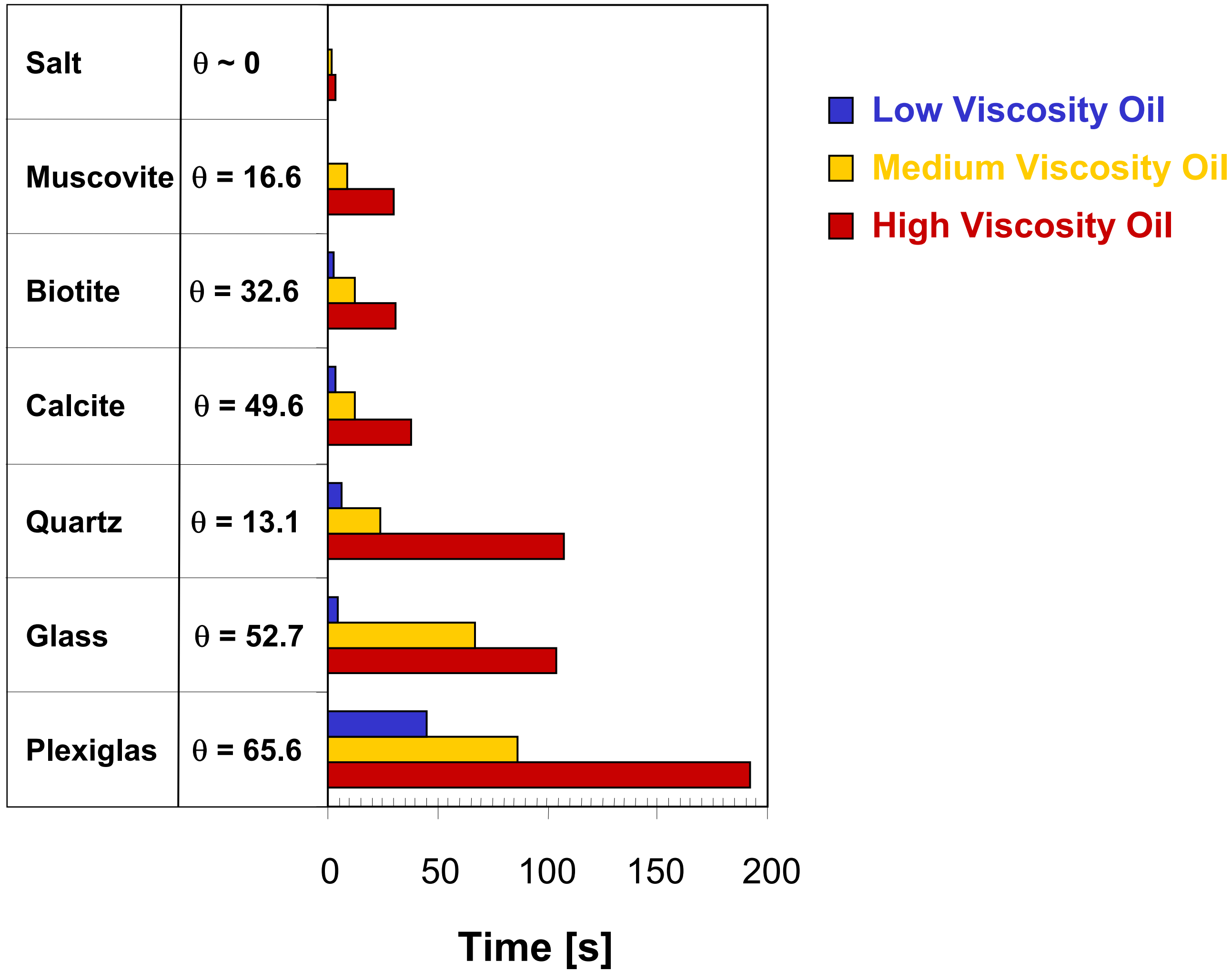




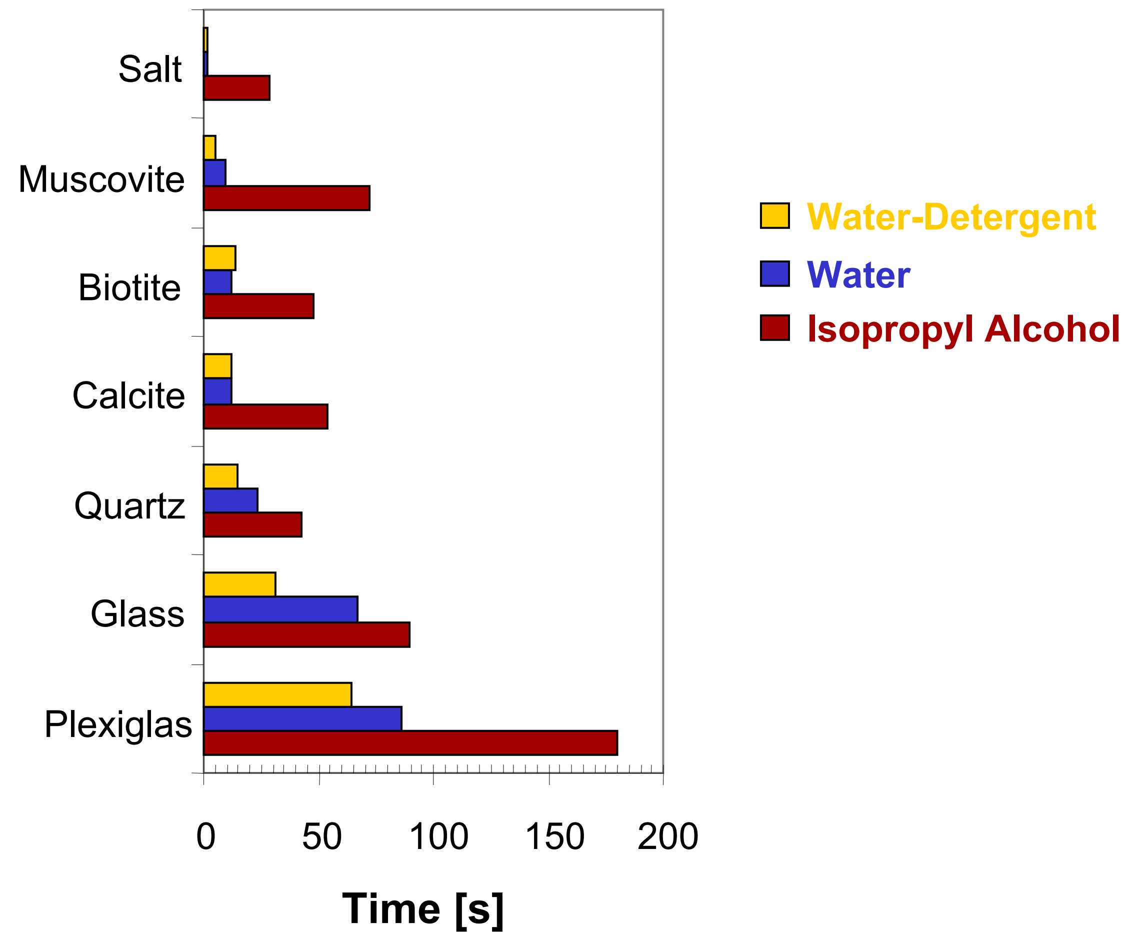
Time for Film Breakage



Time for Film Breakage



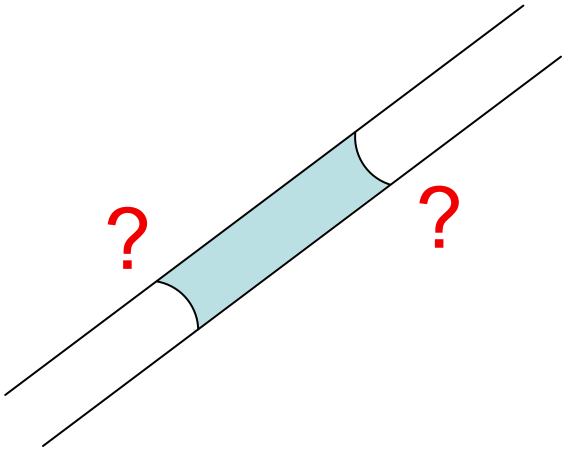
Time for Film Breakage



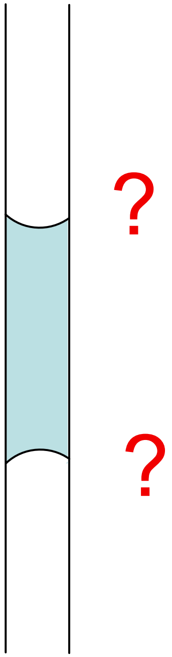
INTERACTING MENISCI

Droplet in Capillary Tube

Droplet in Capillary Tube



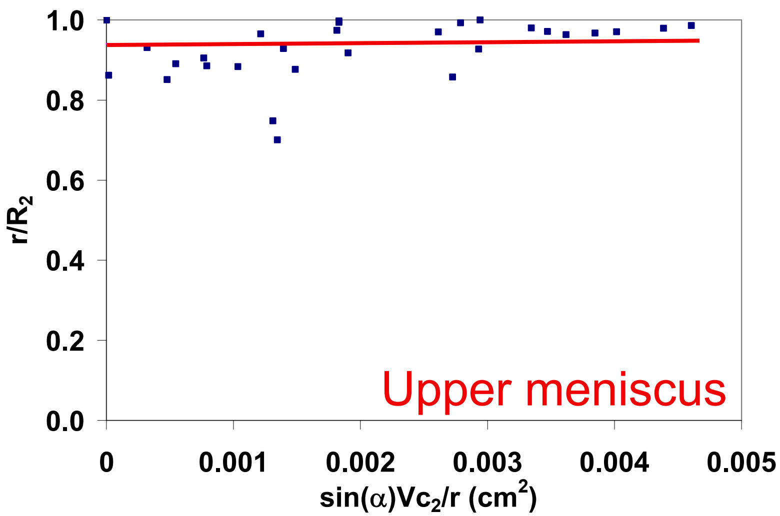
Droplet in Capillary Tube

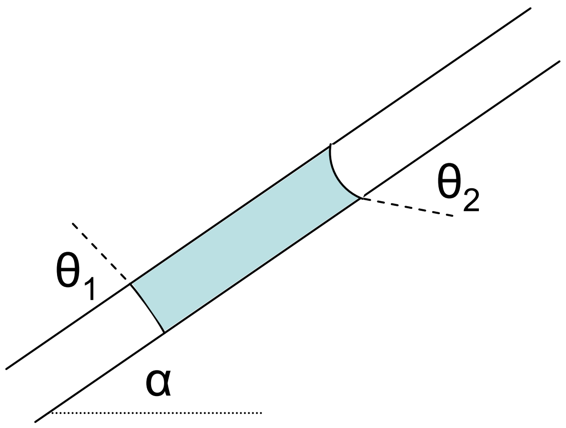


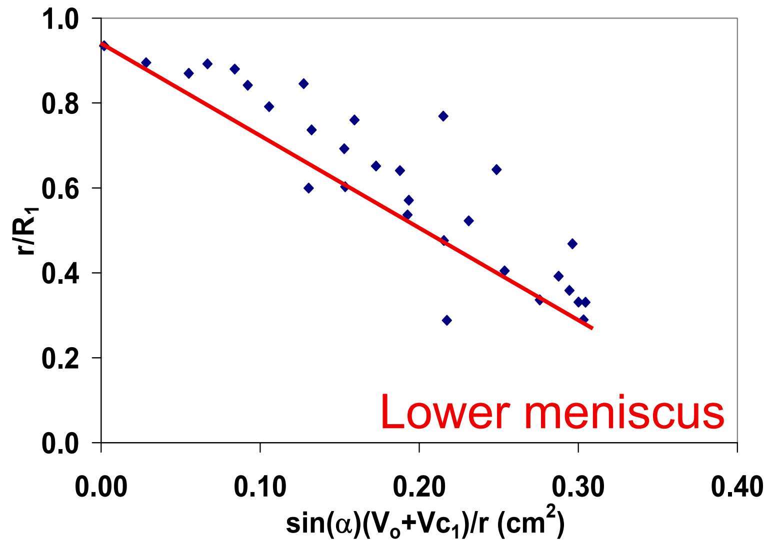
stable ?

Contac angle: Gravity

Water and borosilicate tube





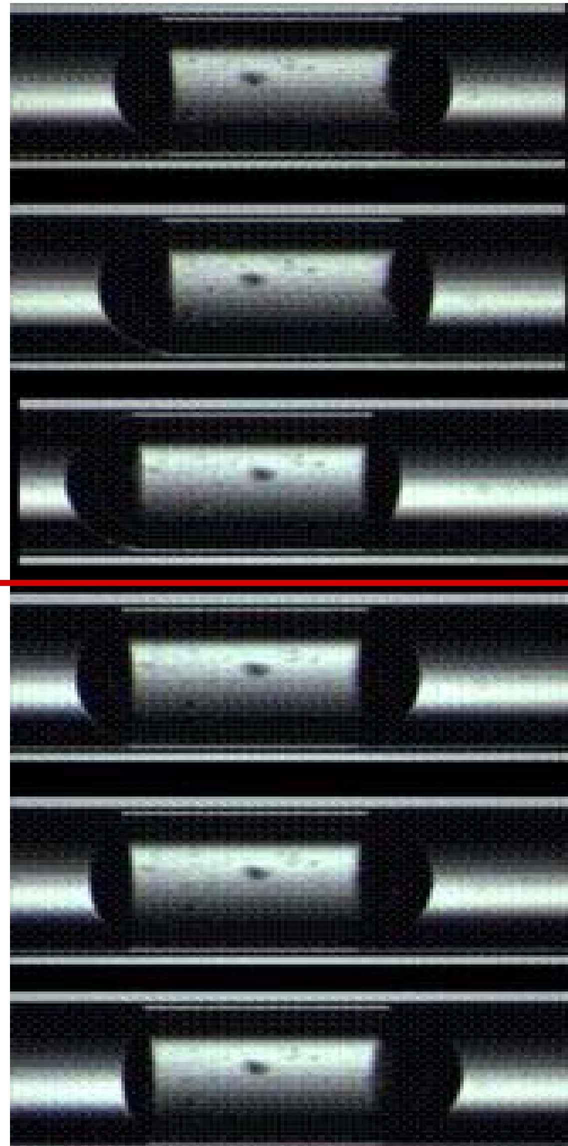


$$\cos(\theta_2) = \frac{r}{R_2} = \cos(\theta_o) + \frac{\rho \cdot g \cdot \sin(\alpha)}{2 \cdot \pi \cdot r \cdot \gamma_{lg}} \cdot (Vc_2)$$

$$\cos(\theta_1) = \frac{r}{R_1} = \cos(\theta_o) - \frac{\rho \cdot g \cdot \sin(\alpha)}{2 \cdot \pi \cdot r \cdot \gamma_{lg}} \cdot (V_o + Vc_1)$$

Lines: model for surface tens. $72 \cdot 10^{-3}$ N/m and mass density 1000 kg/m^3

Contact angle: Pressure gradient



1 P ↑

2 P ↑

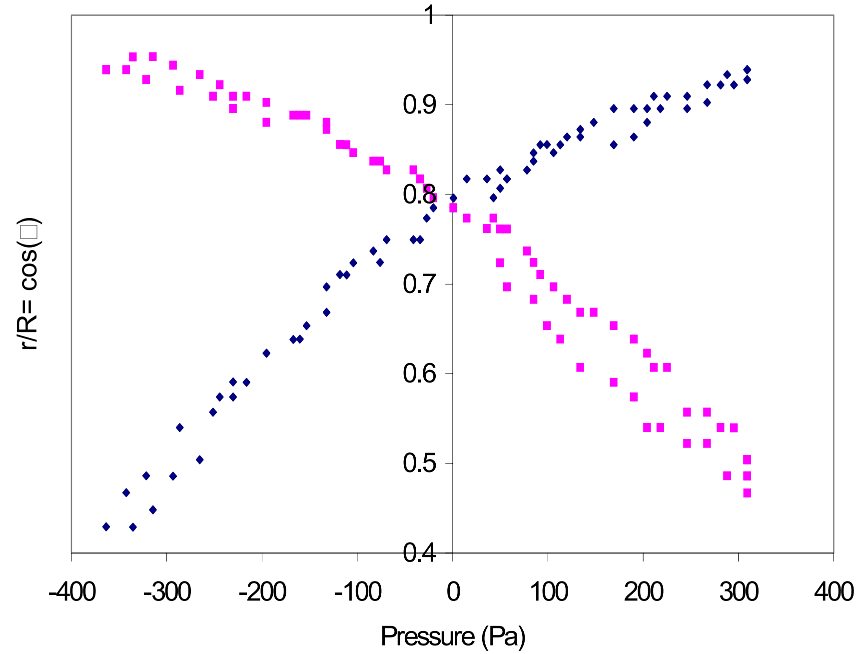
3 P ↑ Failure, bubble moves

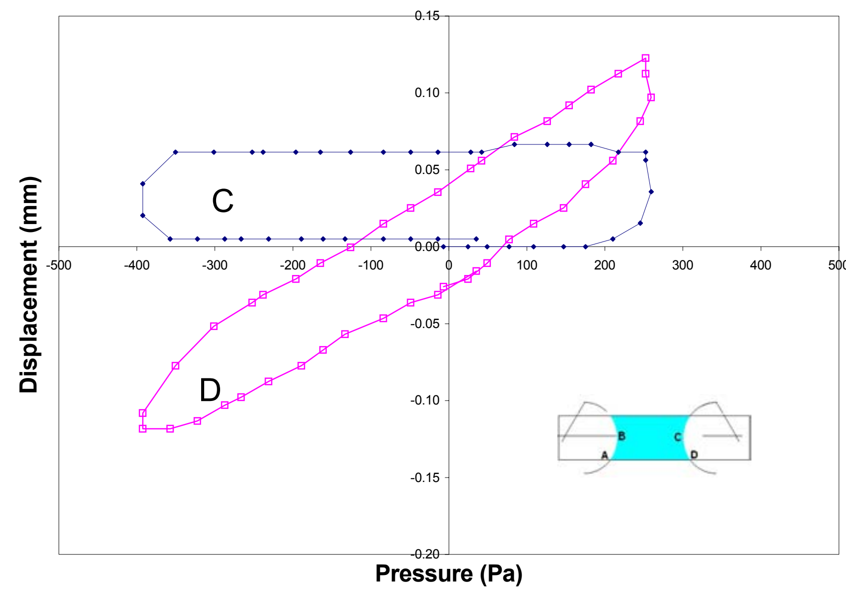
4 P ↓

5 P ↓

6 P ↓ Failure, bubble moves

Contact angle: Pressure gradient

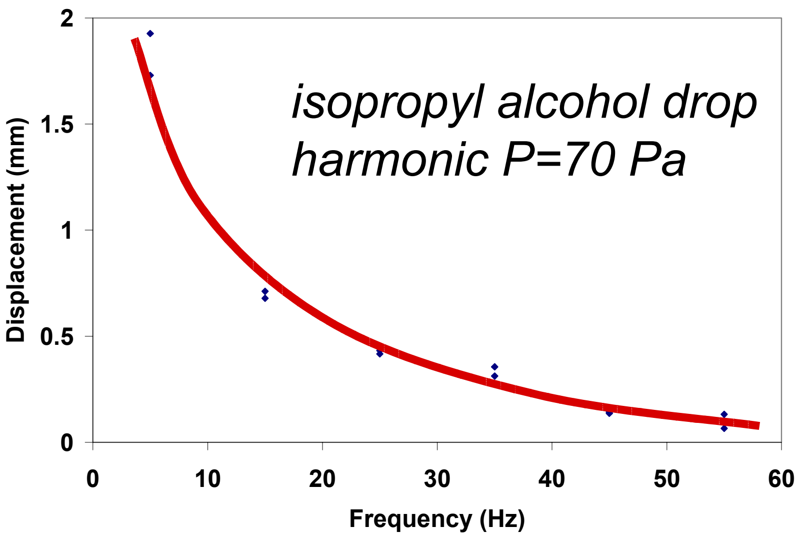


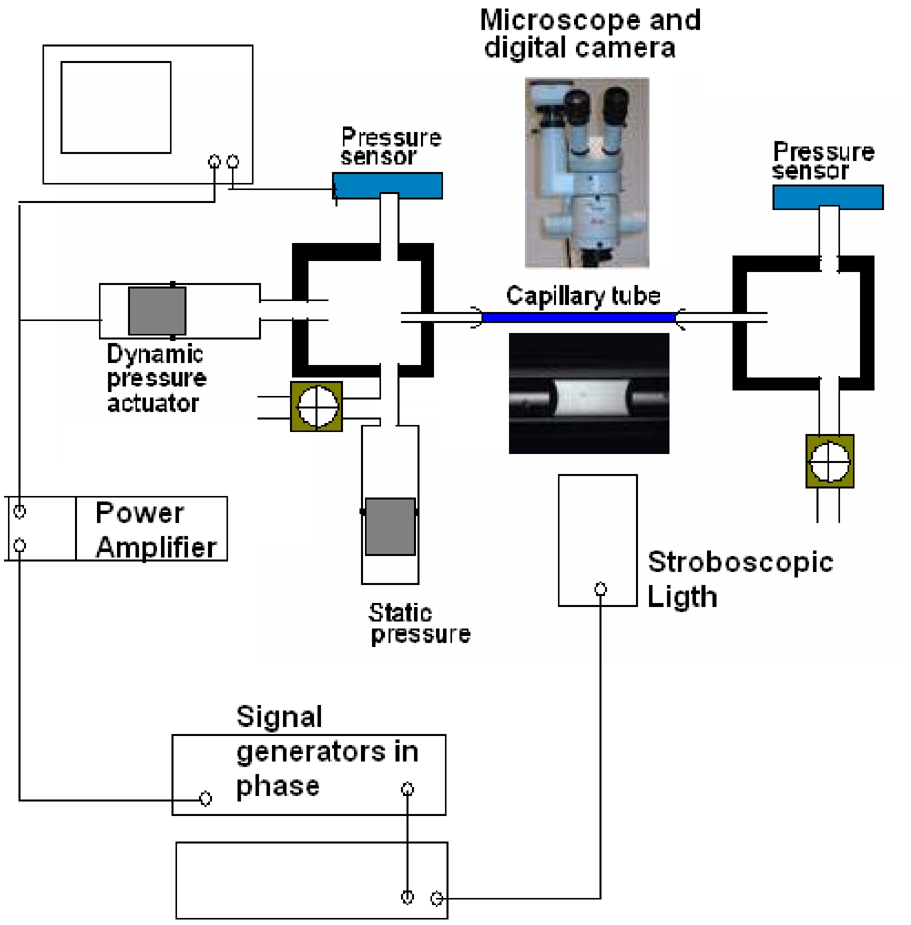


$$\cos(\theta_1) = \frac{r}{R_1} = \frac{\Delta\gamma}{\gamma_{lg}} - \frac{r}{4\cdot\gamma_{lg}}\cdot\left(\frac{r^2}{h_1\cdot R_1} - 1\right)\cdot(P_1 - P_2)$$

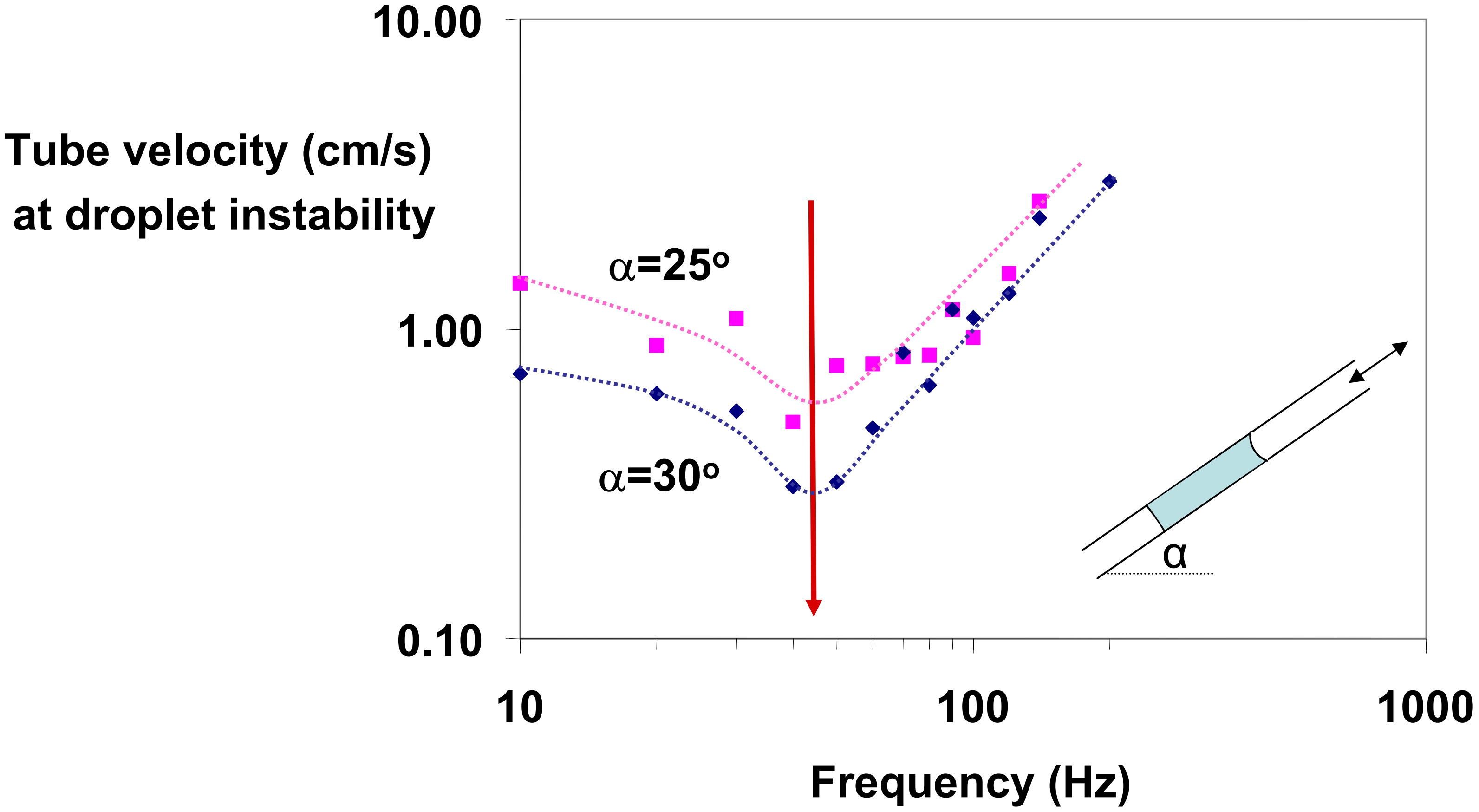
$$\cos(\theta_2) = \frac{r}{R_2} = \frac{\Delta\gamma}{\gamma_{lg}} + \frac{r}{4\gamma_{lg}}\cdot\left(\frac{r^2}{h_2\cdot R_2} - 1\right)\cdot(P_1 - P_2)$$

AC Fluid Pressure: Relaxation

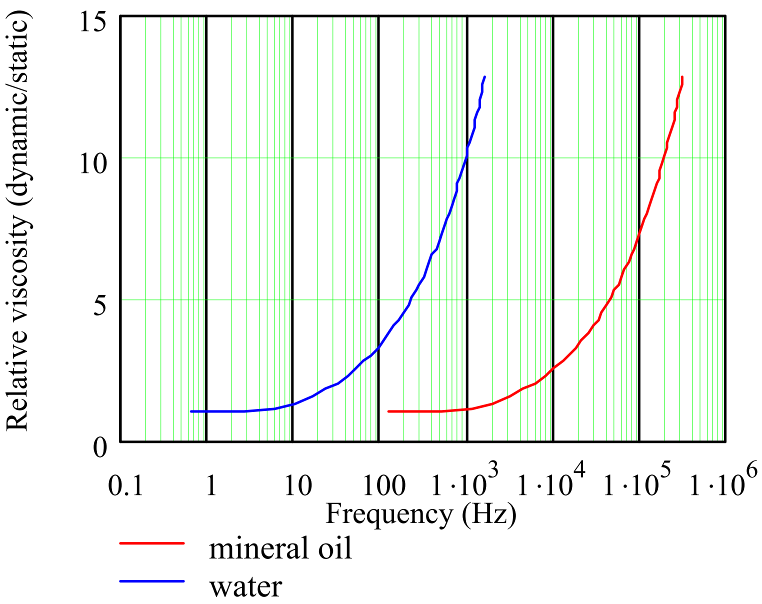


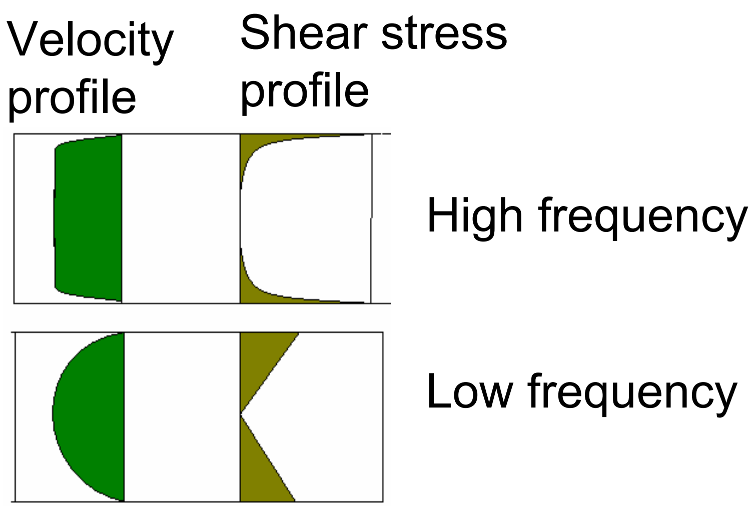


AC Tube Vibration: Resonance



Biot solution

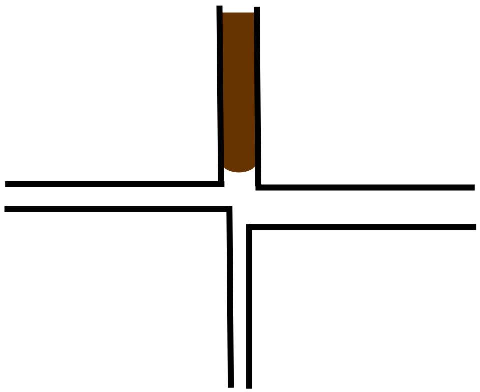




SPATIAL VARIABILITY

Advancing a Non-wetting Fluid

Pore network



$$N_{cap} = \frac{F_{viscous}}{F_{capil,}} = \frac{v_{darcy}\,\mu_w}{\gamma_{ow}\cos\theta}$$

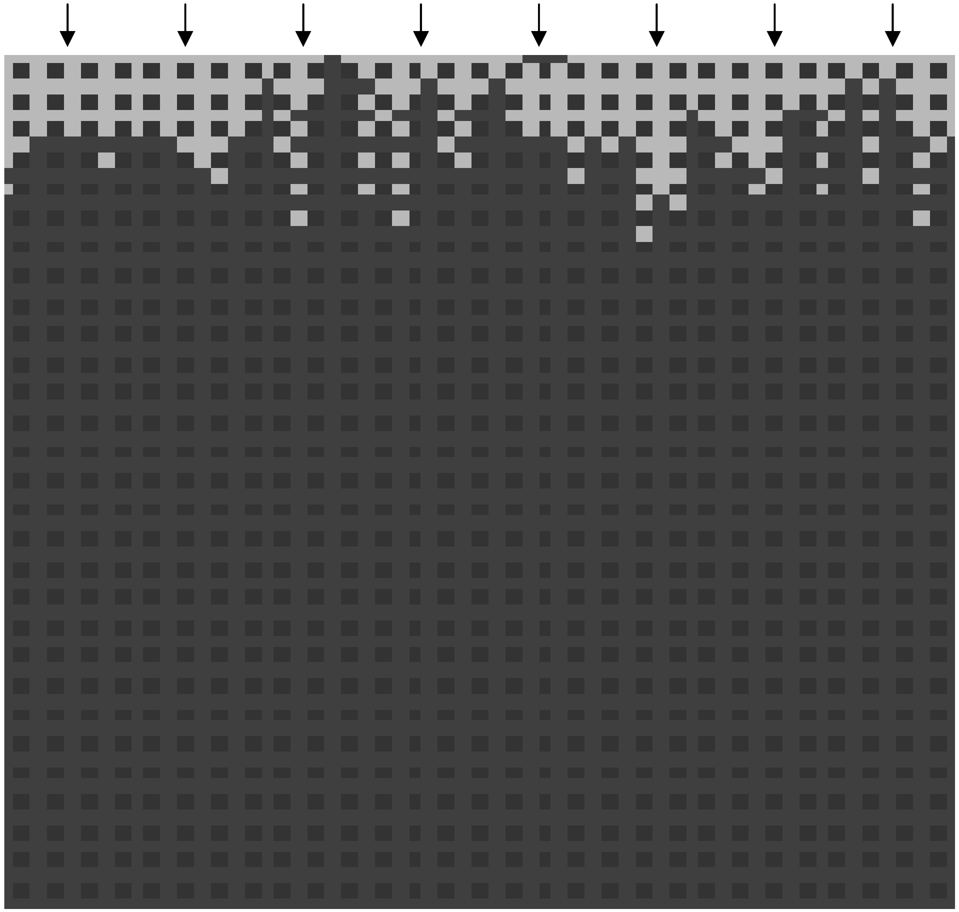
$N_{Cap} < 10^{-5}$ constant irreducible saturation

$N_{Cap} > 10^{-4}$ irreducible saturation $f(v_{darcy})$

$$N_{bond} = \frac{F_{gravity}}{F_{capil.}} = \frac{\Delta\rho\, g\, k_w\, k_{rw}}{\gamma_{ow}\cos\theta}$$

Advancing a Non-wetting Fluid

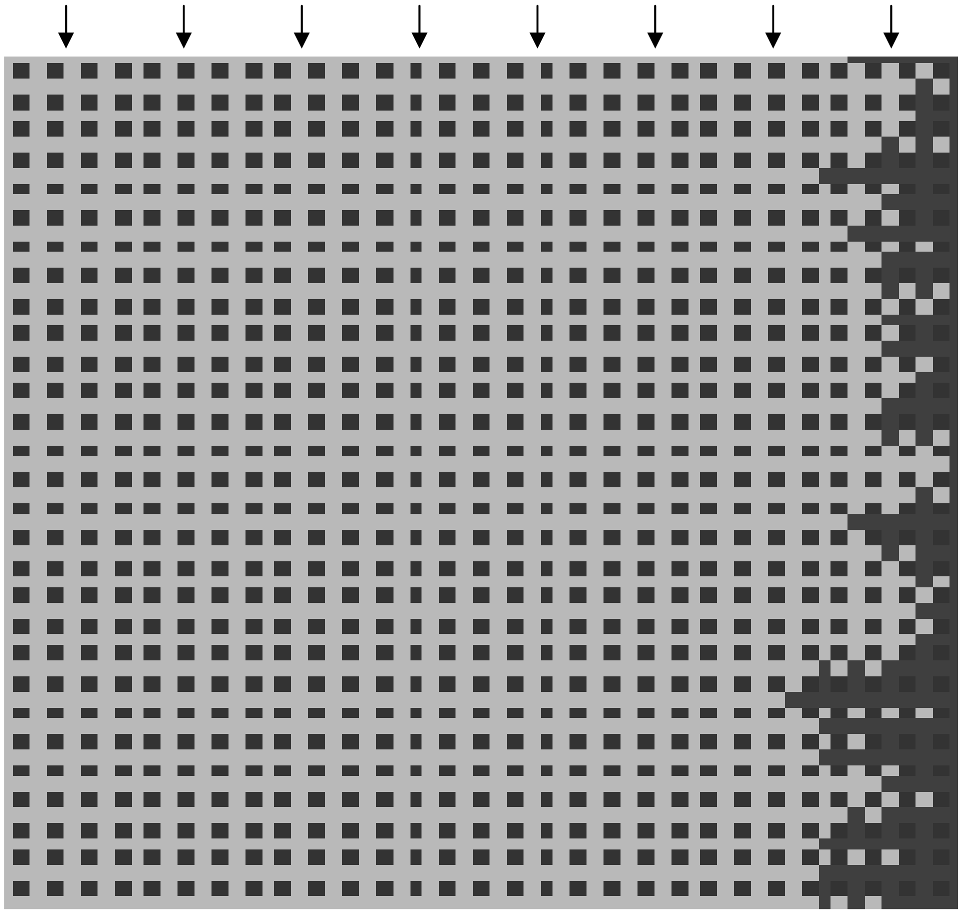
pore size decreases with depth (e.g., volcanic ash soils)



N_{Cap}<10^{-5} dark - Oil-invaded pores

Advancing a Non-wetting Fluid

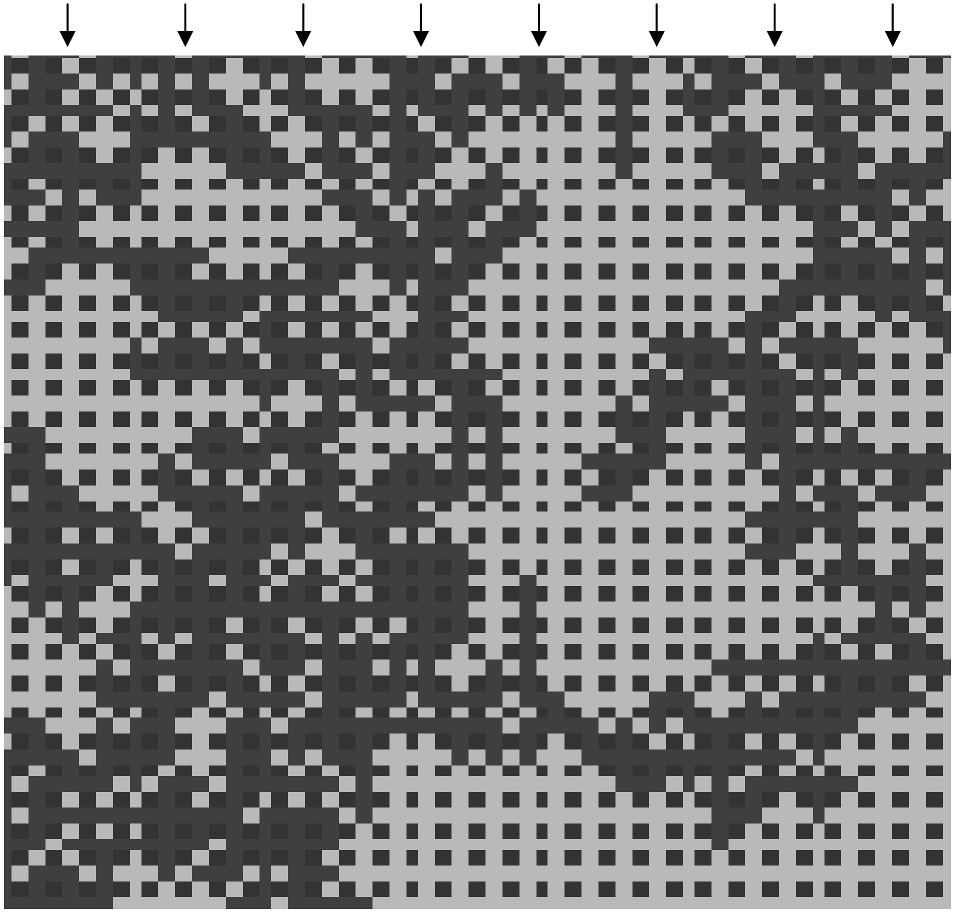
pore size increases from left to right



N_{Cap}<10^{-5} dark - Oil-invaded pores

Advancing a Non-wetting Fluid

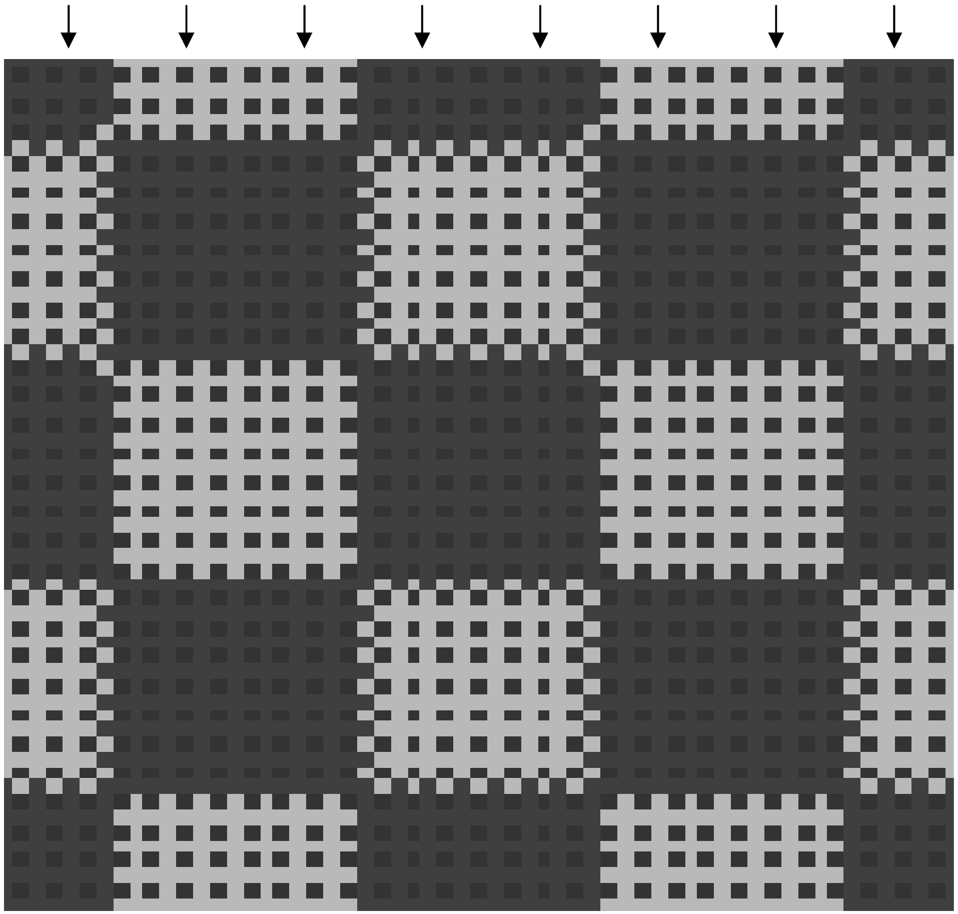
random pore size distribution



$N_{Cap}<10^{-5}$ **dark - Oil-invaded pores**

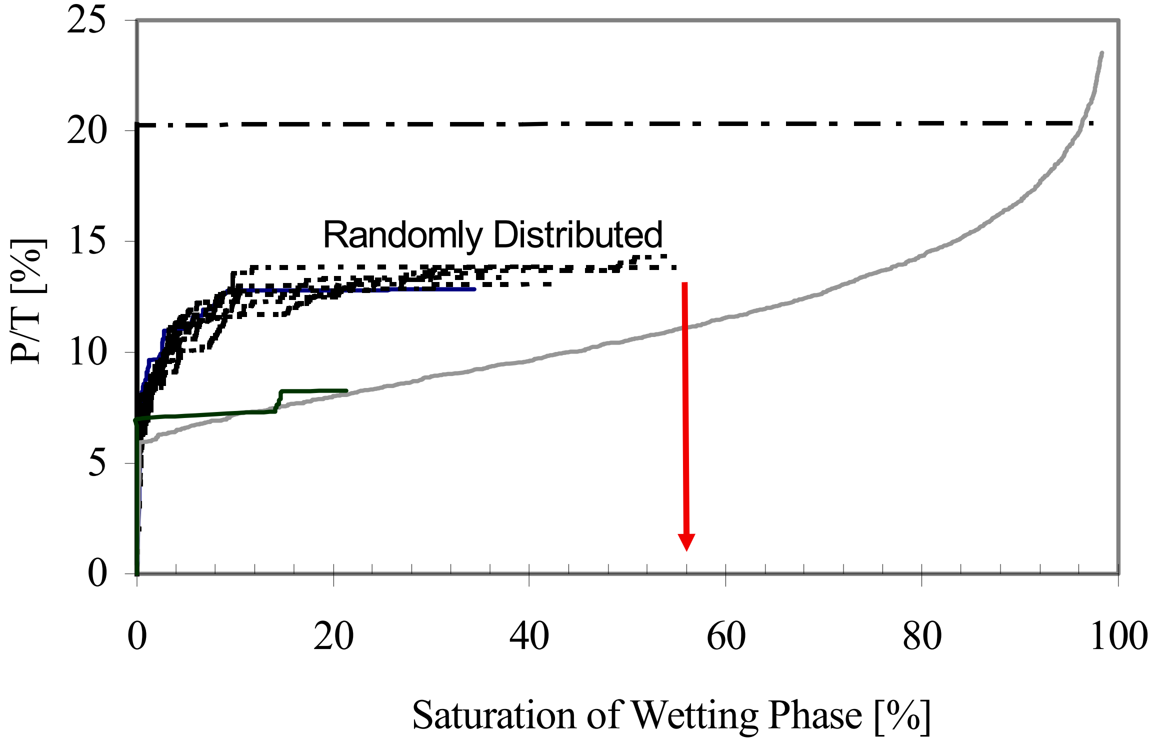
Advancing a Non-wetting Fluid

"correlated" random field



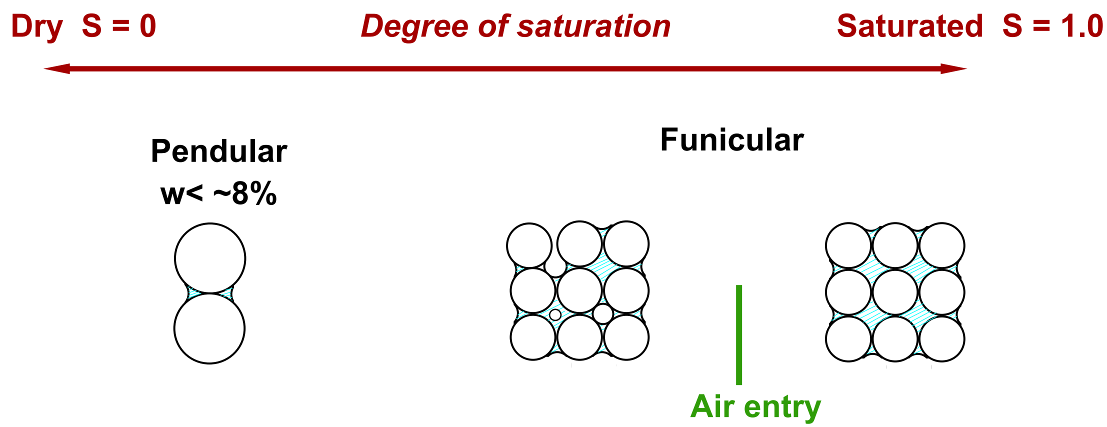
$N_{Cap}<10^{-5}$ dark - Oil-invaded pores

Advancing a Non-wetting Fluid

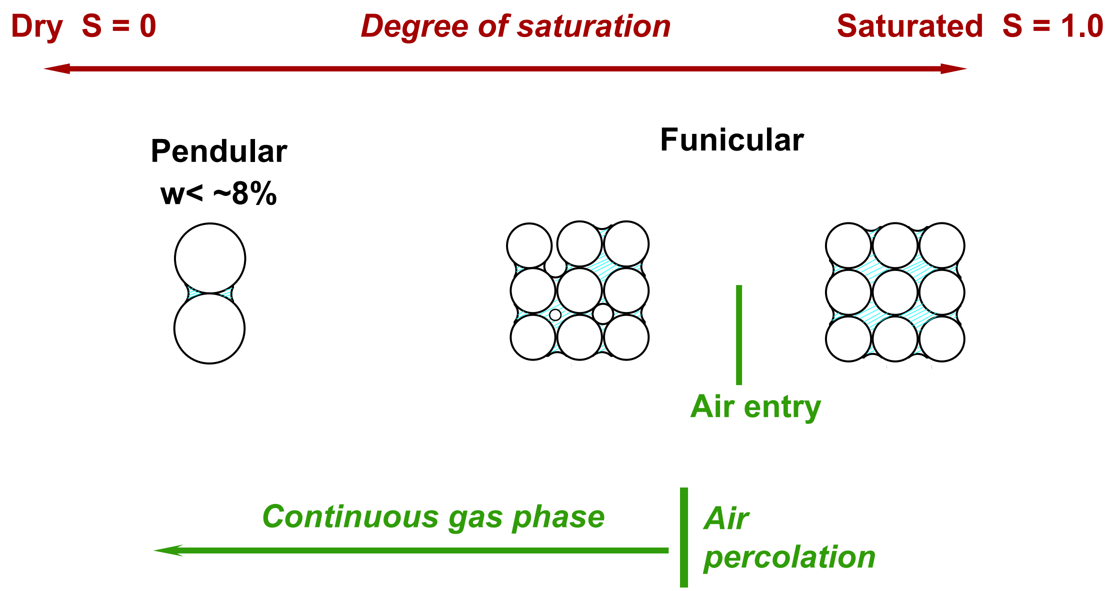


SATURATION REGIMES

Saturation Regimes:



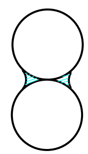
Saturation Regimes:



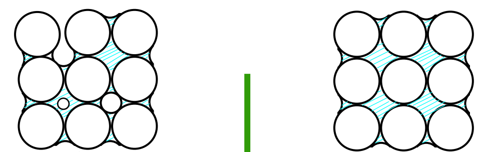
Saturation Regimes:

Dry S = 0 — *Degree of saturation* — Saturated S = 1.0

Pendular
w< ~8%



Funicular



Air entry

Continuous gas phase | *Air percolation*

Water percolation | *Continuous water phase*

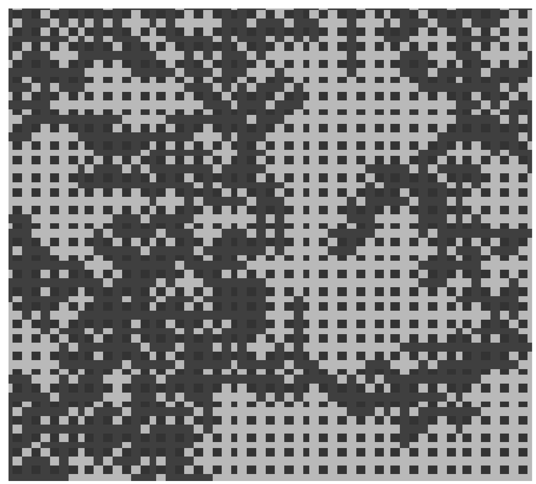
water pressure homogenization:	Through vapor pressure	By pressure diffusion

Saturation Regimes:

Dry S = 0 ***Degree of saturation*** **Saturated S = 1.0**

Water percolation

Air percolation



fractal !

Property= $c.(\text{size})^{-D}$

PARTICLE FORCES

Particle Forces

Skeletal

Weight

Buoyant

Hydrodynamic

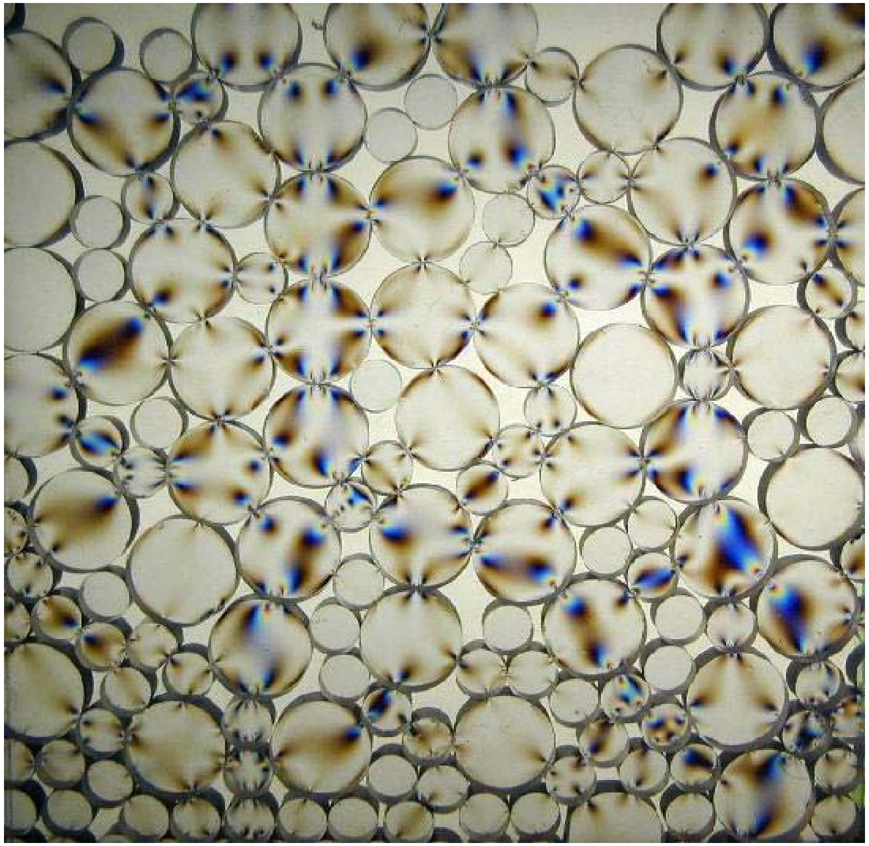
Capillary

Electrical

attraction

repulsion

Cementation



Particle Forces

Skeletal

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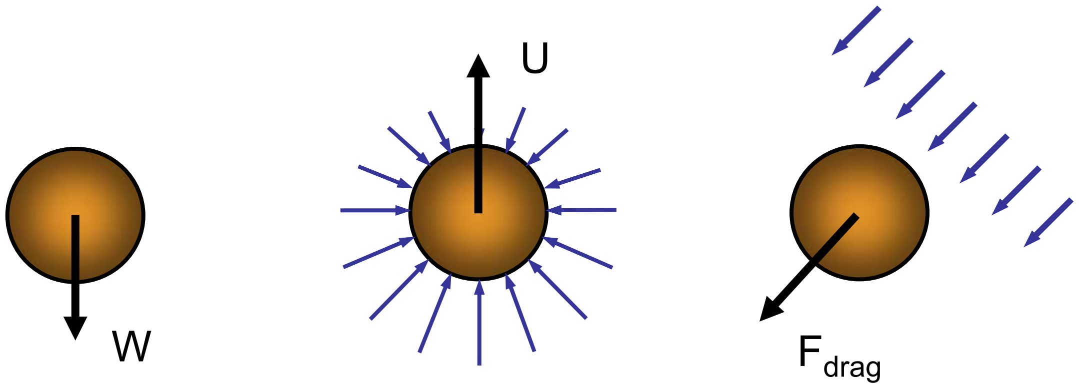

Particle Forces

Skeletal

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Cementation

Particle Forces

Skeletal

Weight

Buoyant

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Capillary

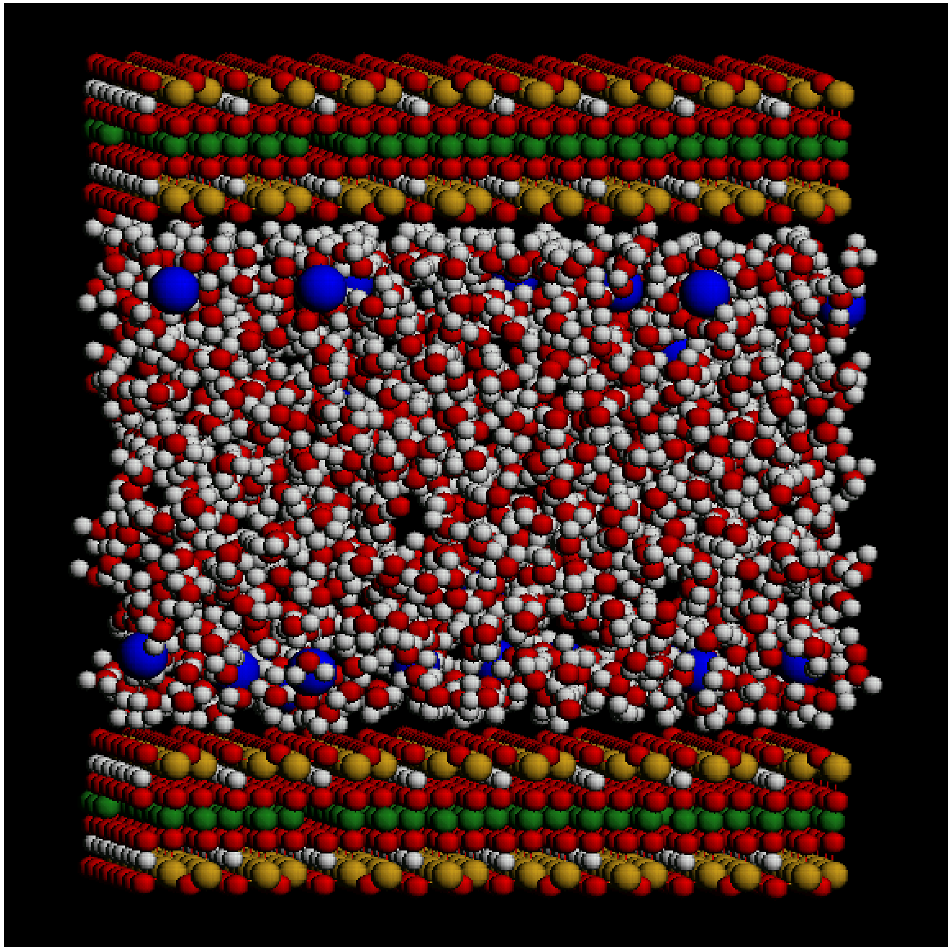
Electrical

attraction

repulsion

Cementation

Laponite 1200 H_2O 24 Na^+



(N. Skipper - UCL)

Particle Forces – Spherical Particles

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

Force Balance: Deformation & Strength

Skeletal

Weight

Buoyant

Hydrodynamic

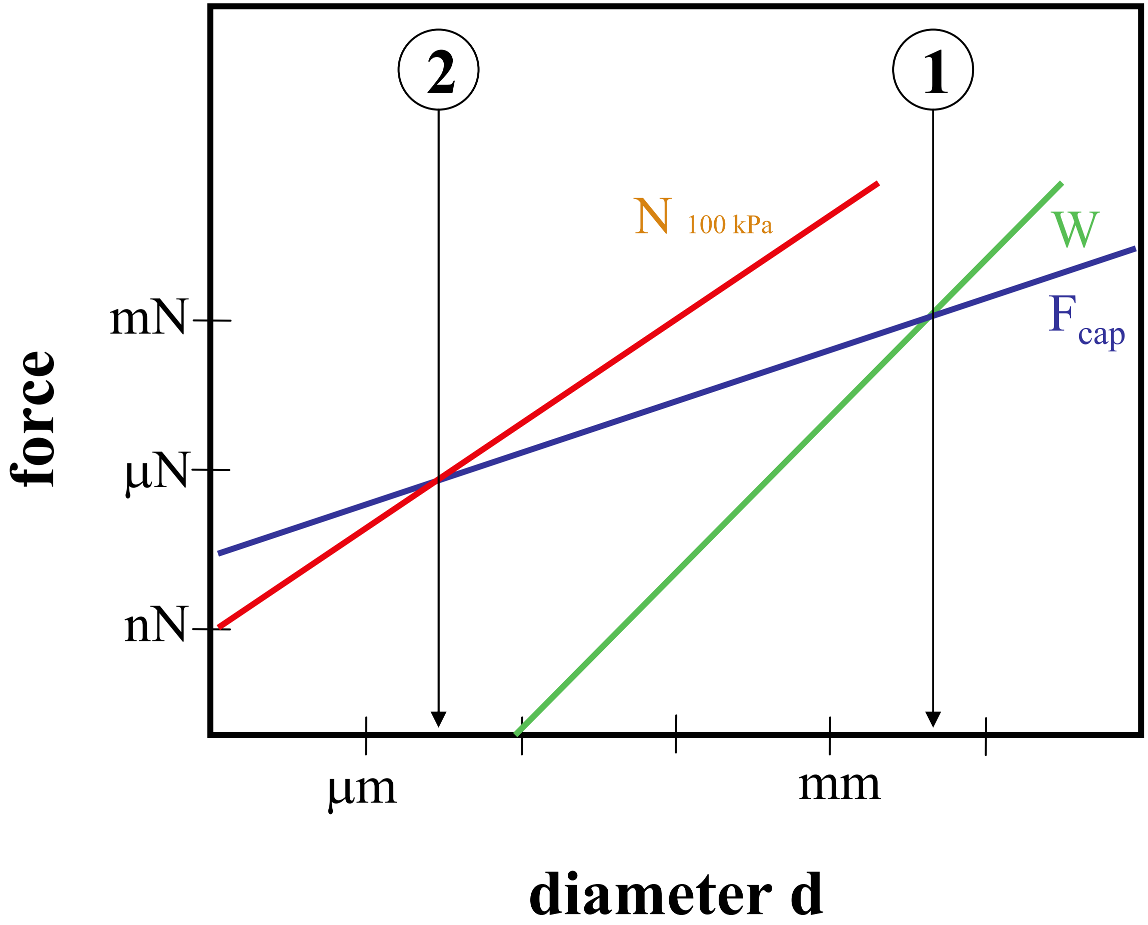
Capillary

Electrical

attraction

repulsion

Cementation



Force Balance: Deformation & Strength

Skeletal

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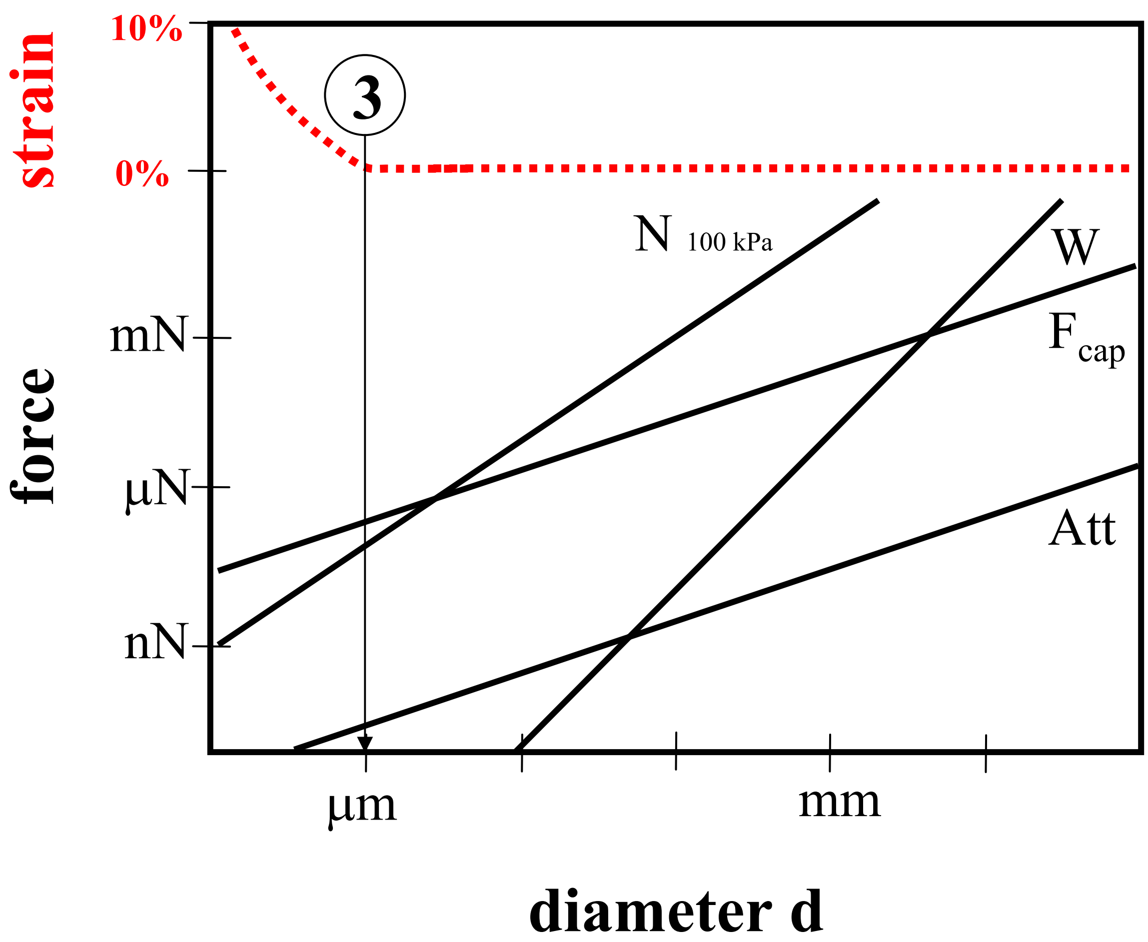
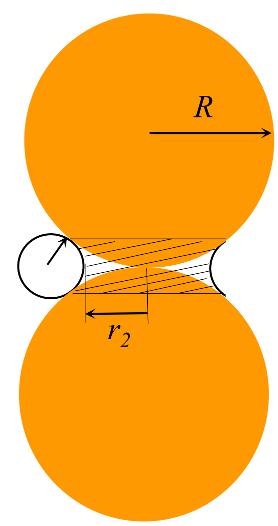
Cementation

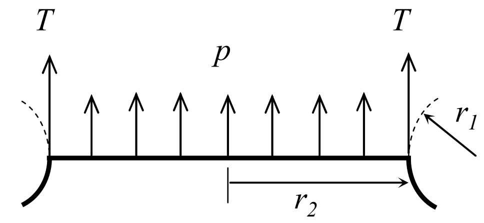


Inter-particle capillary forces

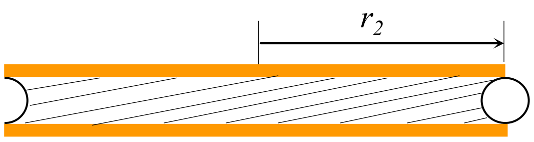
Laplace's Equation $$p = T\left(\frac{1}{r_1} + \frac{1}{r_2}\right)$$

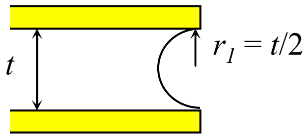
Spherical particles



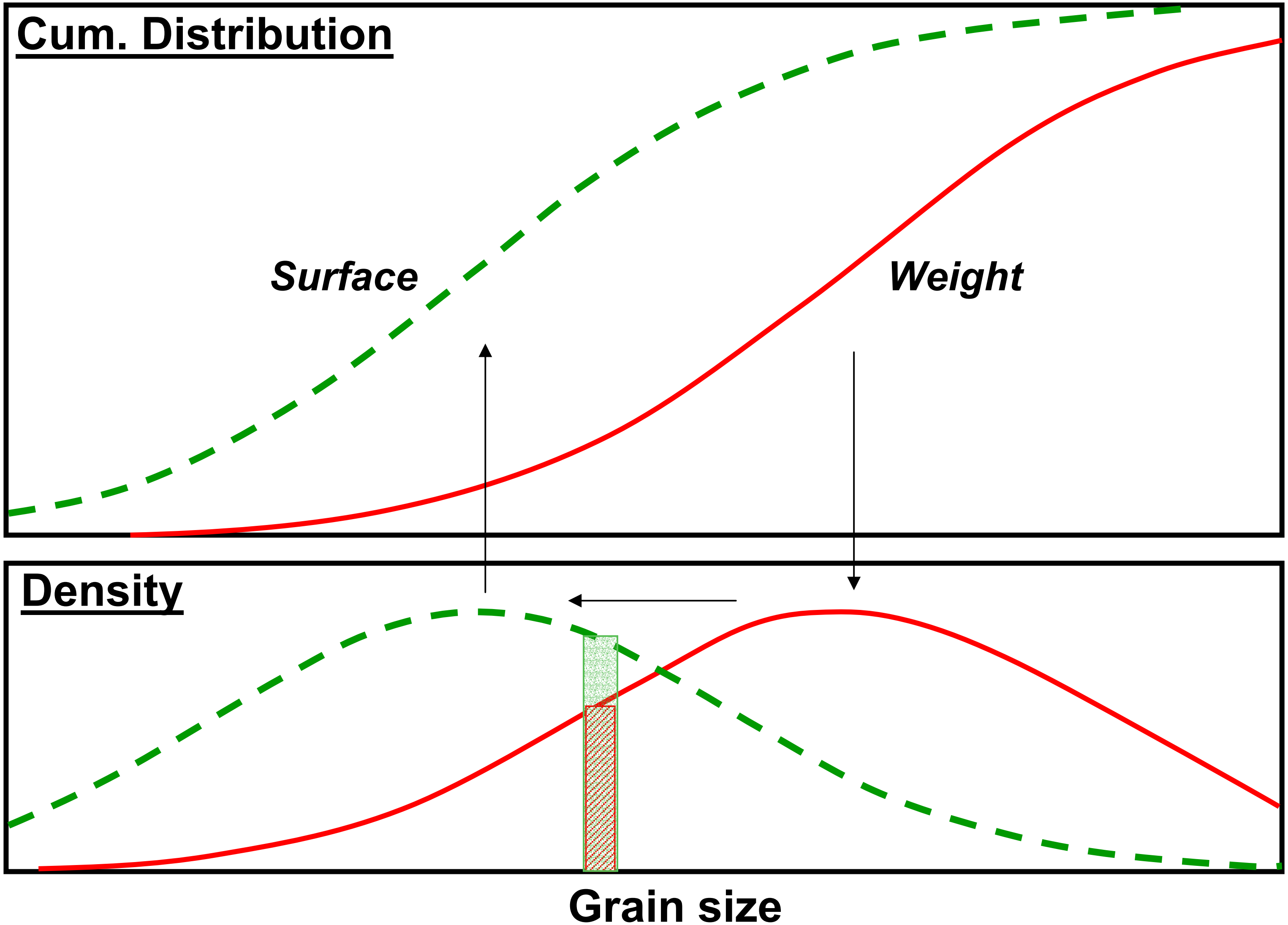


Disk particles

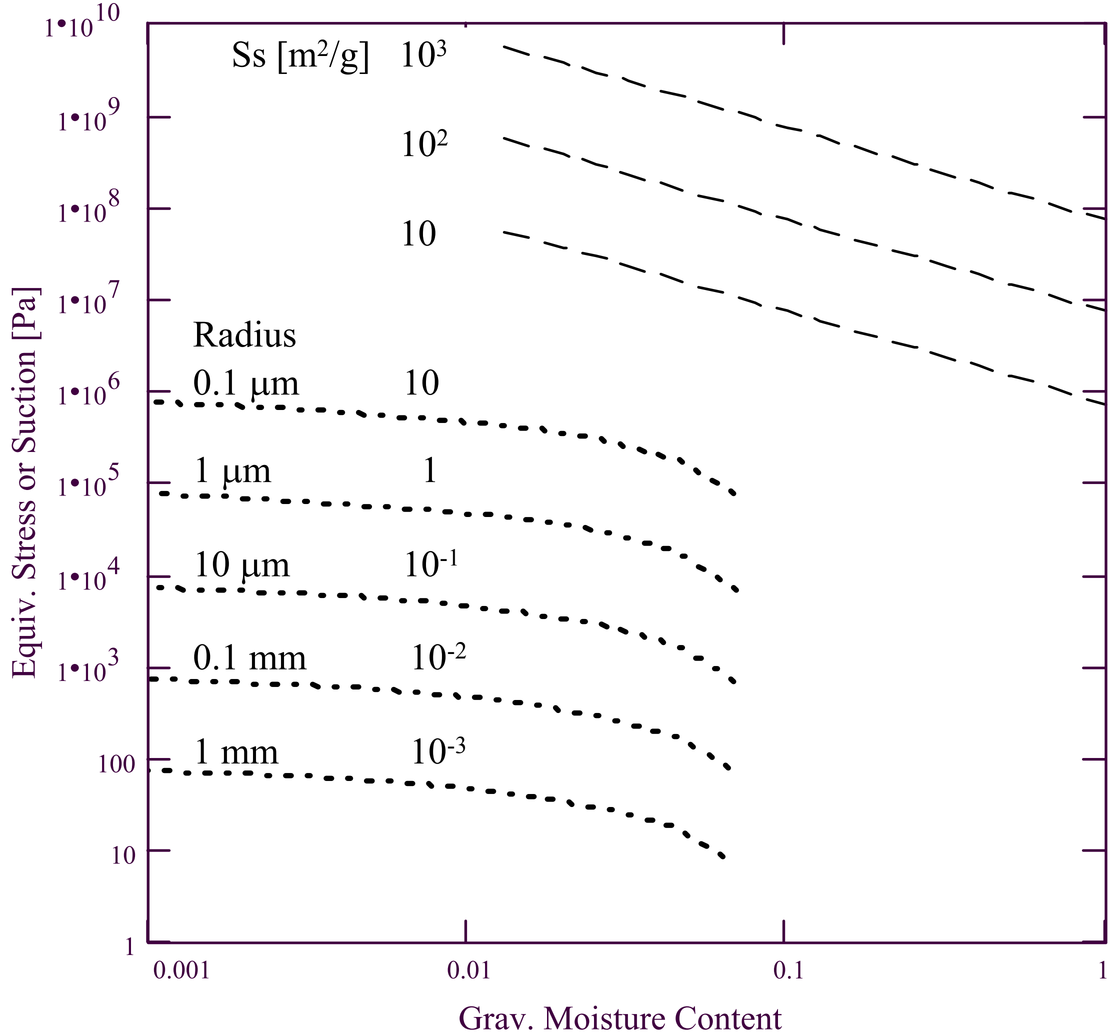




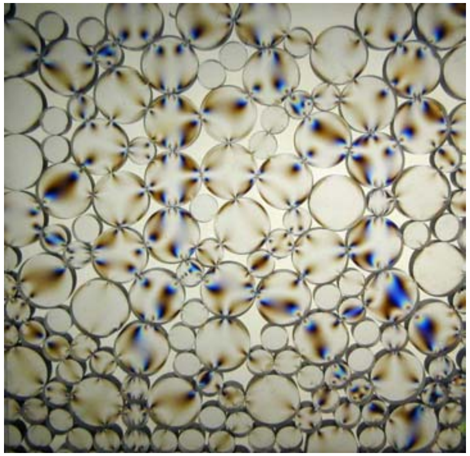
Size and Surface - Surface Phenomena

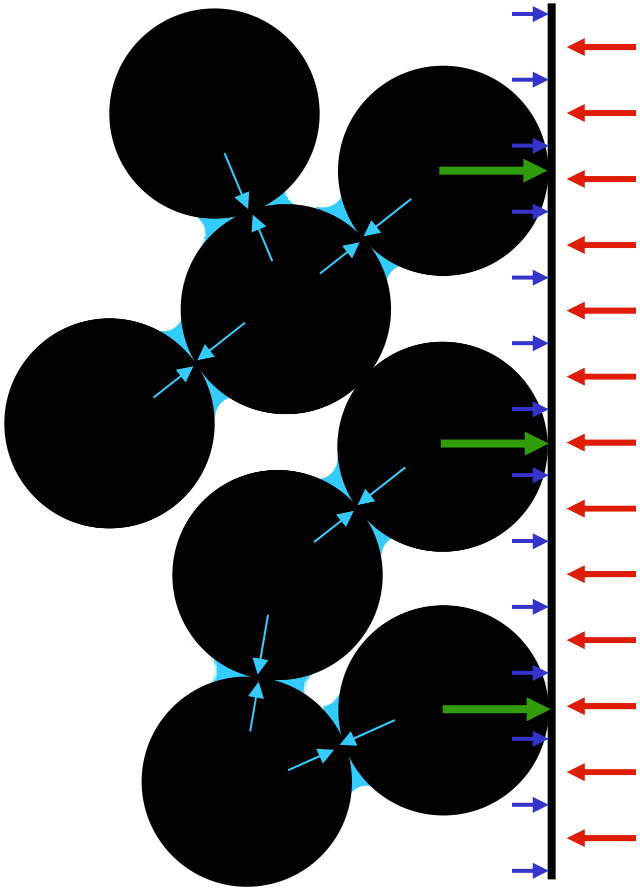


Capillary forces



Effective stress …where?

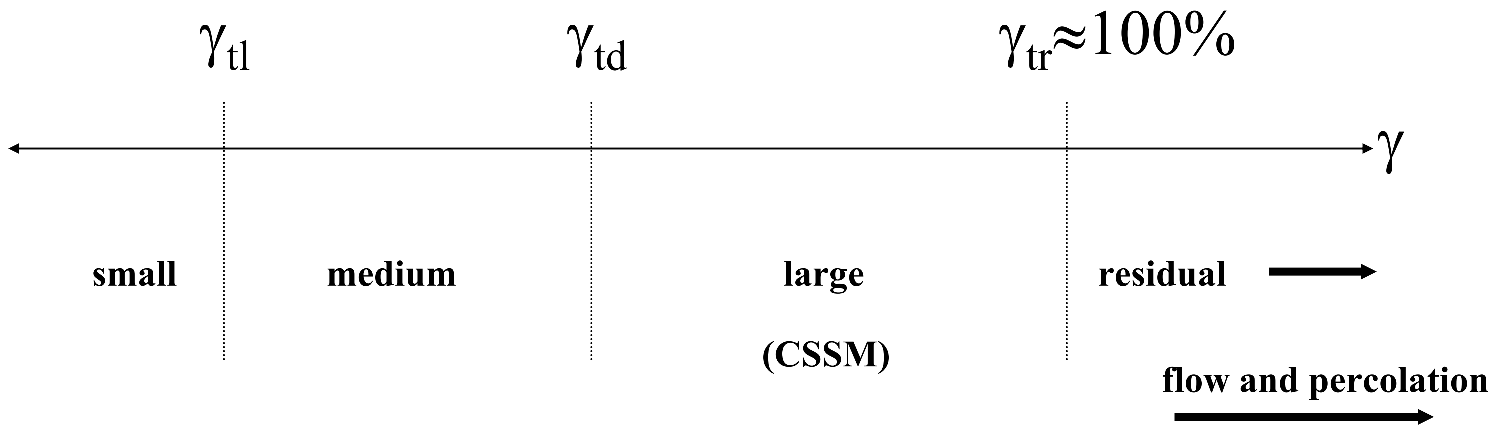




$\sigma' + u = \sigma$

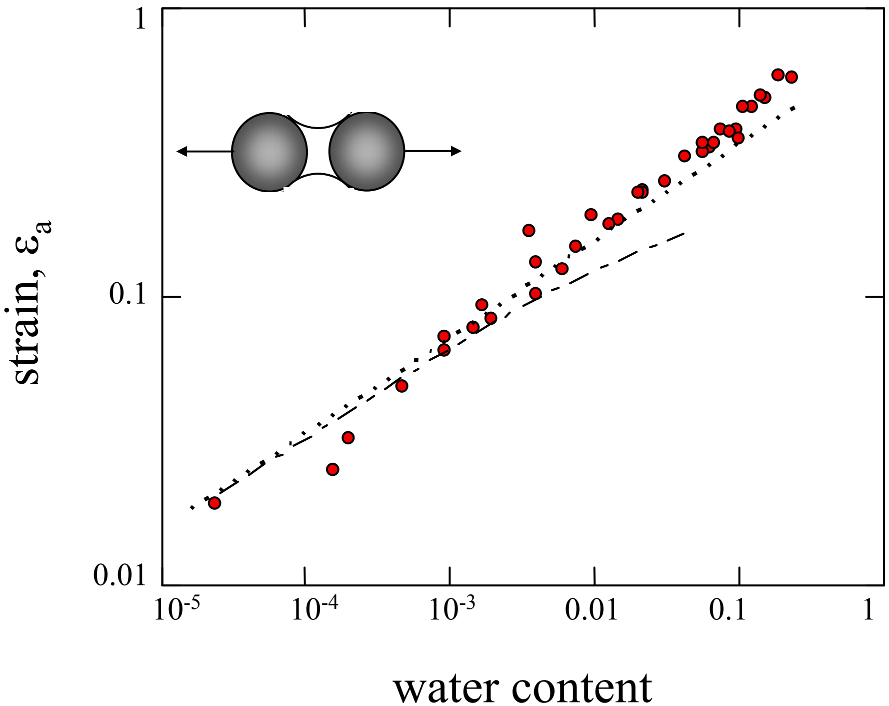
STRAIN REGIMES

Strain regimes

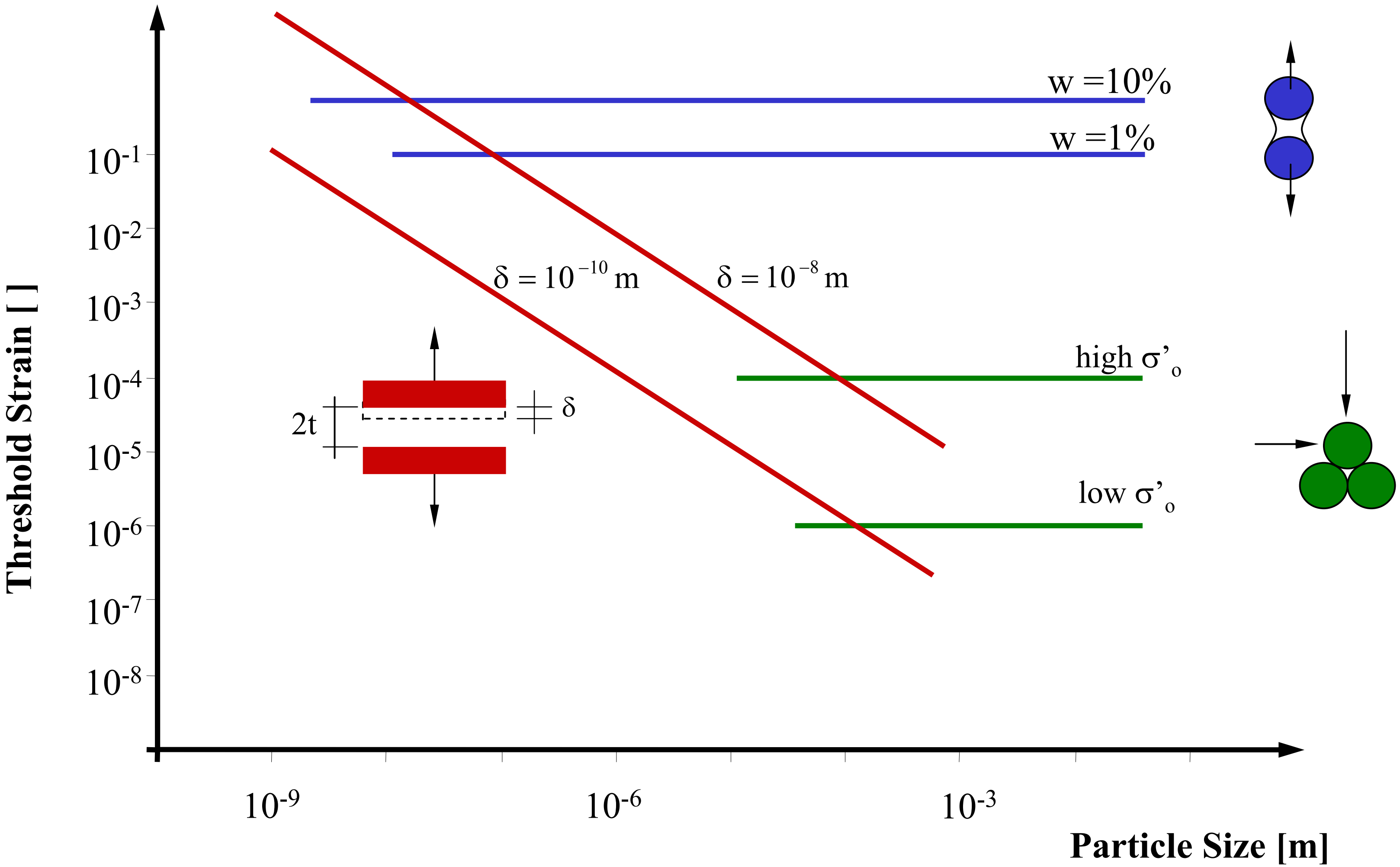


Inter.displacem.$< \approx 10^{-10}$ m	Inter. displacement $< \approx \vartheta$	Change in neighbors	Particle alignment (*platy particles*)
Preserves molecular bonds	Neighbors preserved	Destruction initial fabric	Minimum drained shear strength
Very small energy losses	Minor fabric changes	Δu (undrain ΔVol (drain)	Minimum drained shear strength
		High energy losses	Strain localization

Threshold strain for menisci failure

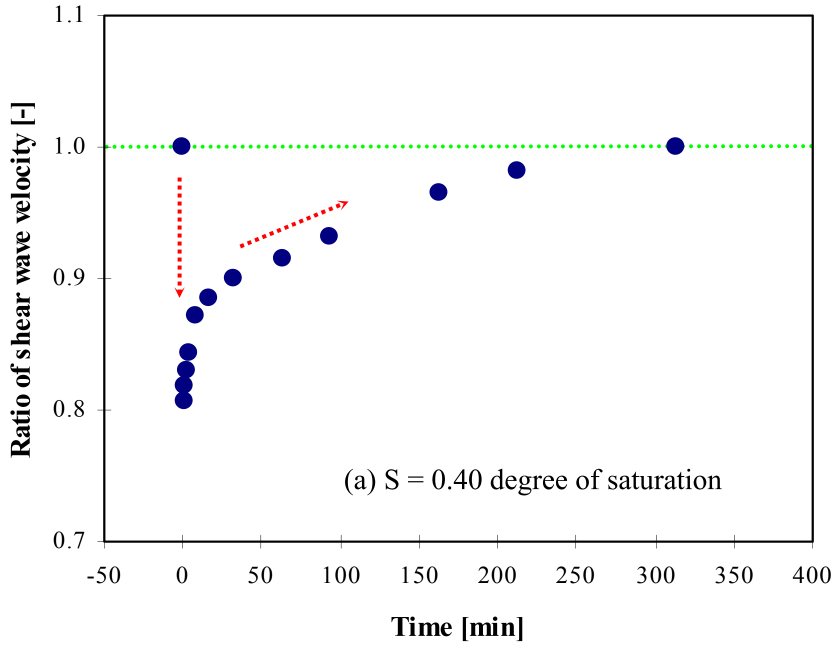


Threshold strains - Ranges



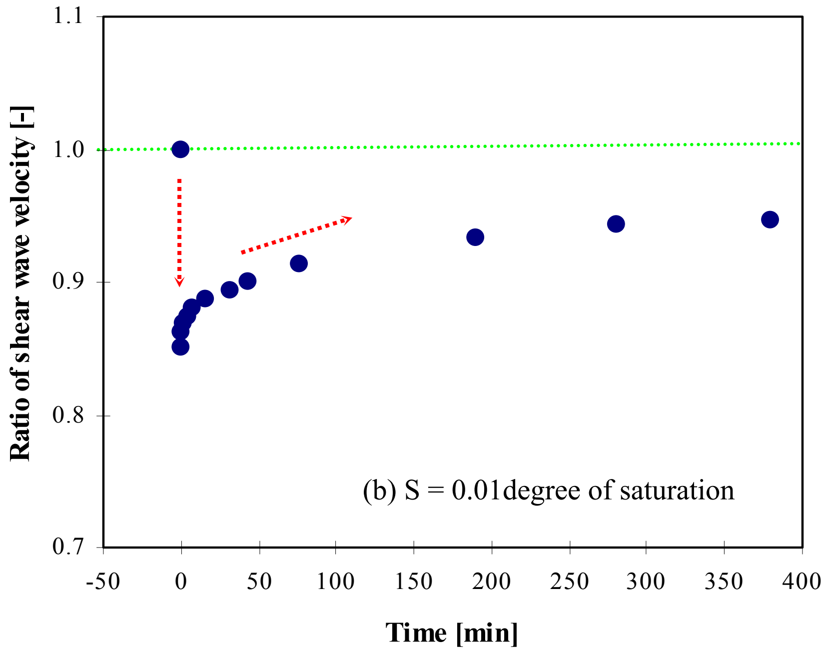
Thixotropy

S = 40% (Funicular)



By pressure diffusion

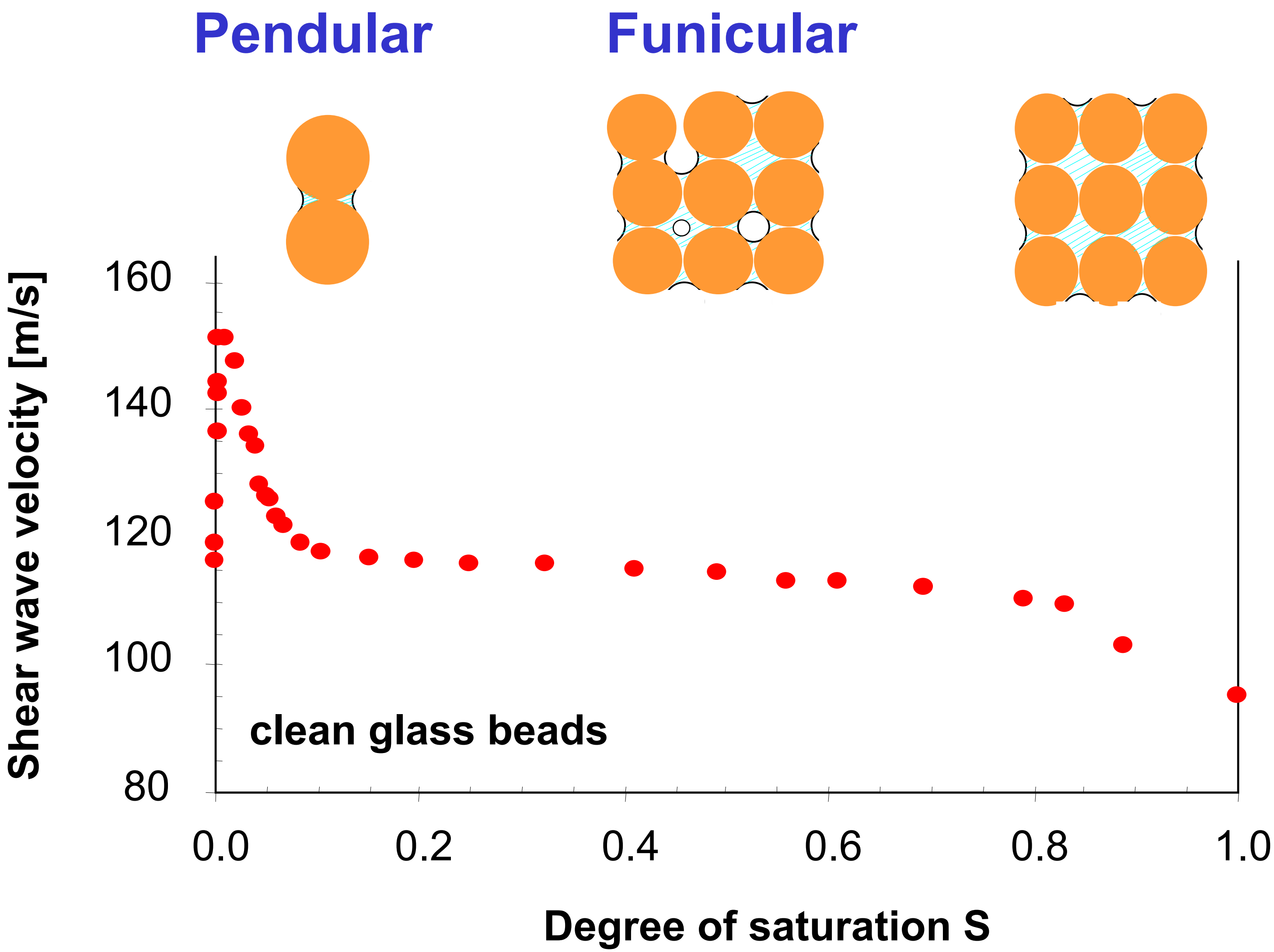
S = 1% (Pendular)



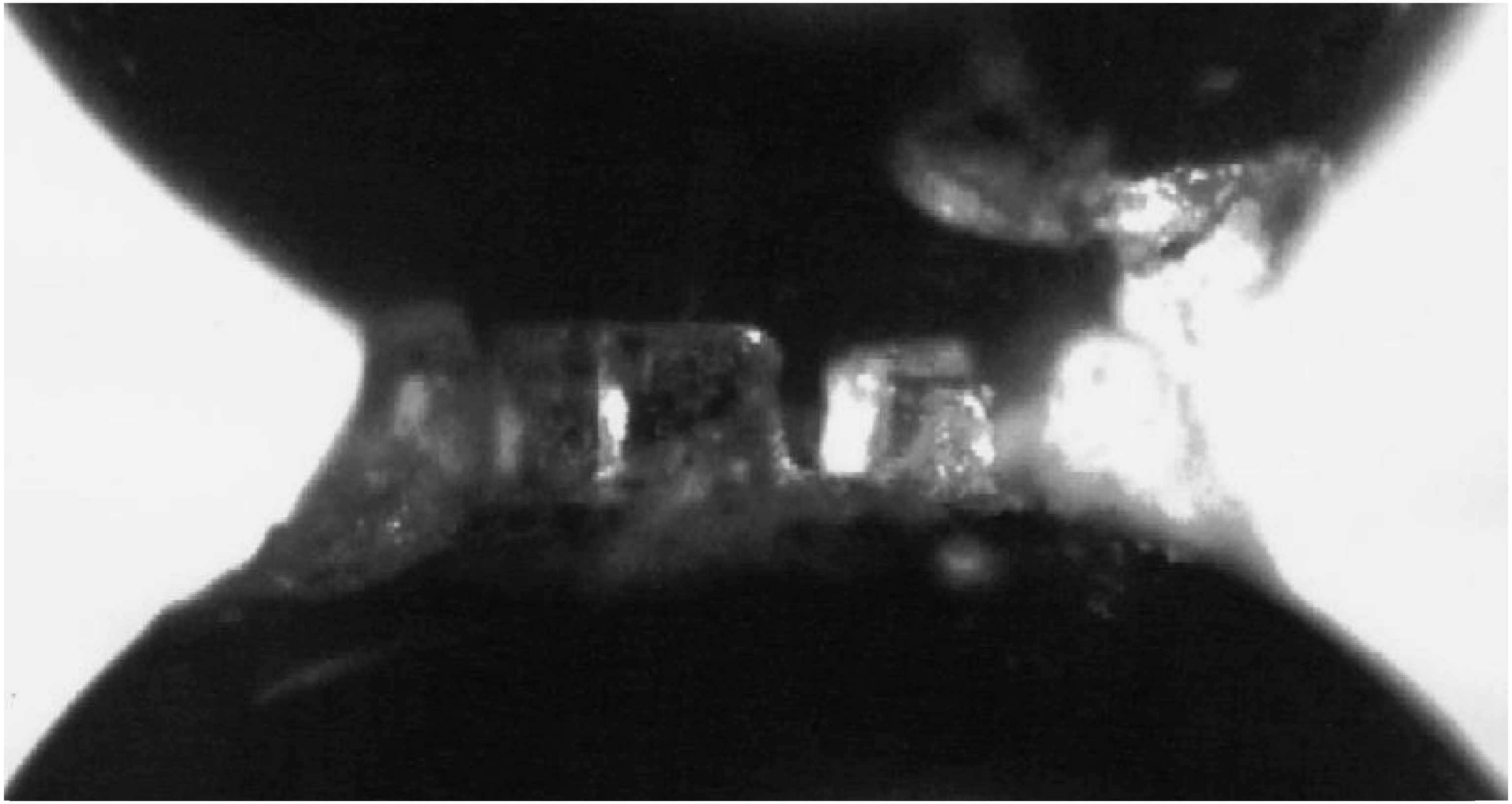
Through vapor pressure

SMALL-STRAIN SKELETAL STIFFNESS

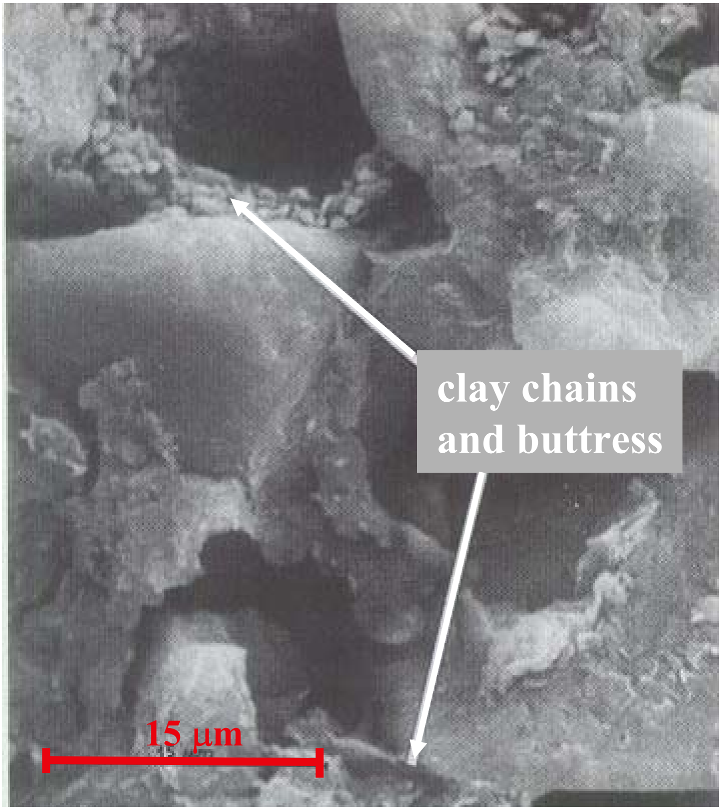
Drying – Unsaturated media

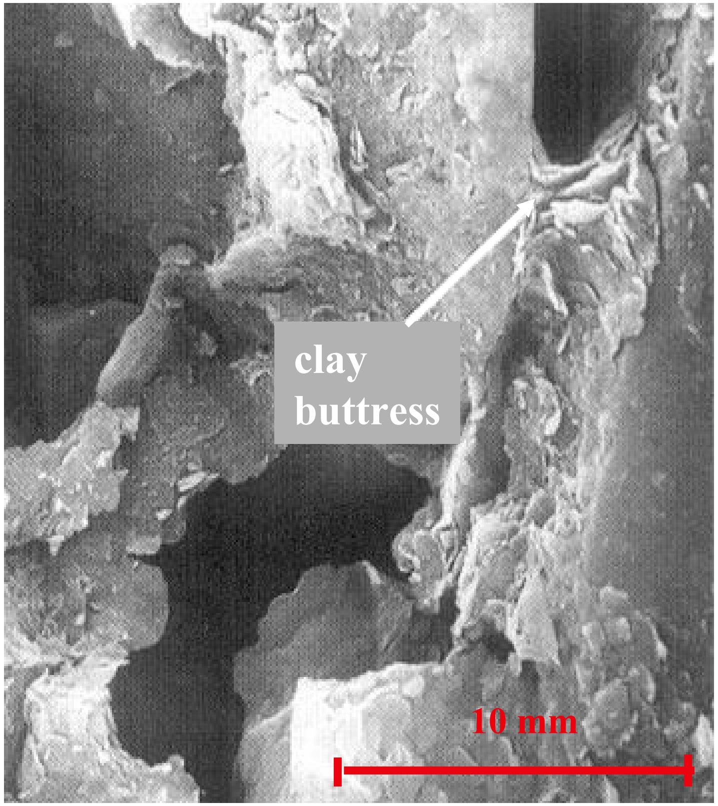


Inter-particle capillary forces



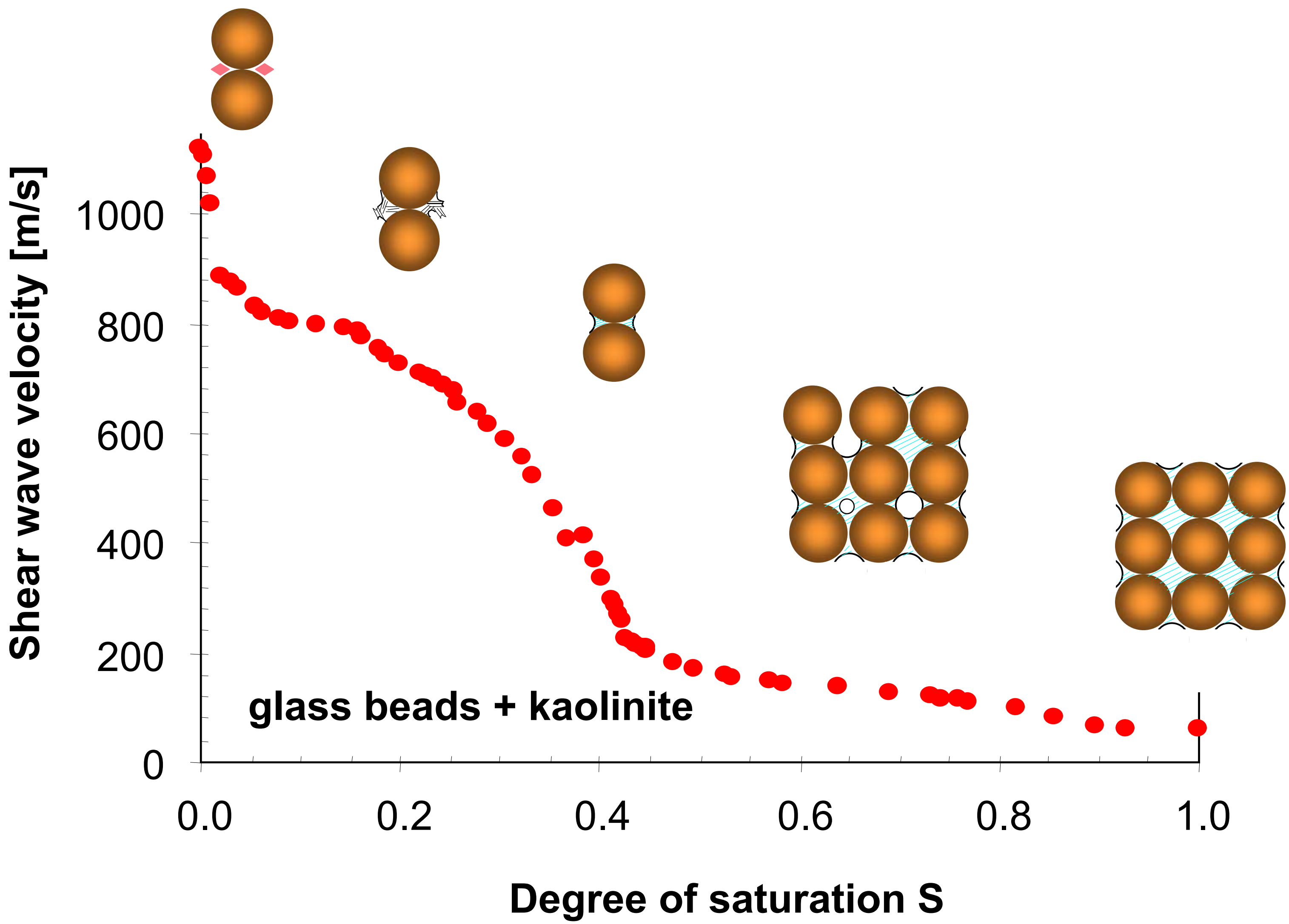
Loess





(*Grabowska-Olszewska*)

Drying – Unsaturated media



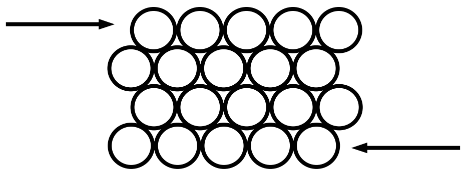
STRAIN LOCALIZATION

Case: Dilative drained

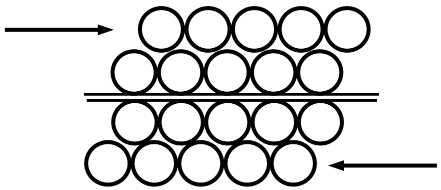
Soil: Sandboil sand

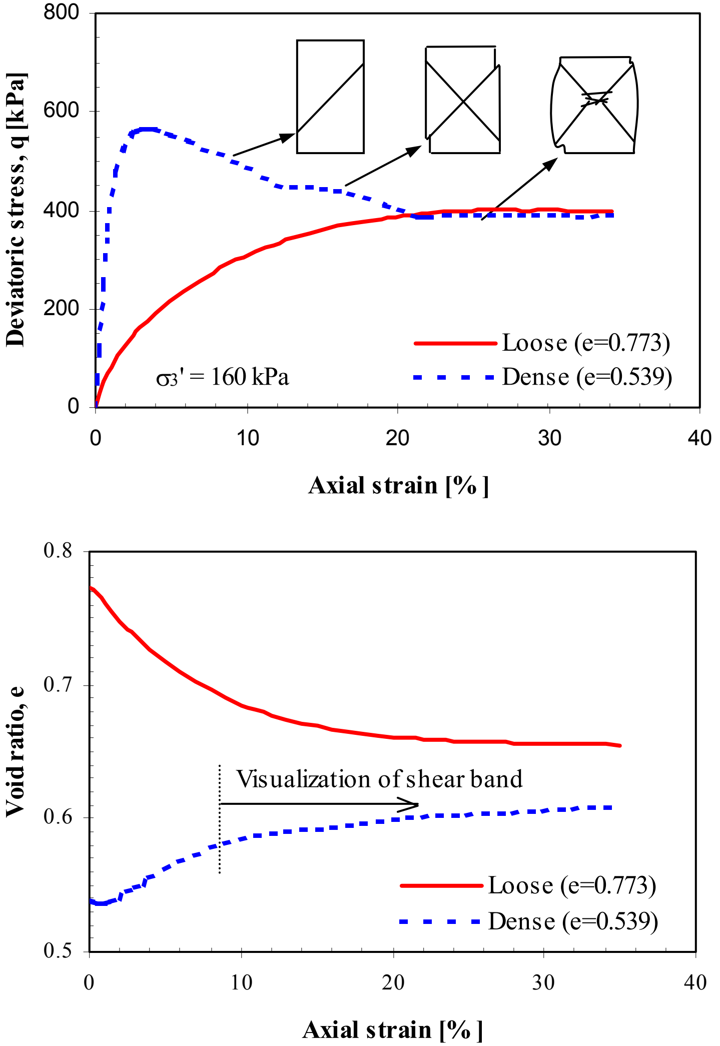
Mechanism: Dilatancy, buckling

- Initial



- Intermediate



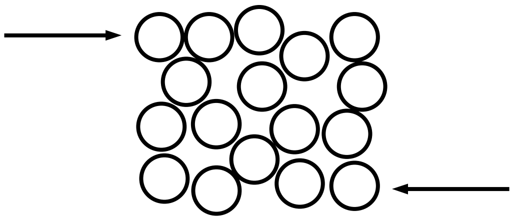


Case: Contractive undrained

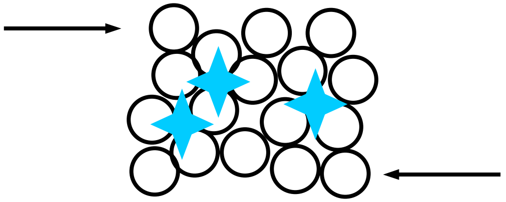
Soil: Ottawa 20-30 sand

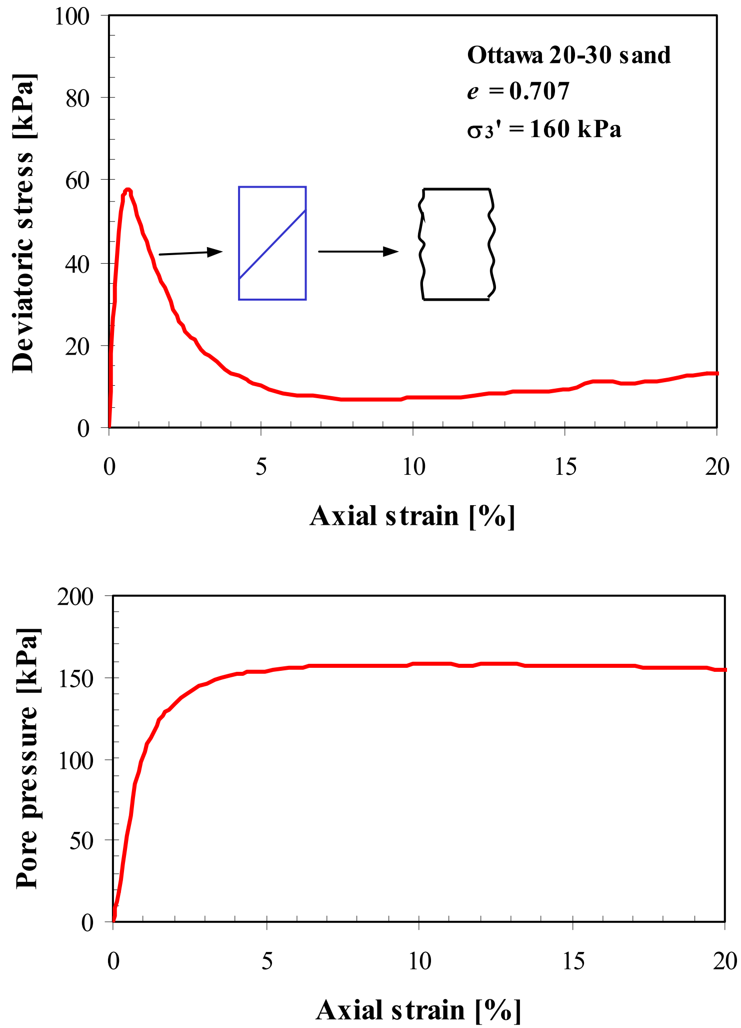
Mechanism: Irregular high u_w

- Initial



- Intermediate

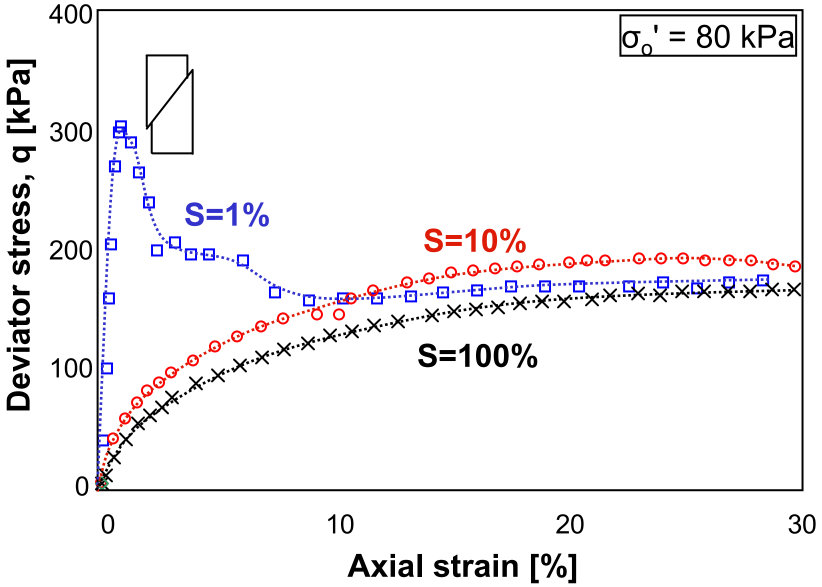


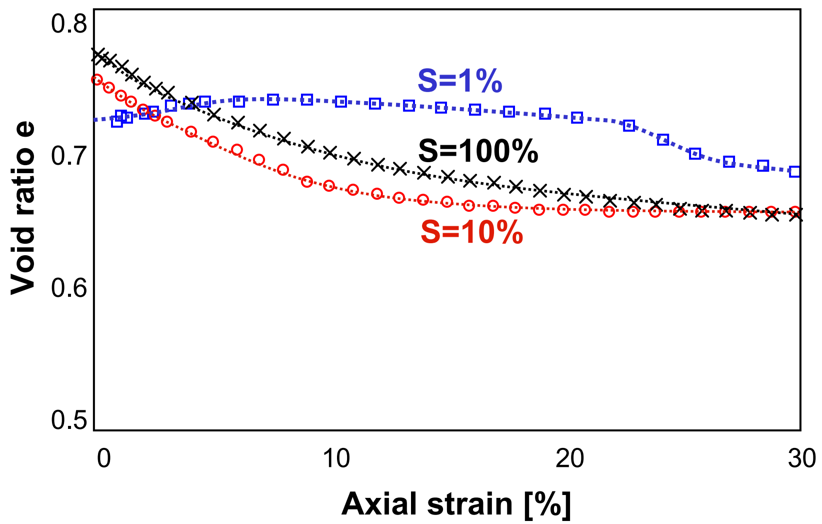


Case: Unsaturated soil

Soil: **90% Ottawa F110**
10% kaolin

Preparation:
moist-tamped (loose)
saturation
air percolation (until target S%)

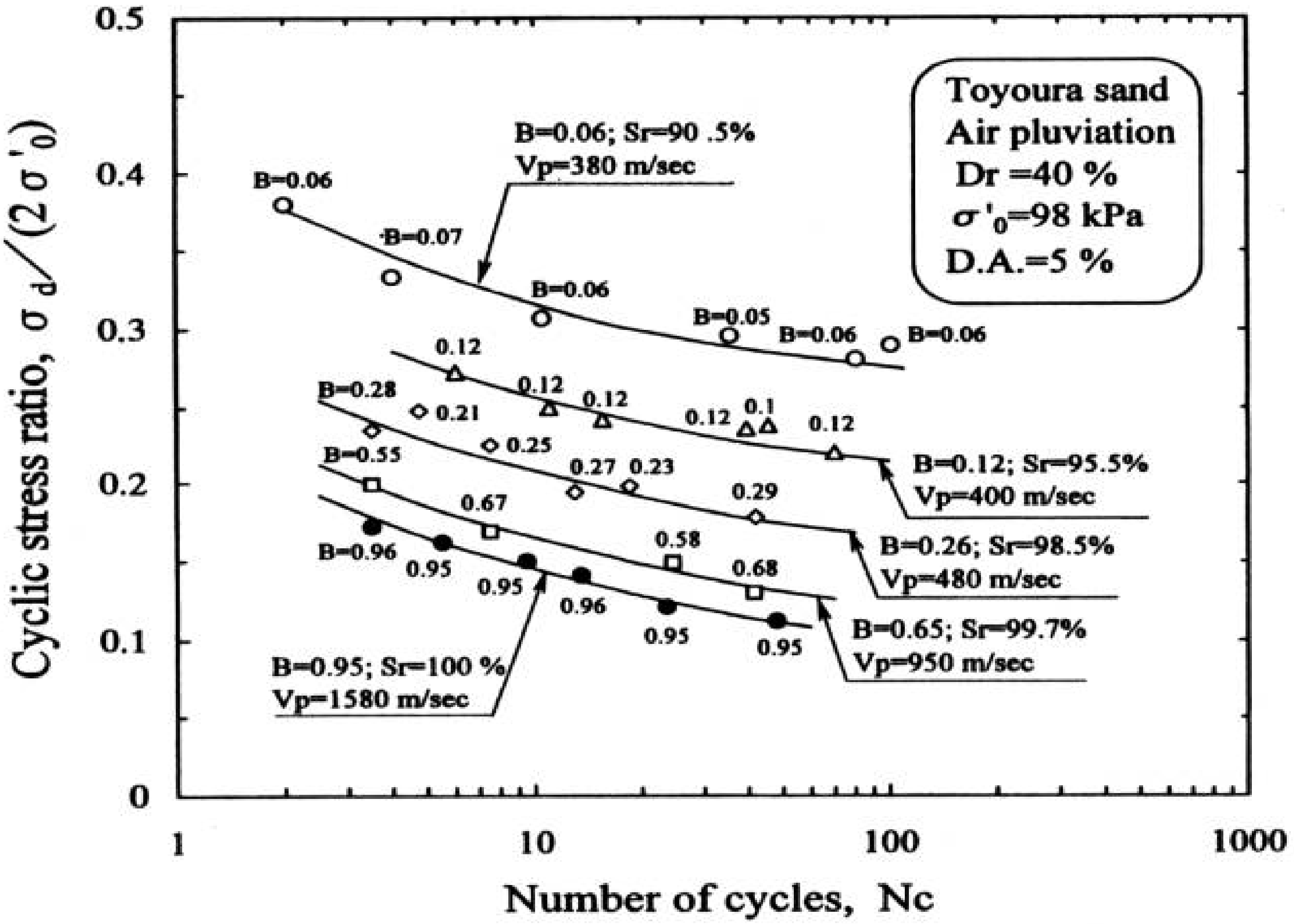




LIQUEFACTION

P-Waves: Saturation

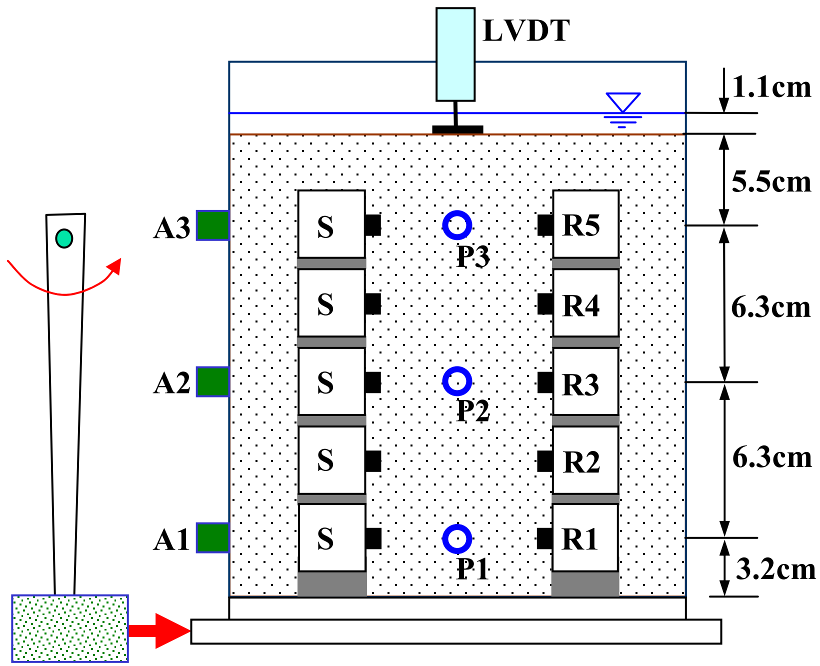
$$B_{mix} = \sqrt{\frac{\left(B_{sk} + \frac{4}{3}G_{sk}\right) + \left[n\left(\frac{S}{B_w} + \frac{1-S}{B_a}\right) + \frac{1-n}{B_g}\right]^{-1}}{(1-n)\rho_g + n S \rho_w}}$$

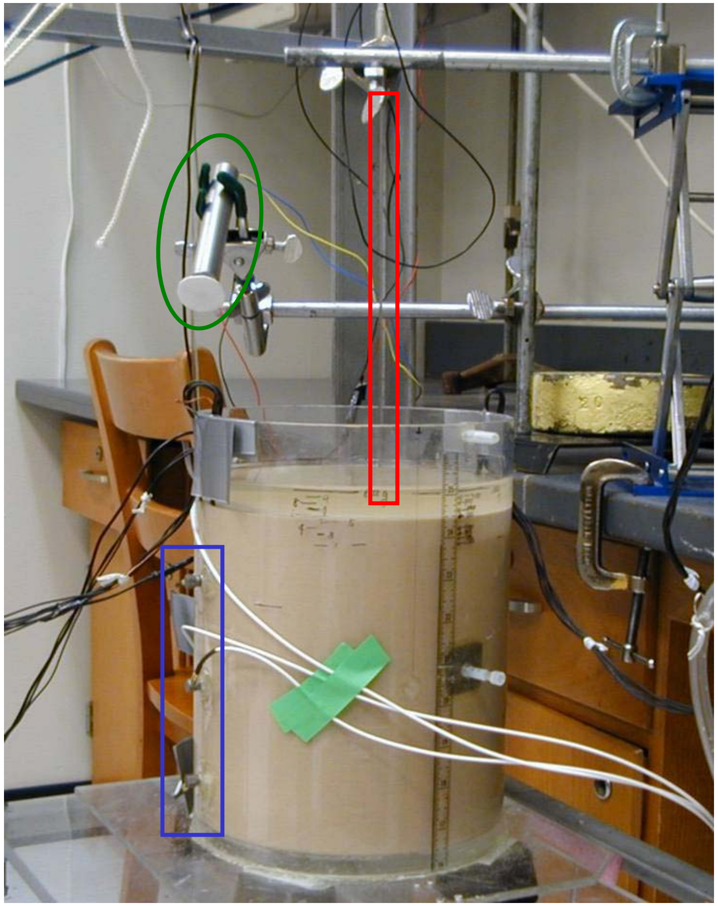


(Ishihara, 1999)

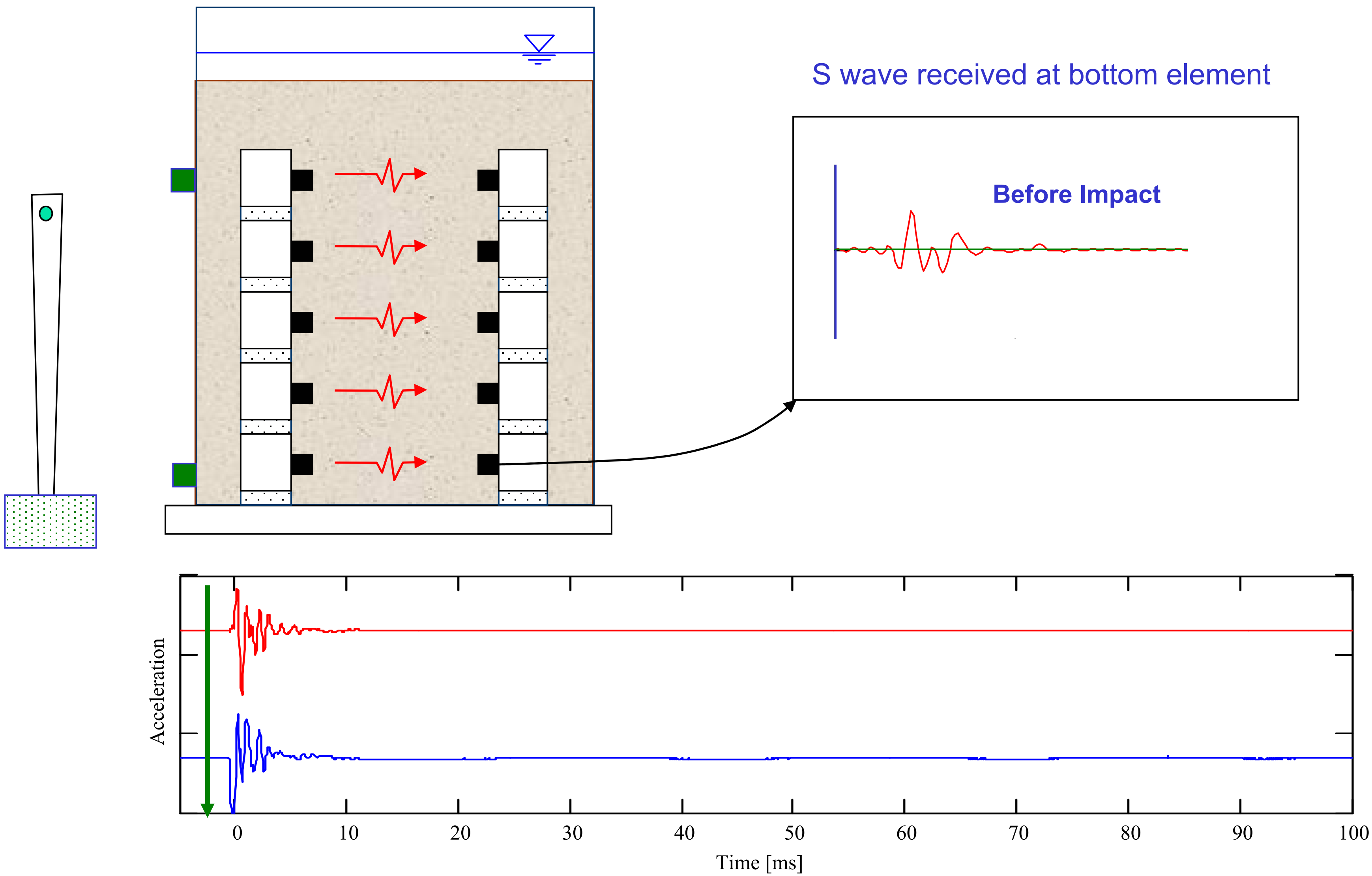
S-Waves: Effective Stress

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

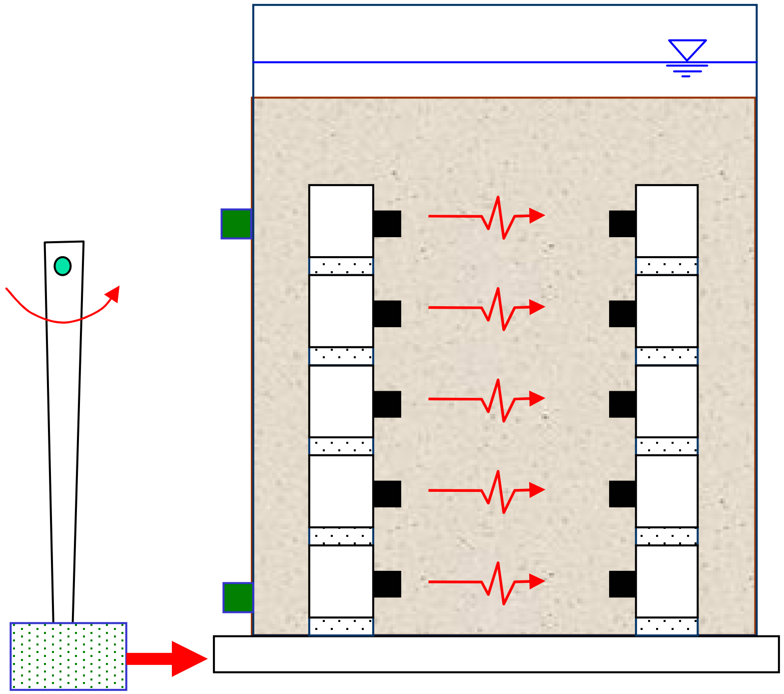




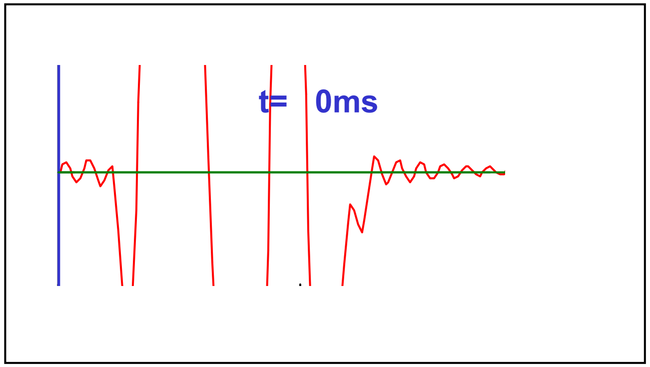
An Impact: S-wave Signature Evolution

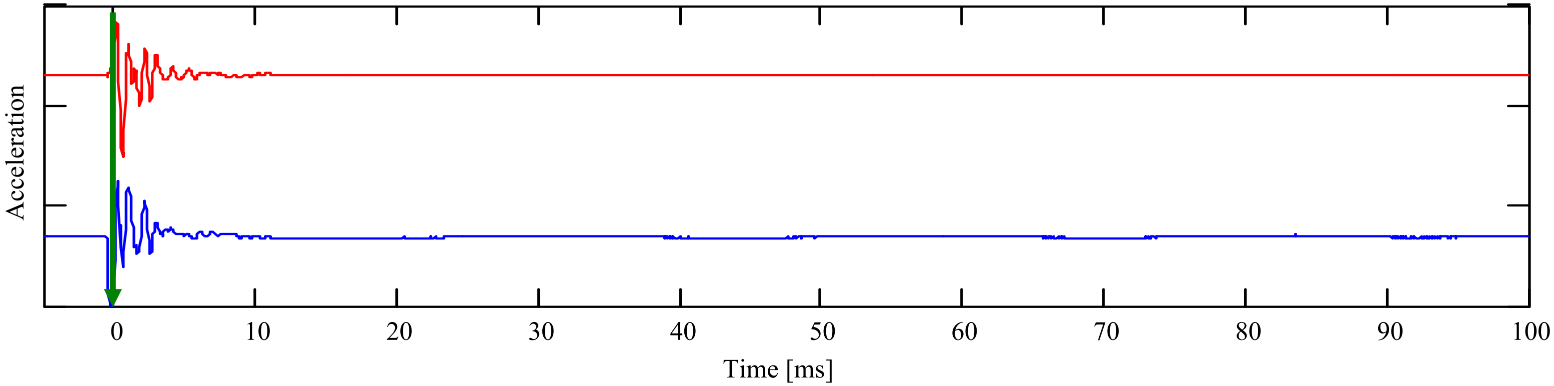


An Impact: S-wave Signature Evolution

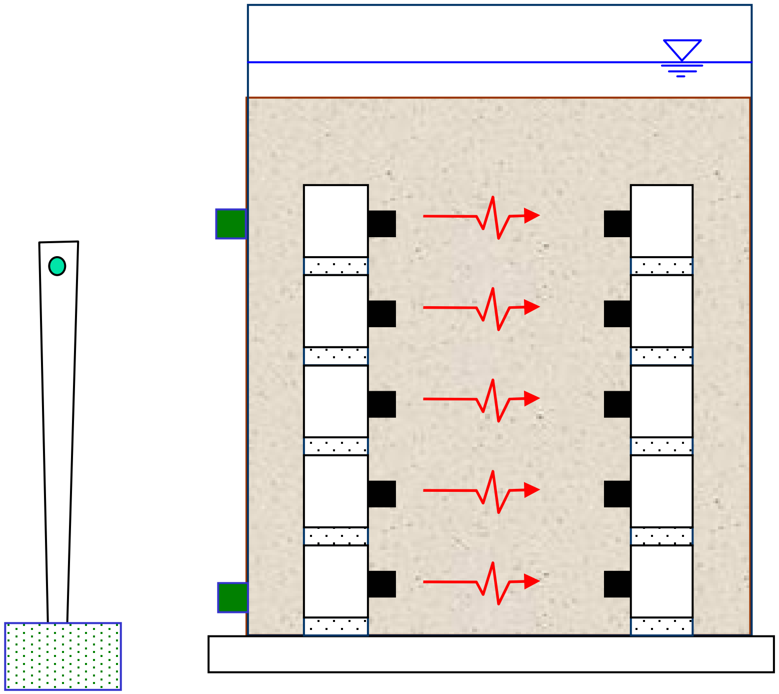


S wave received at bottom element

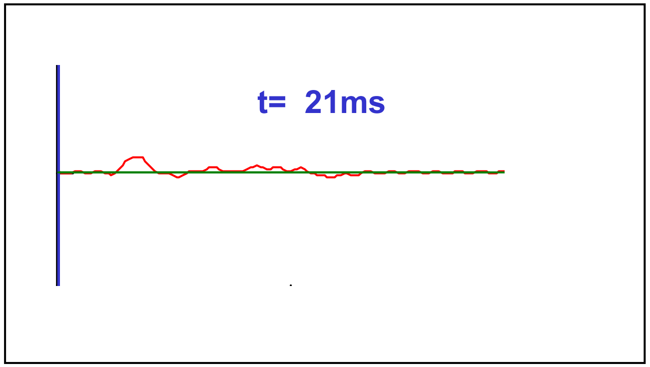


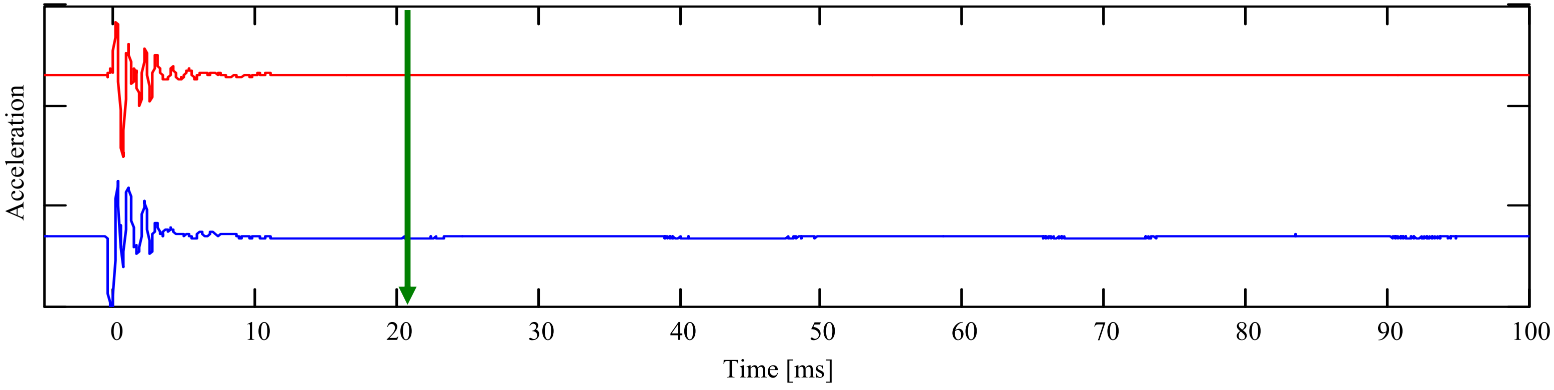


An Impact: S-wave Signature Evolution

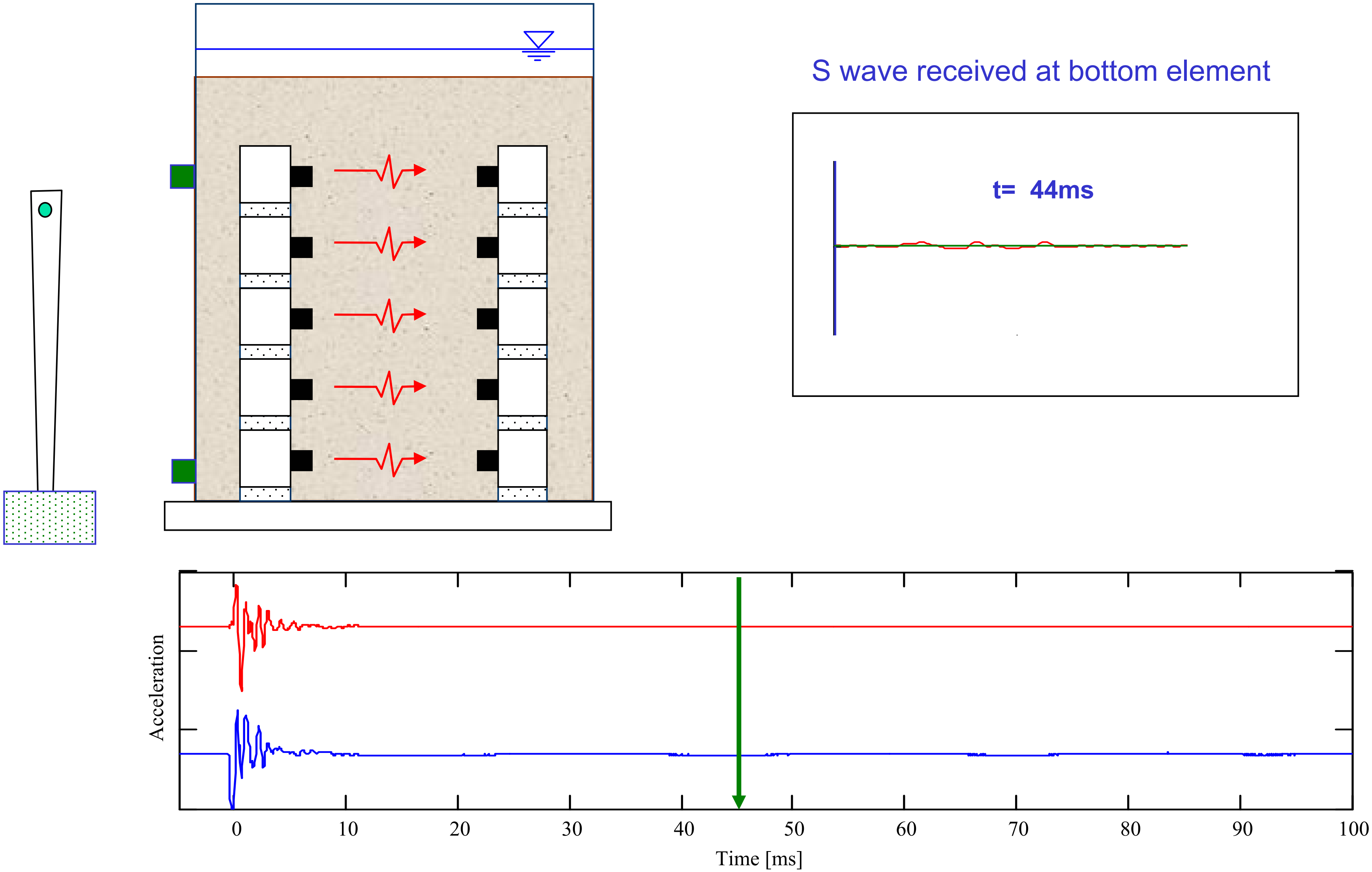


S wave received at bottom element

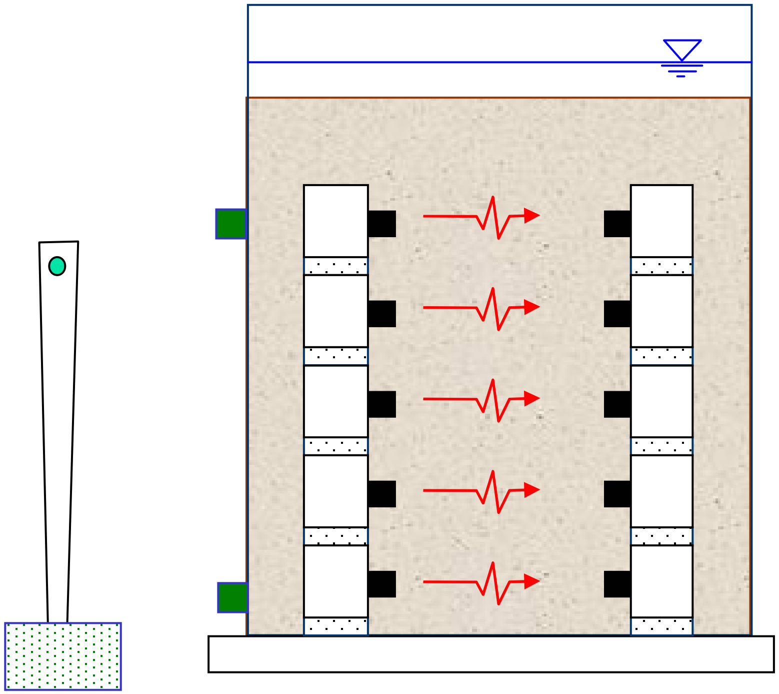




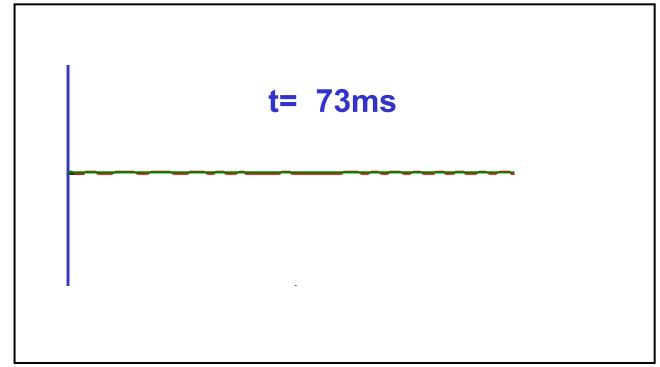
An Impact: S-wave Signature Evolution

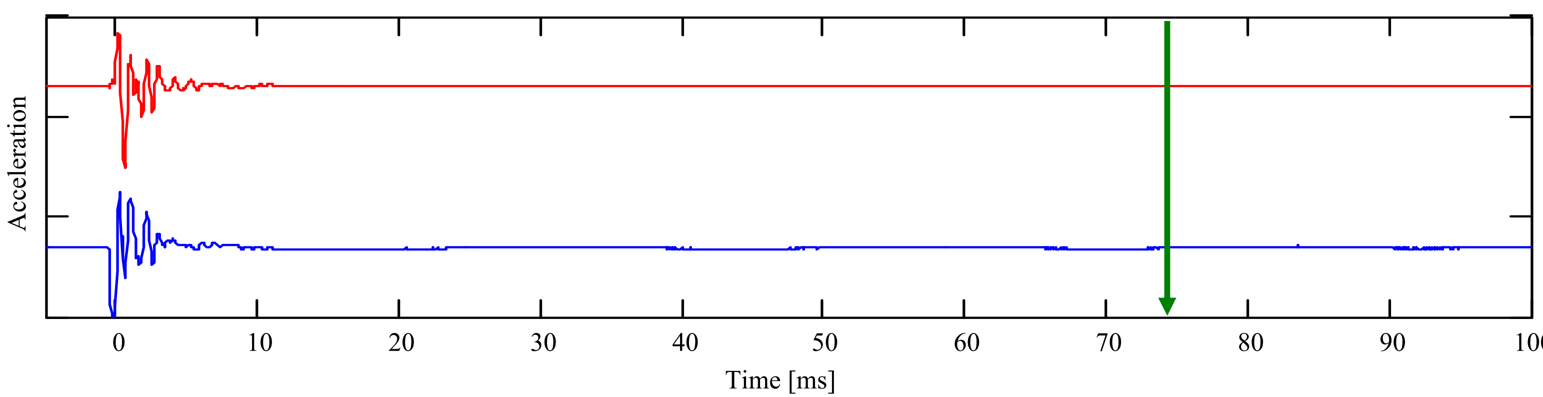


An Impact: S-wave Signature Evolution

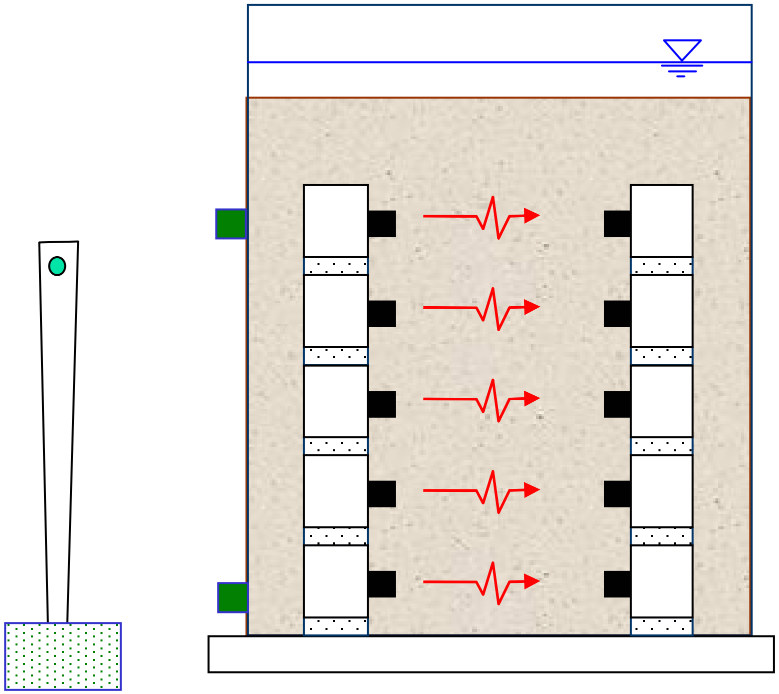


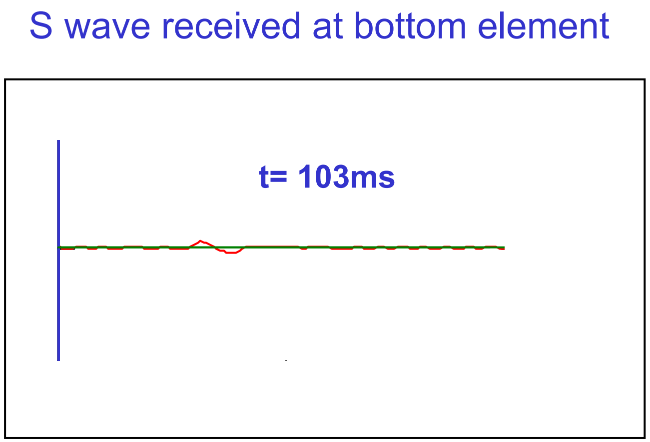
S wave received at bottom element

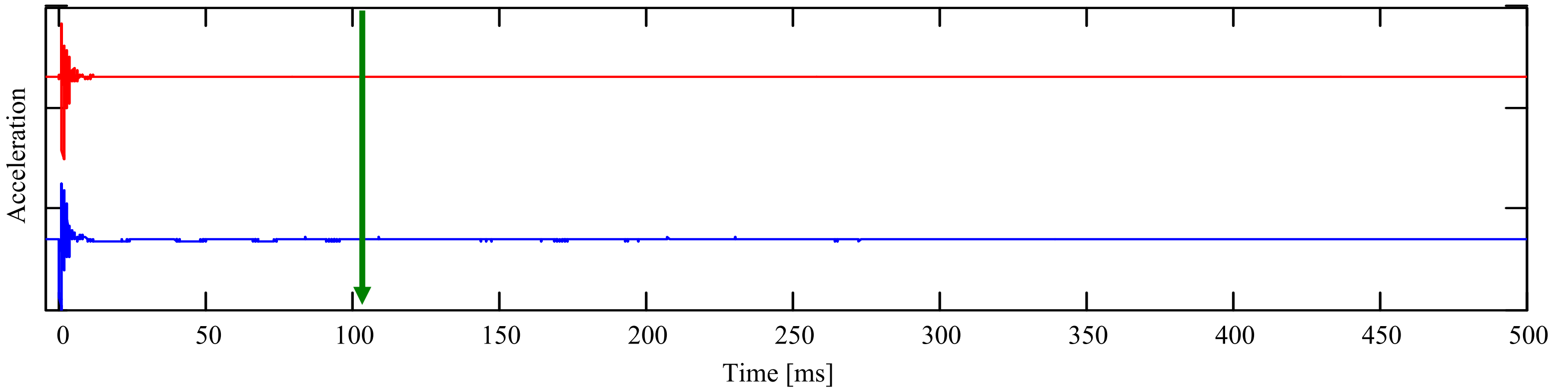




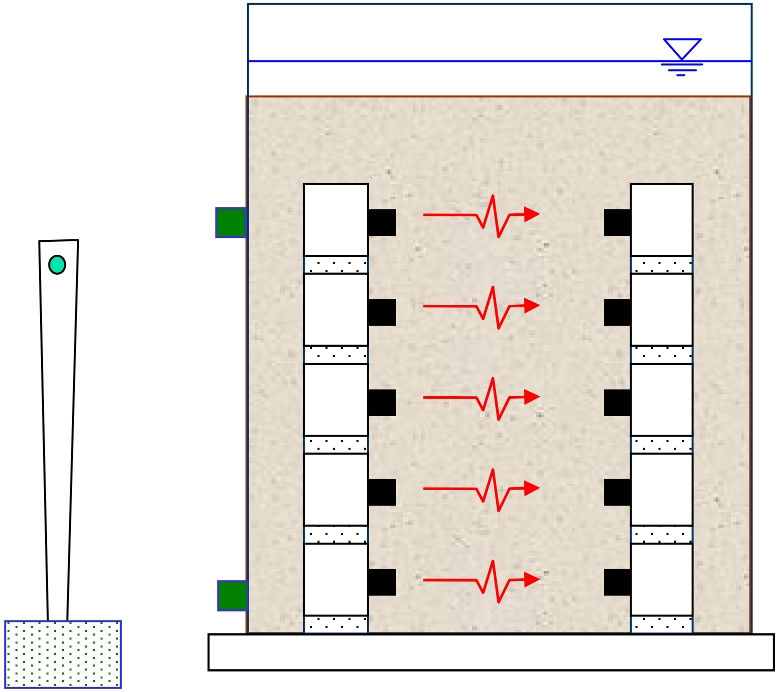
An Impact: S-wave Signature Evolution



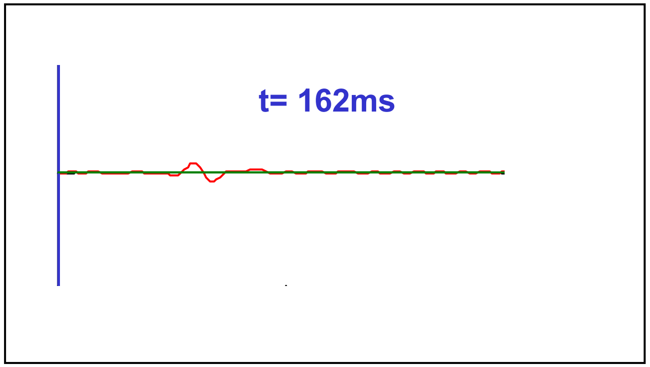


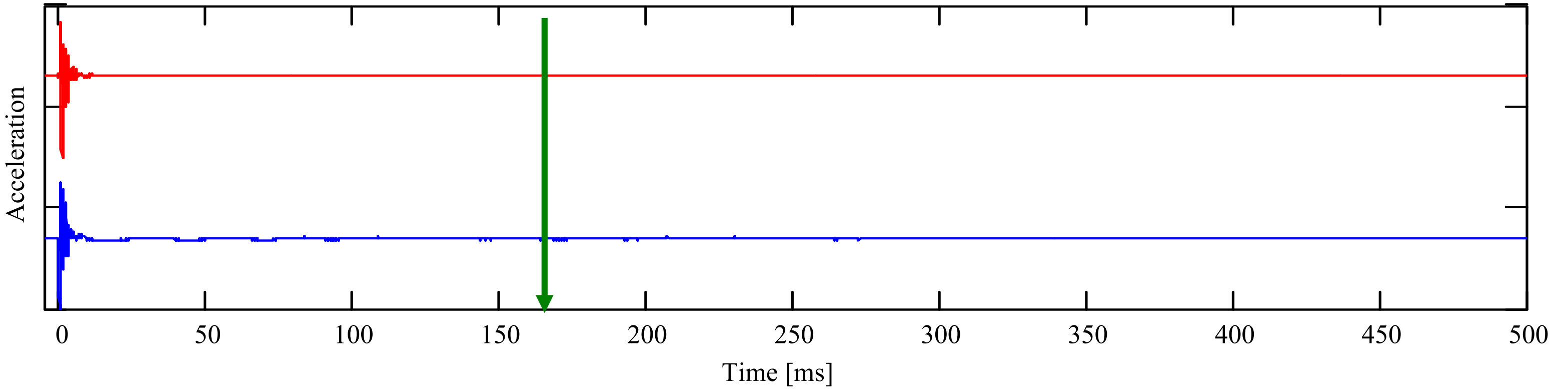


An Impact: S-wave Signature Evolution

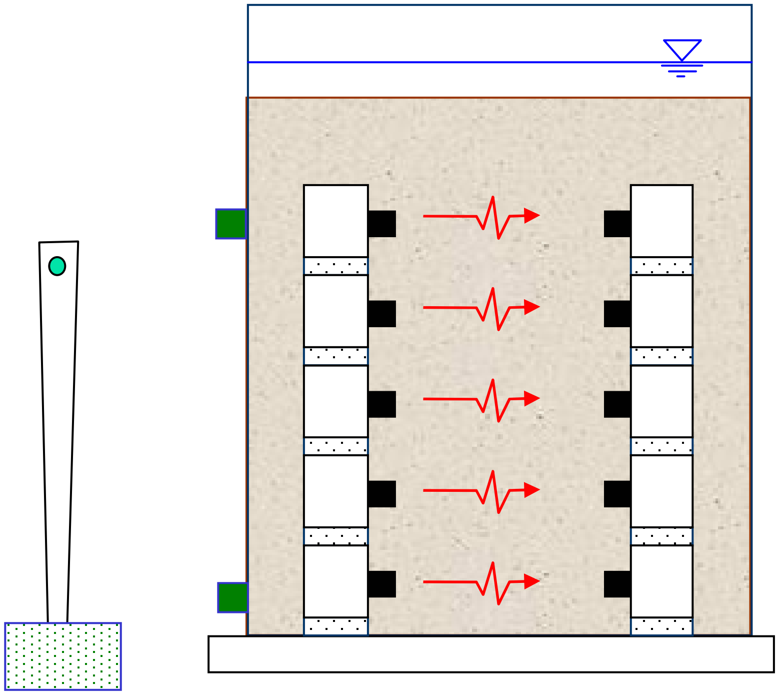


S wave received at bottom element

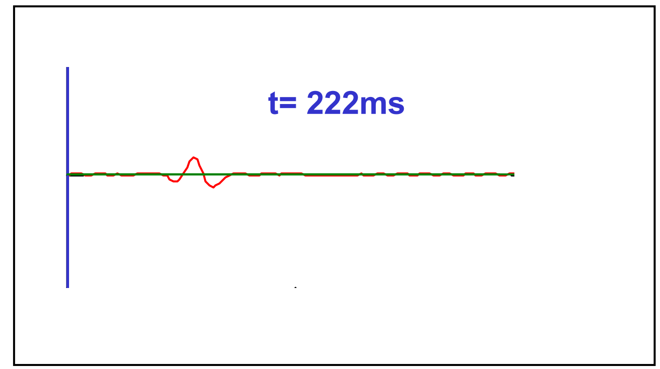


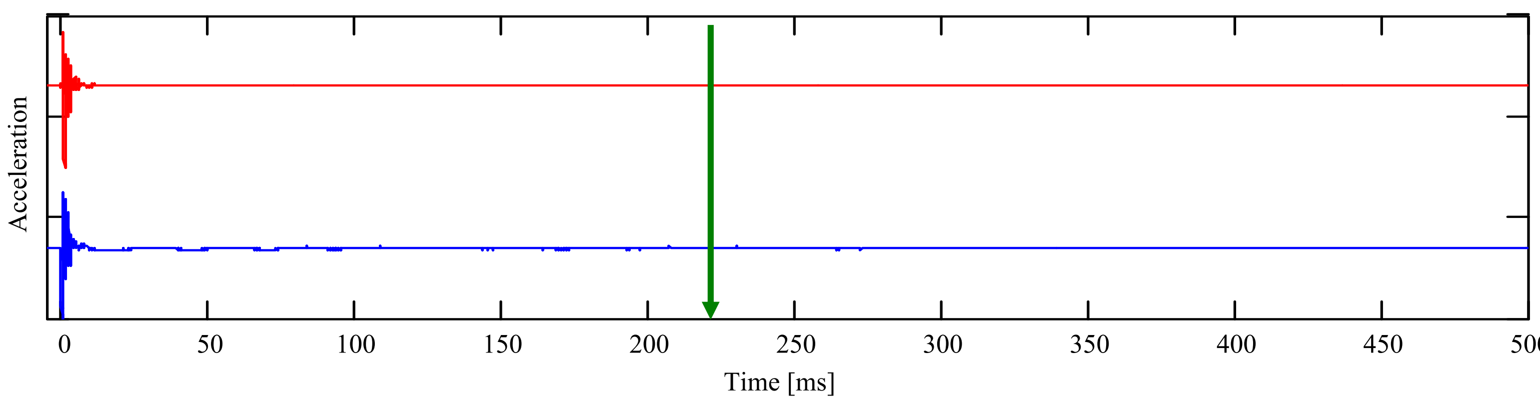


An Impact: S-wave Signature Evolution

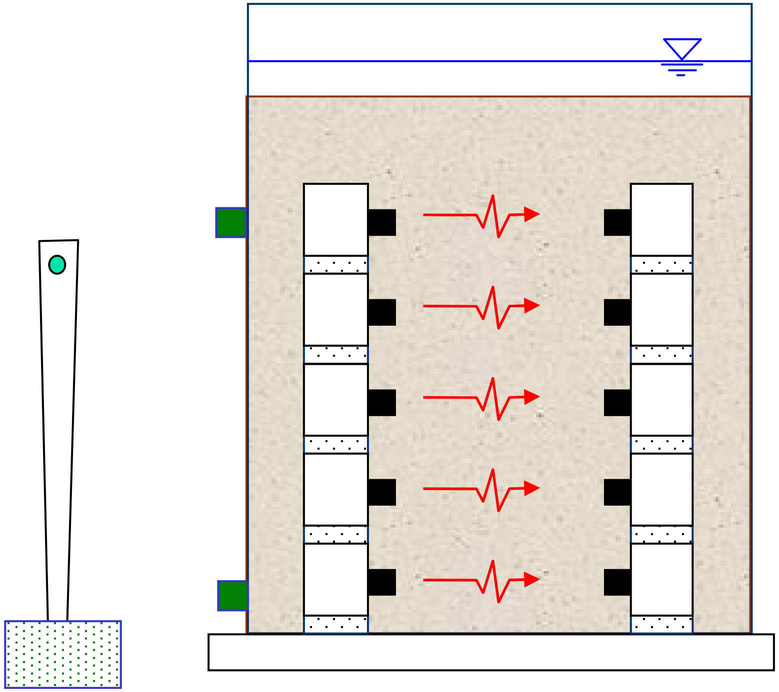


S wave received at bottom element

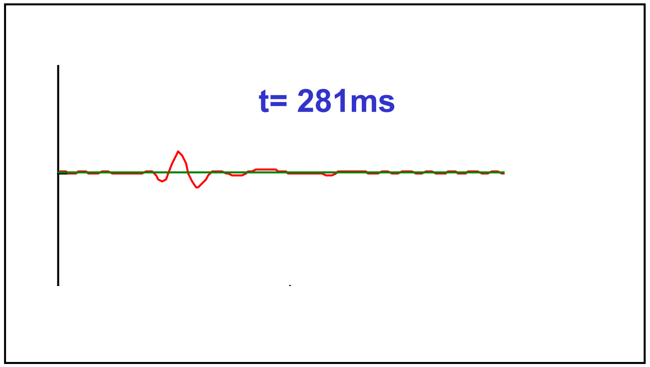


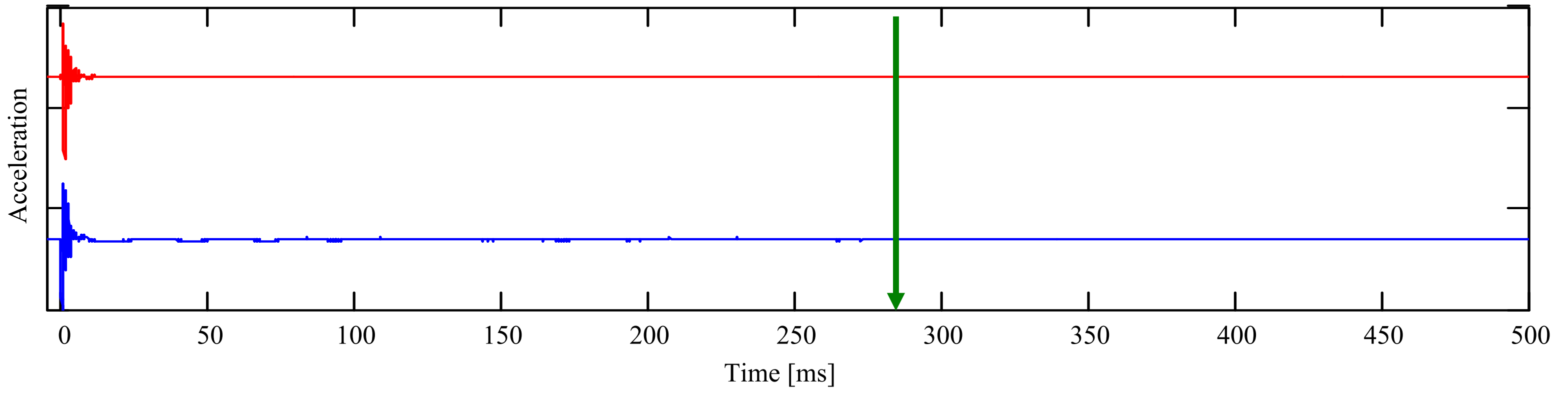


An Impact: S-wave Signature Evolution



S wave received at bottom element





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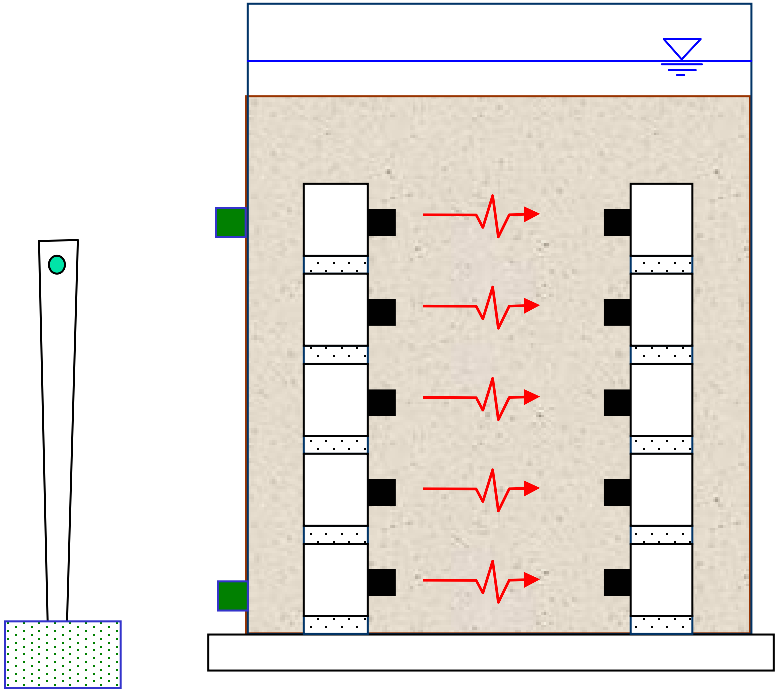
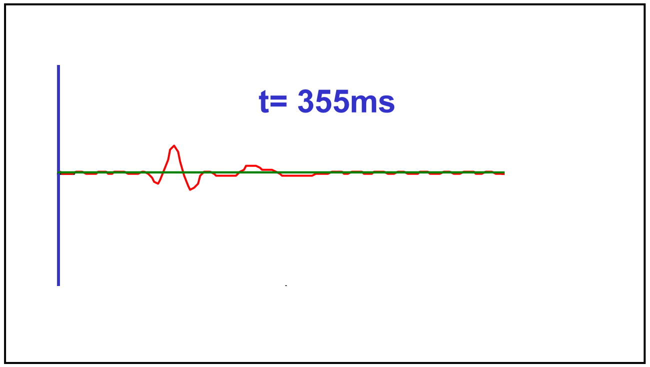
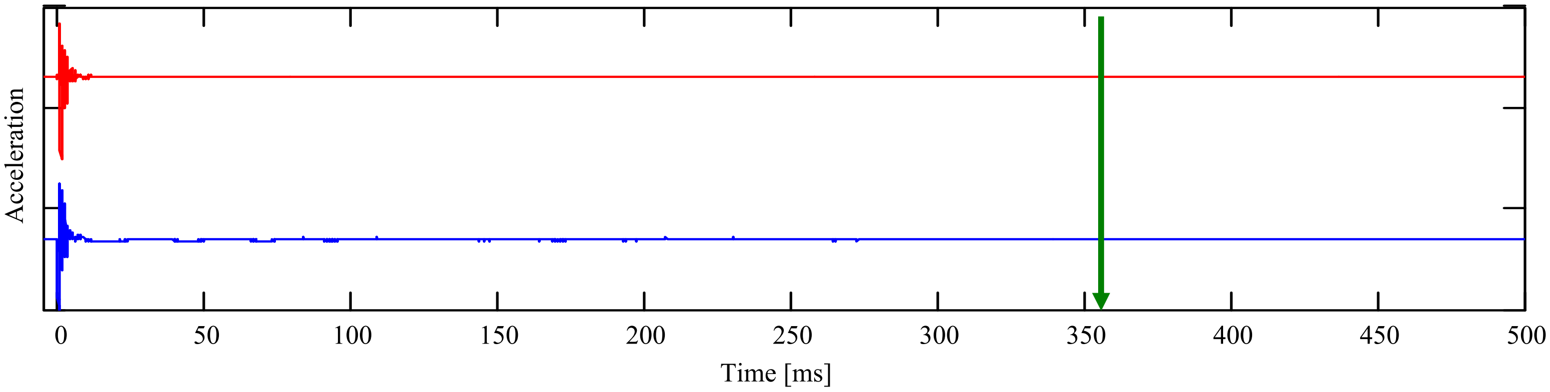
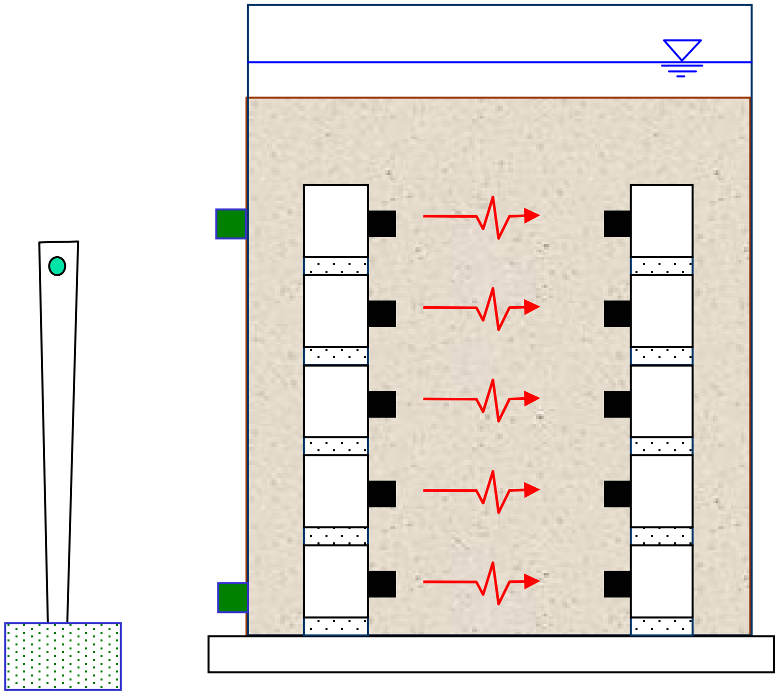
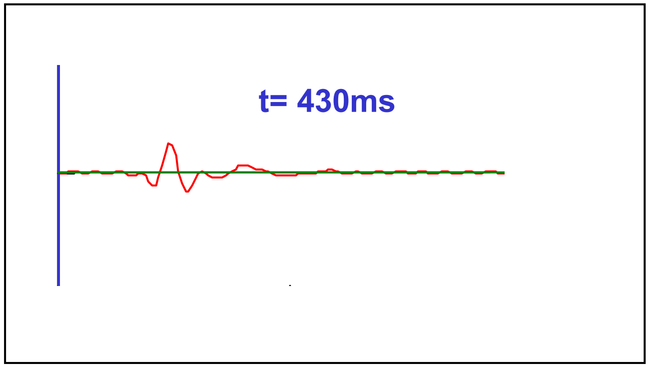


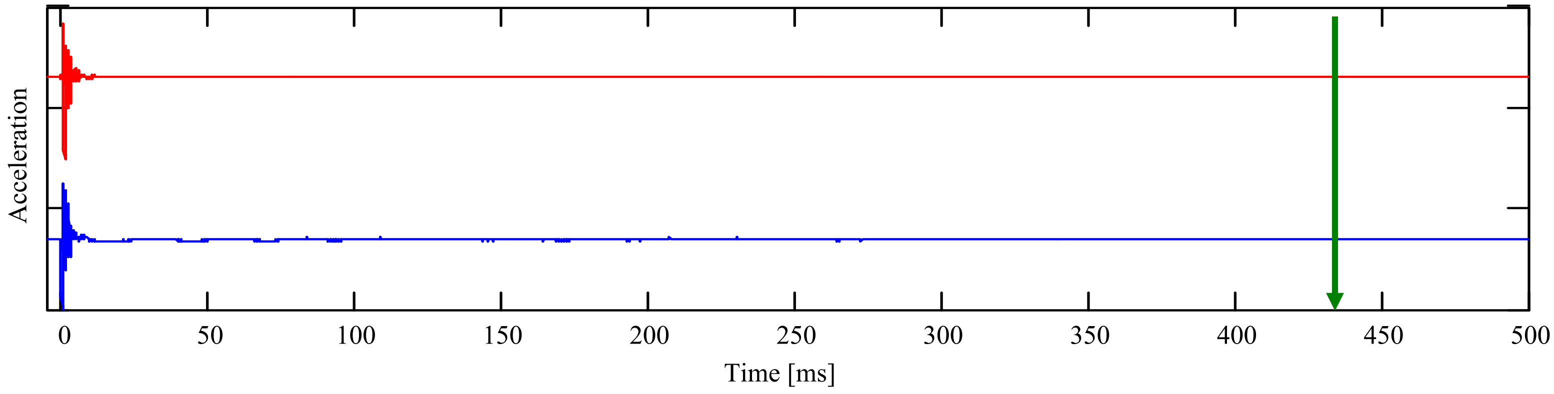




An Impact: S-wave Signature Evolution







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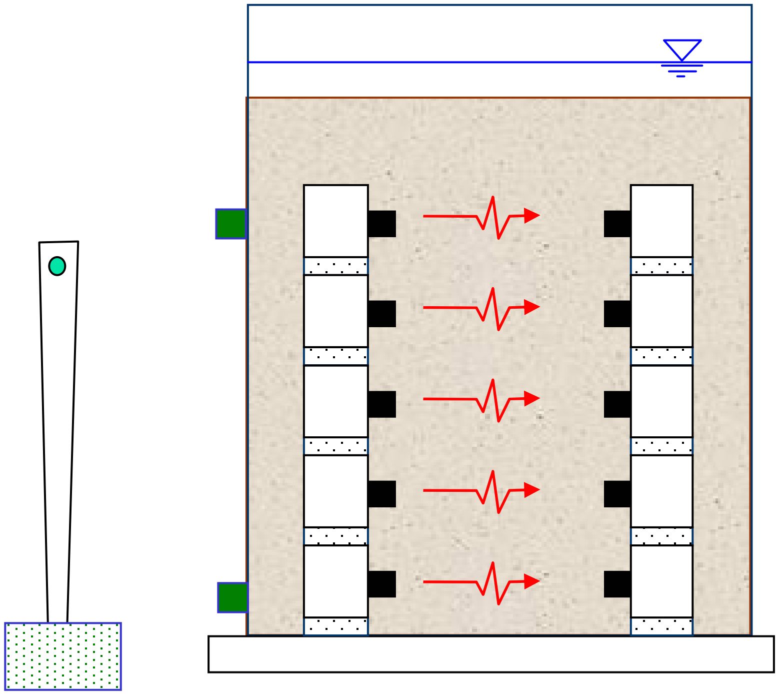
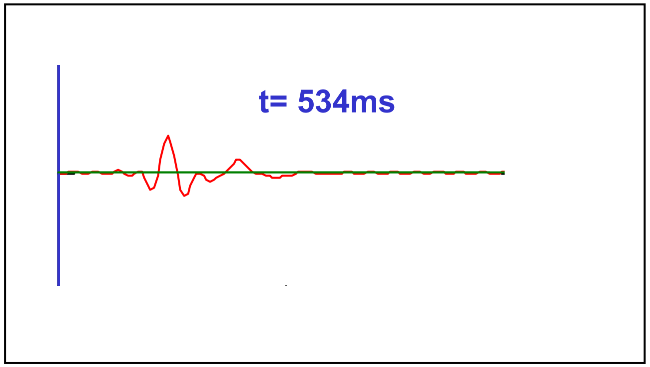
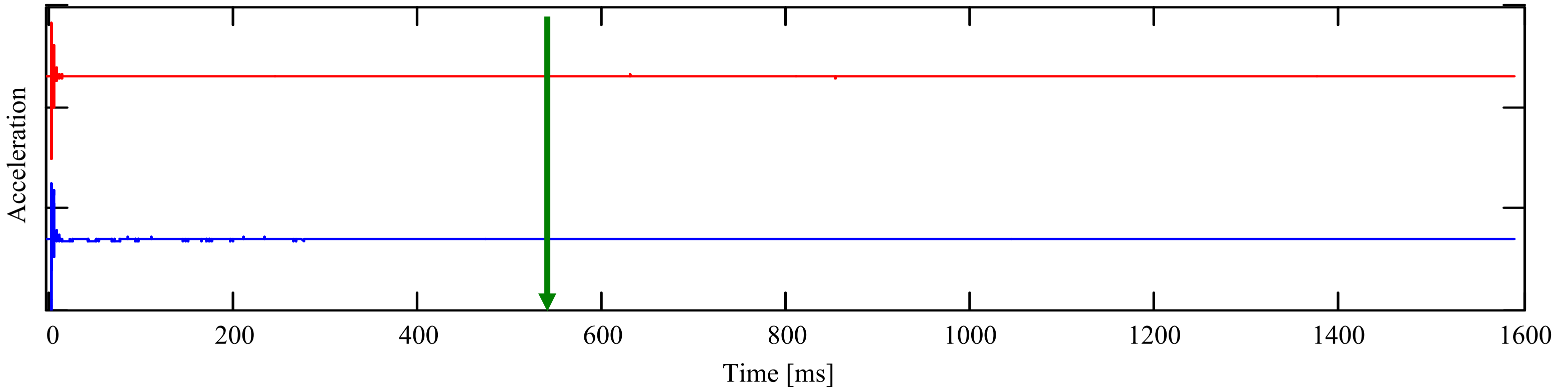


S wave received at bottom element





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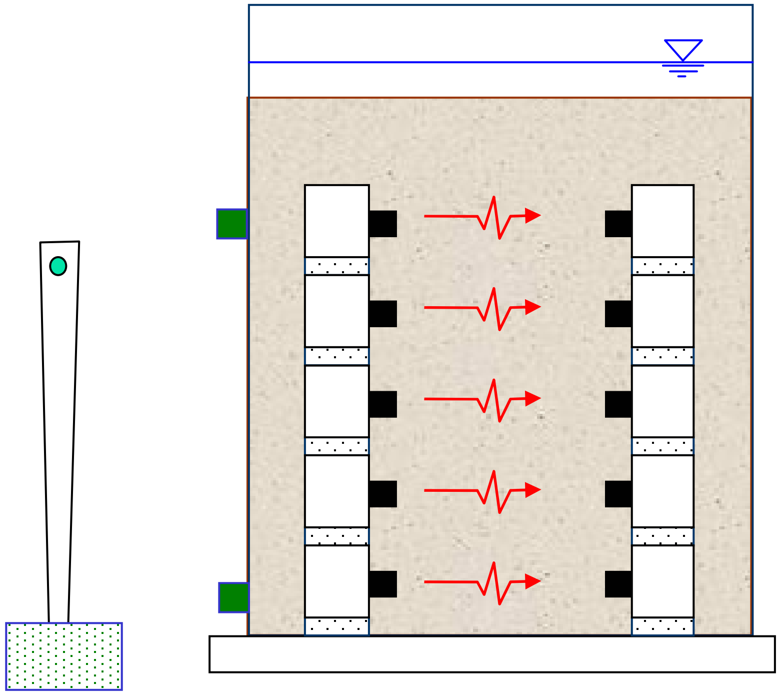
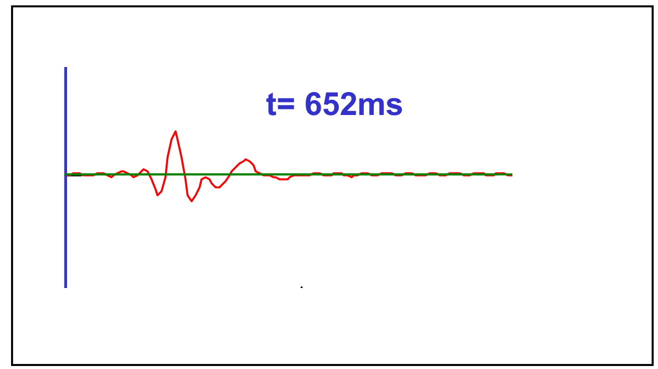
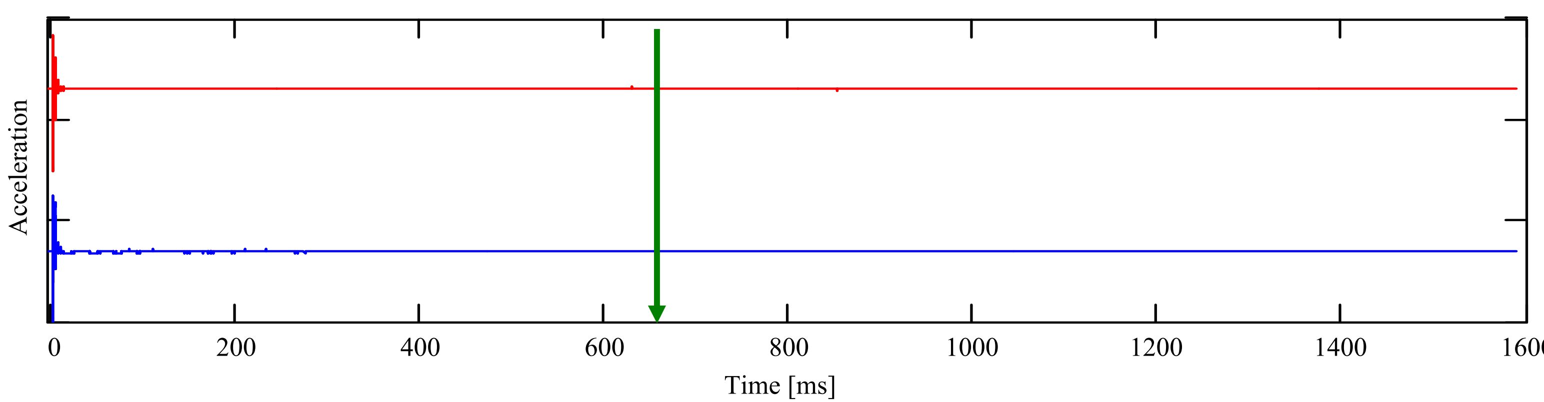


S wave received at bottom element





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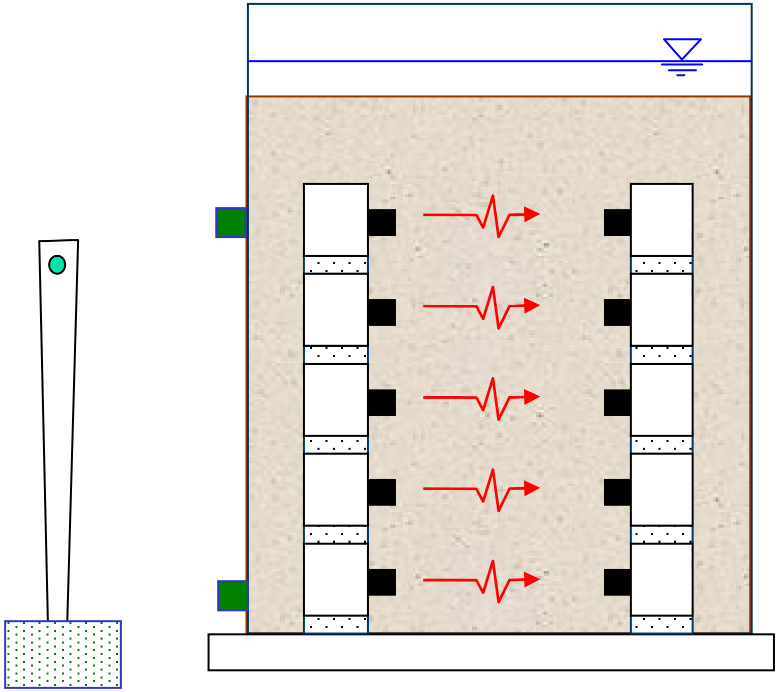
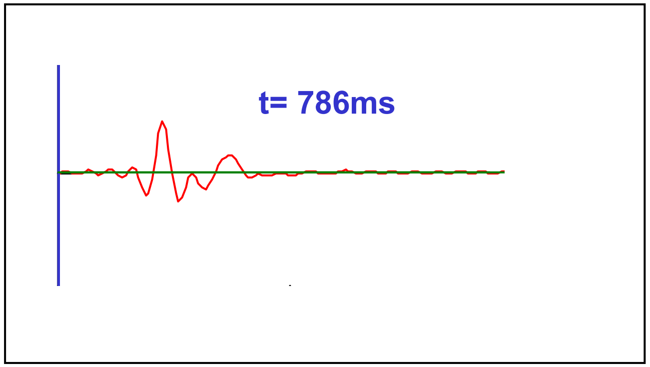
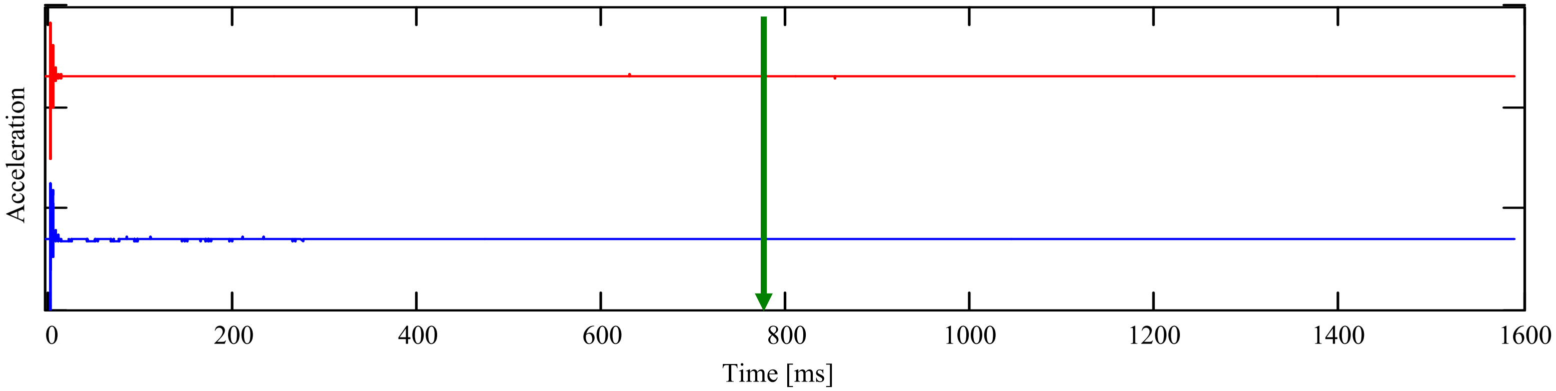
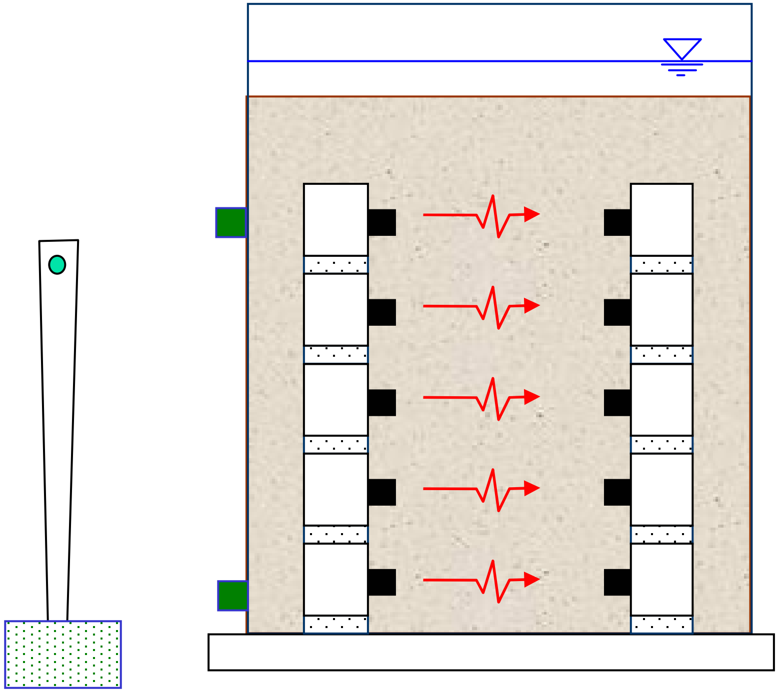


S wave received at bottom element

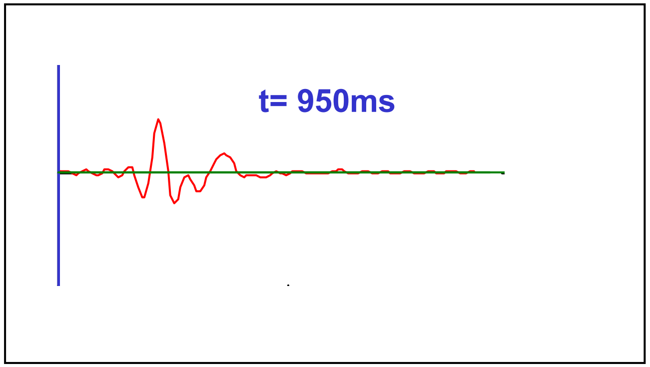


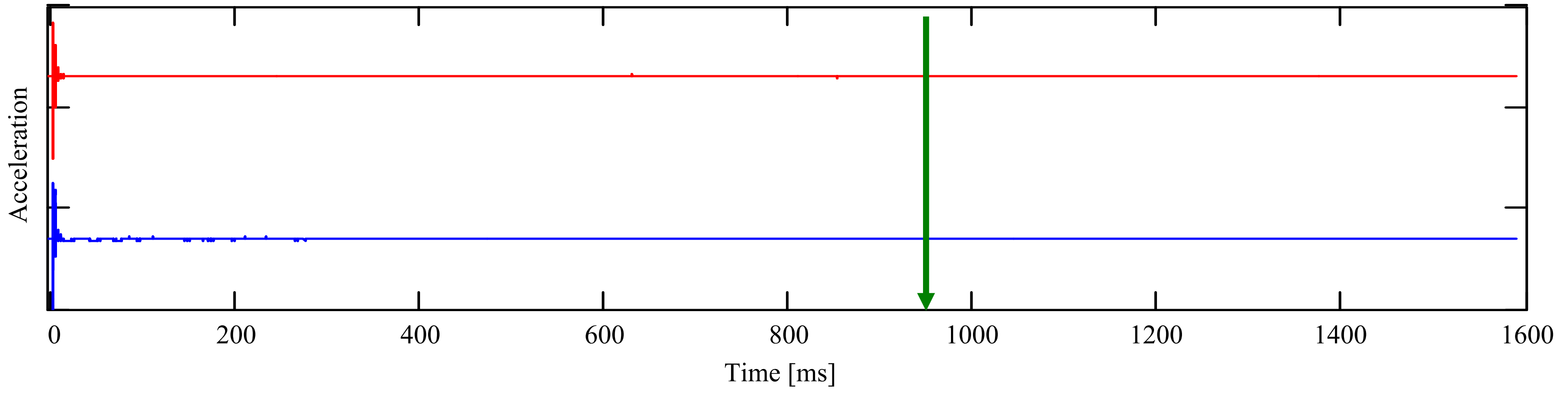


An Impact: S-wave Signature Evolution

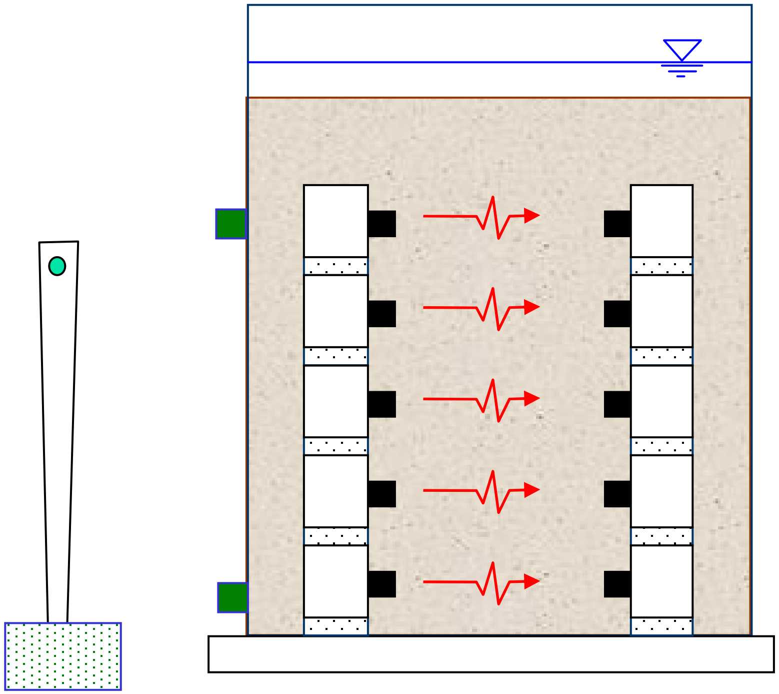


S wave received at bottom element

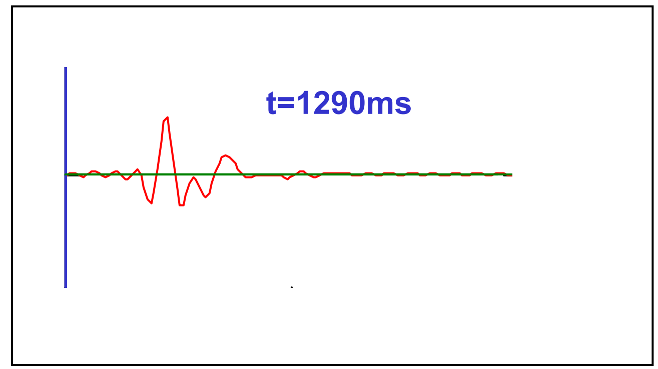


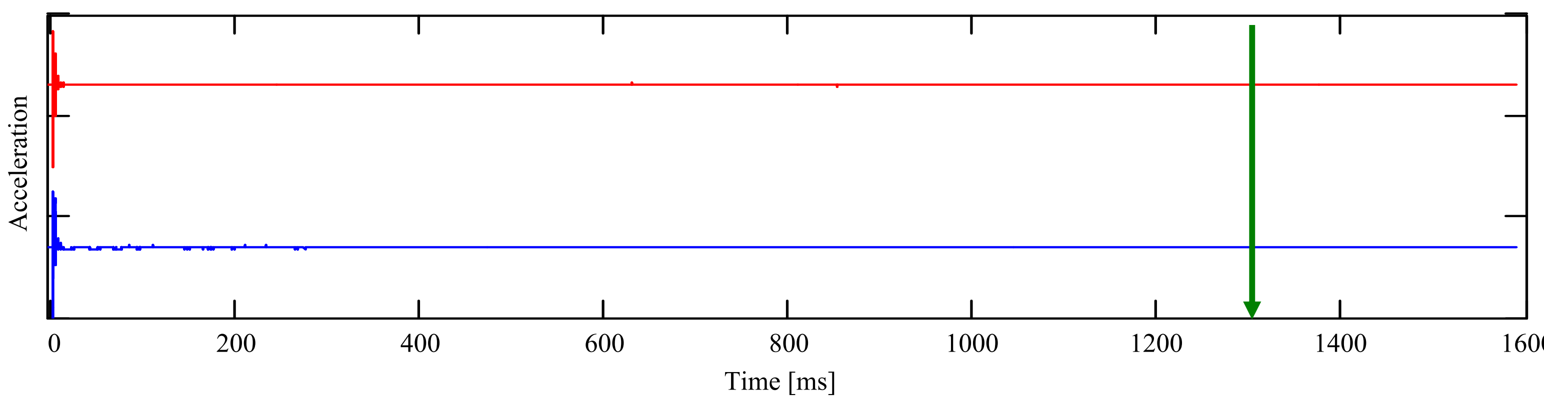


An Impact: S-wave Signature Evolution

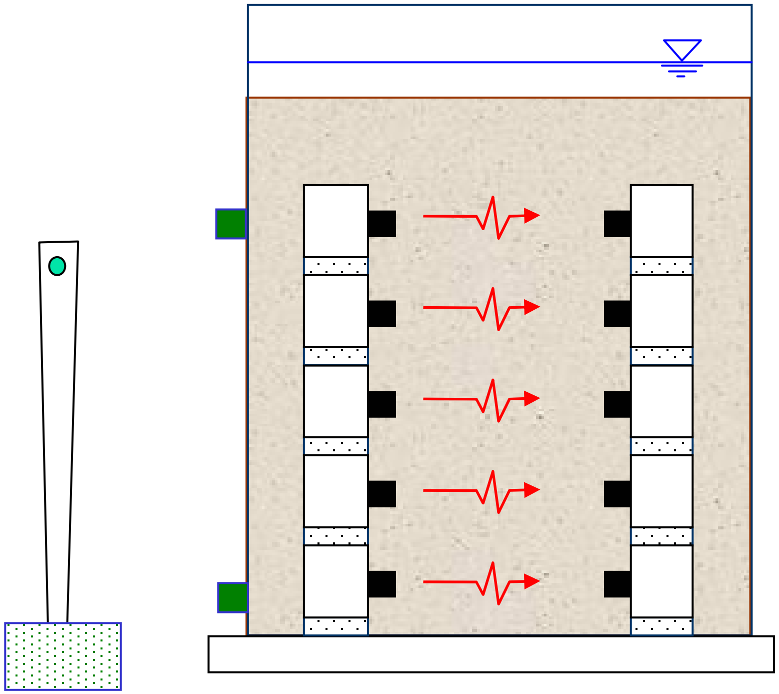


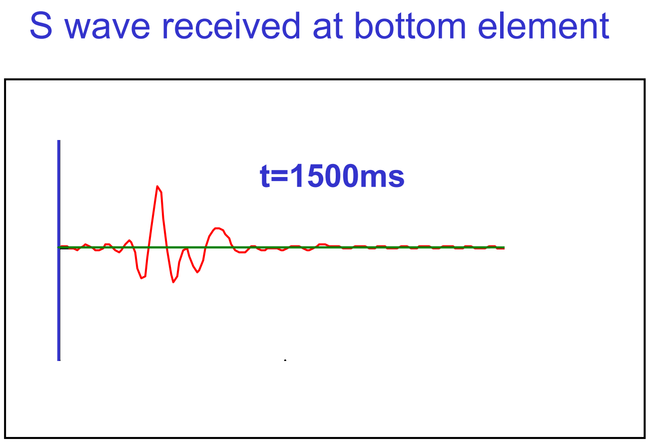
S wave received at bottom element

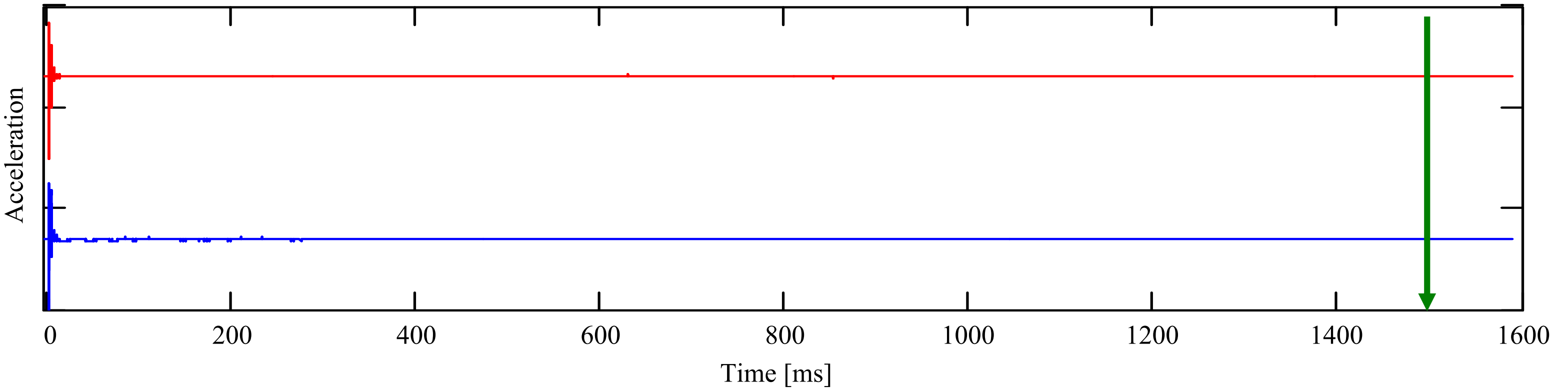




An Impact: S-wave Signature Evolution

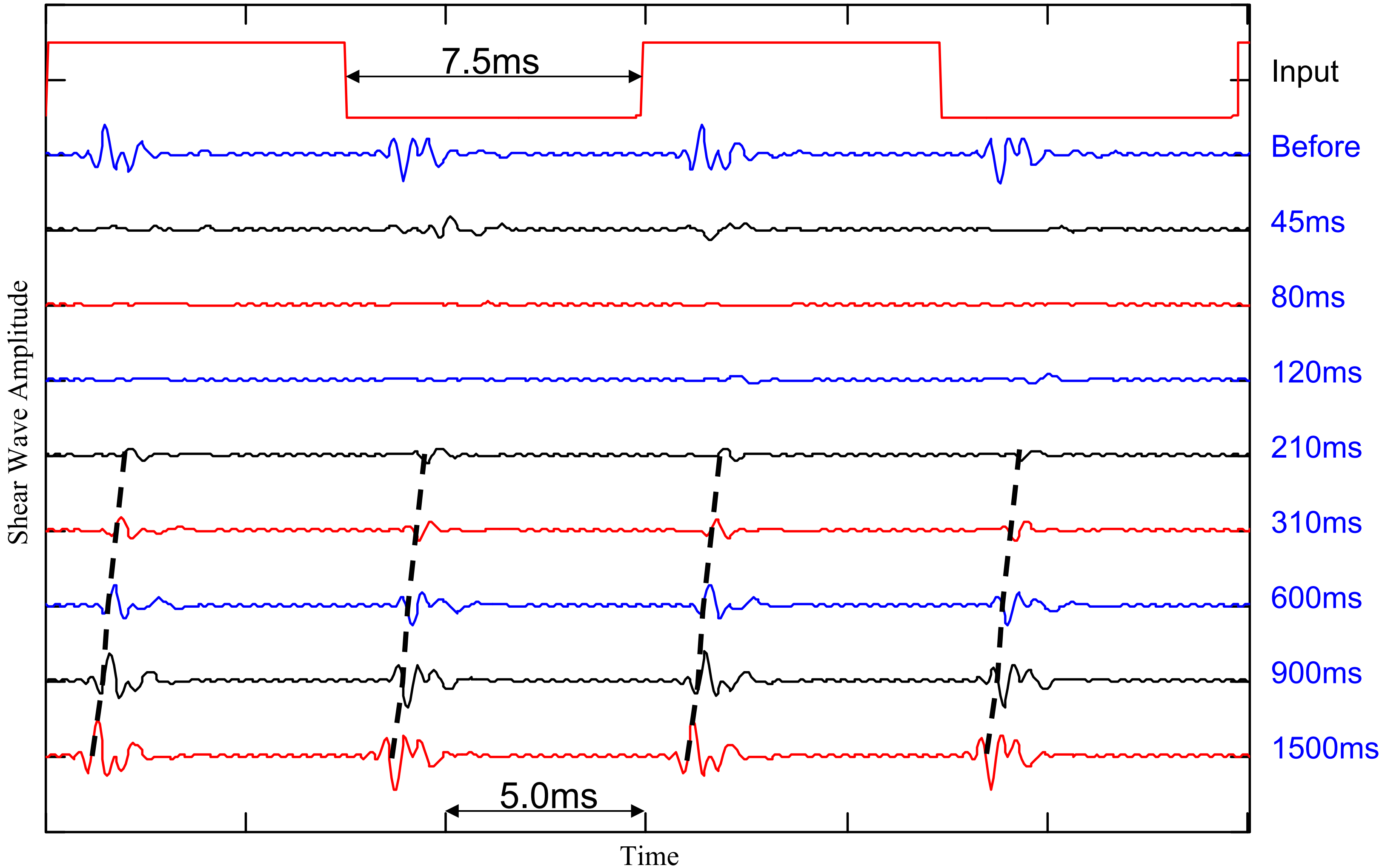




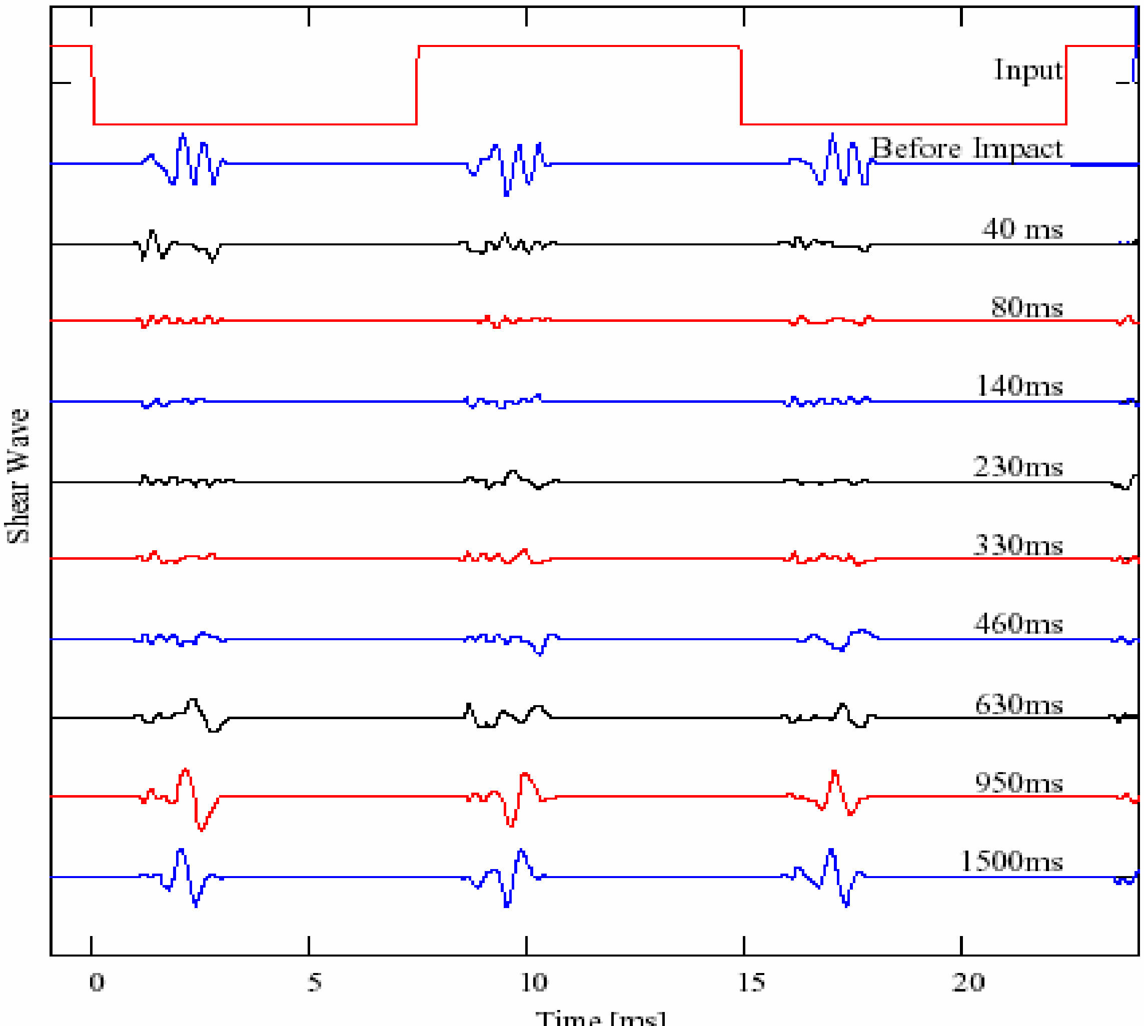


Shear Wave Signals - Saturated Soil

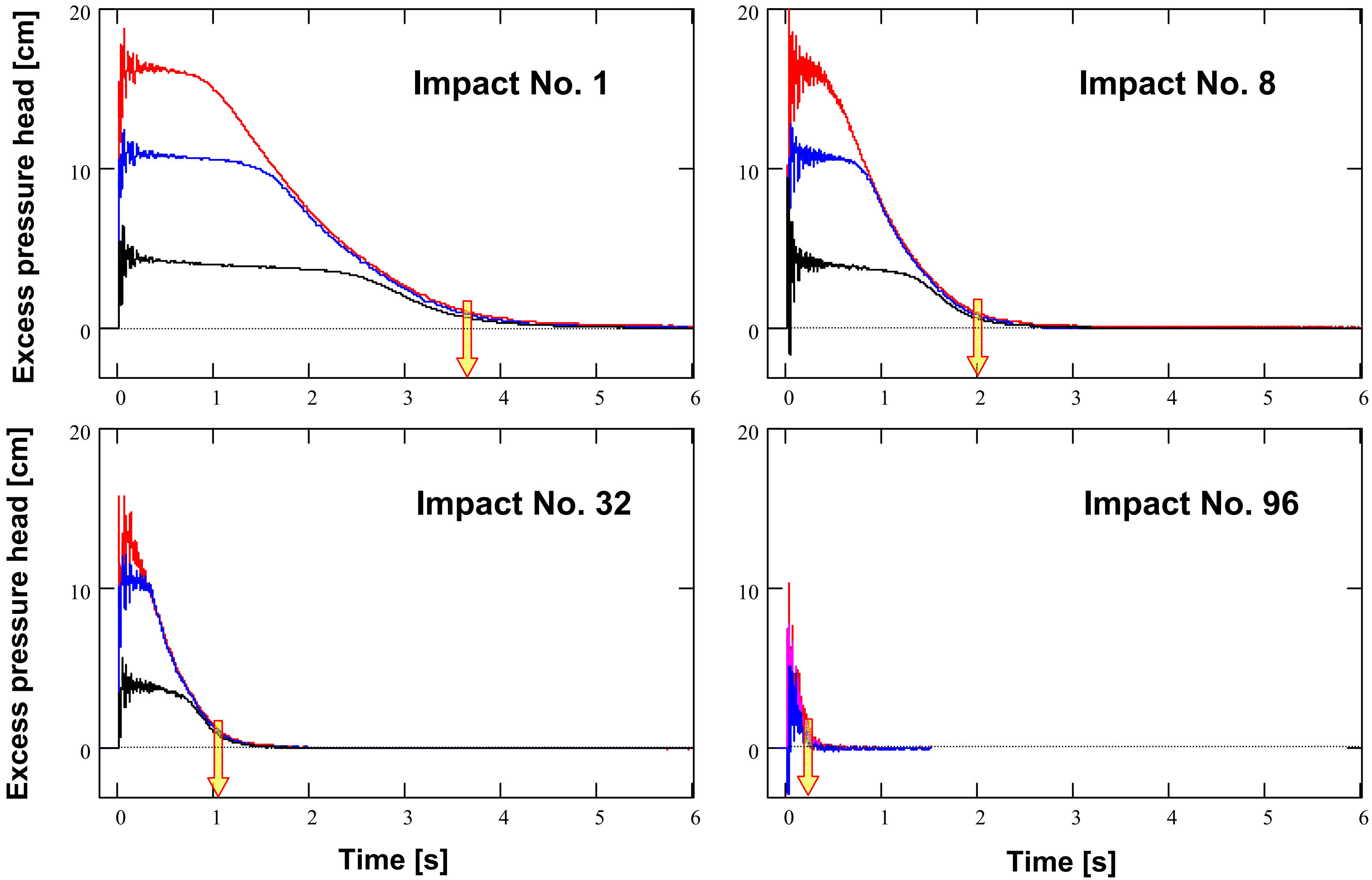
- Received at bottom element



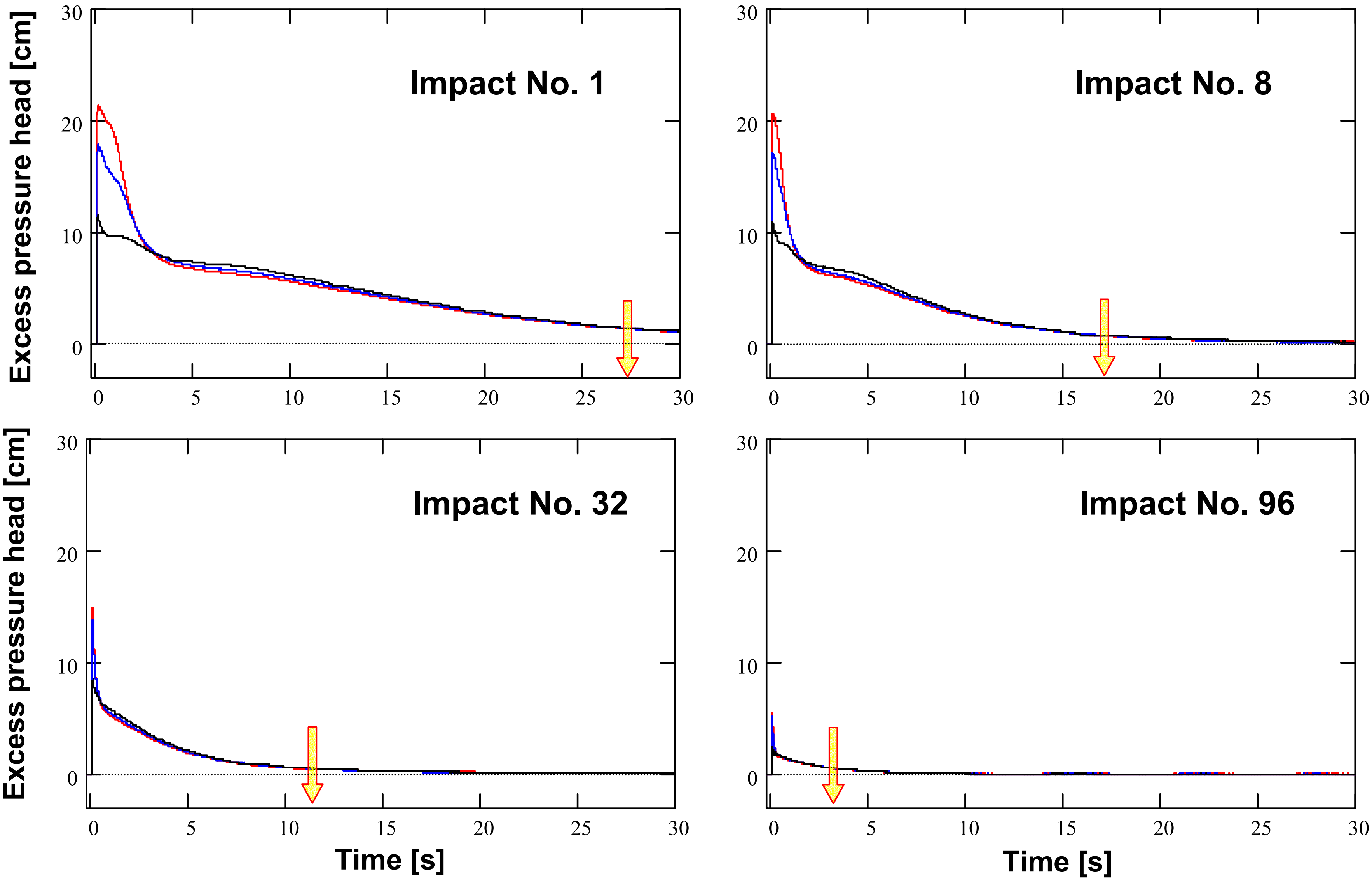
Shear Wave Signals - UNsaturated Soil



Multiple Liquefaction

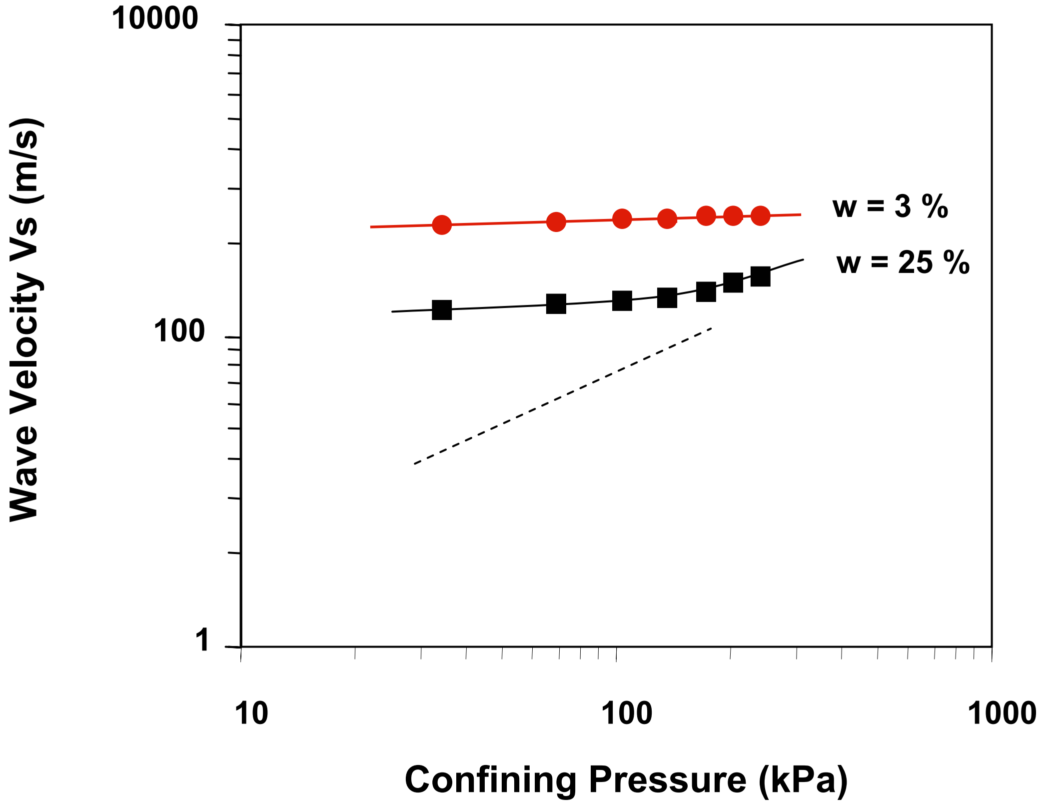


Liquefaction in Unsaturated Soils S<1

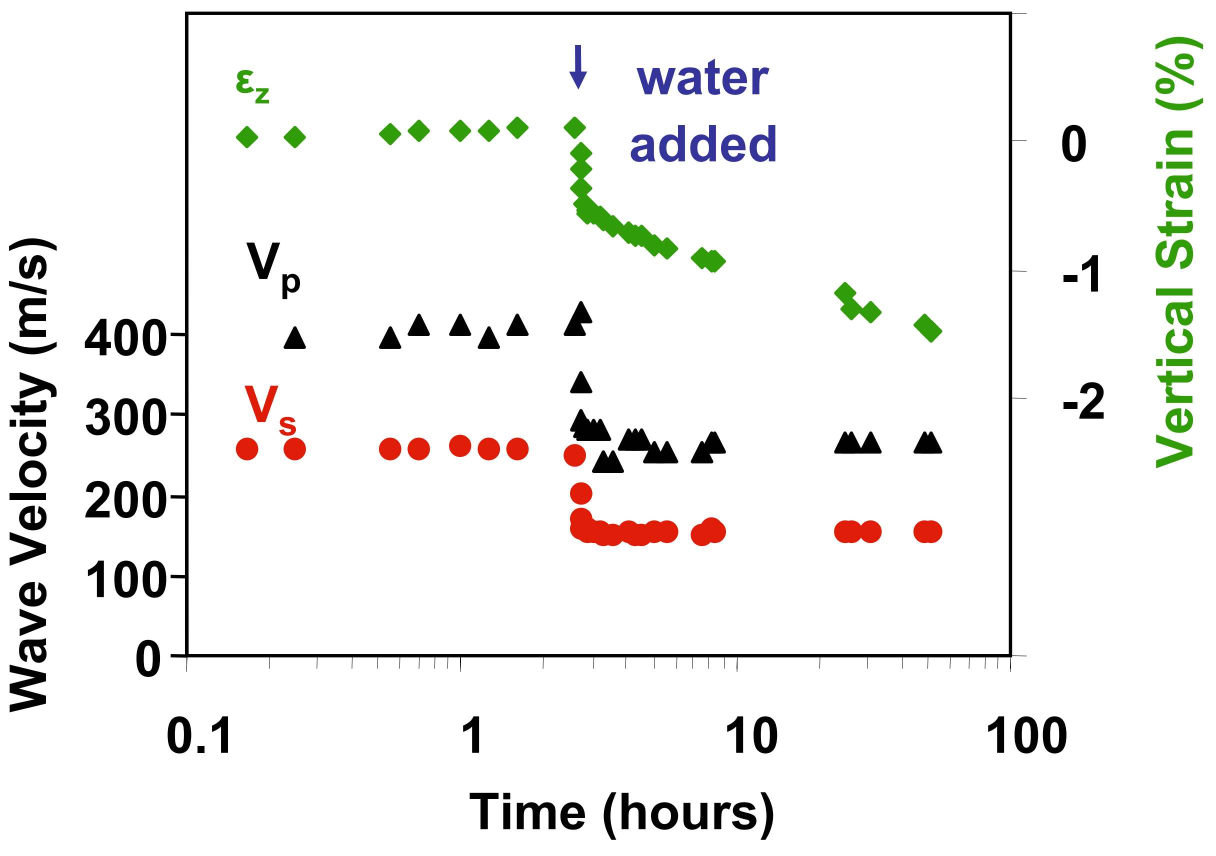


UNSATURATION OR CEMENTATION?

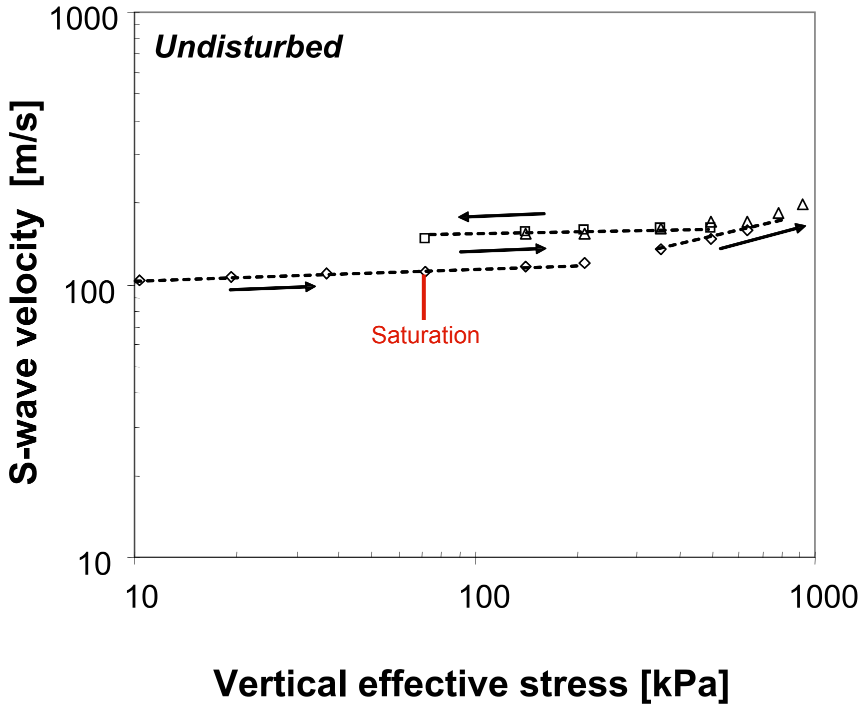
Pampean Loess

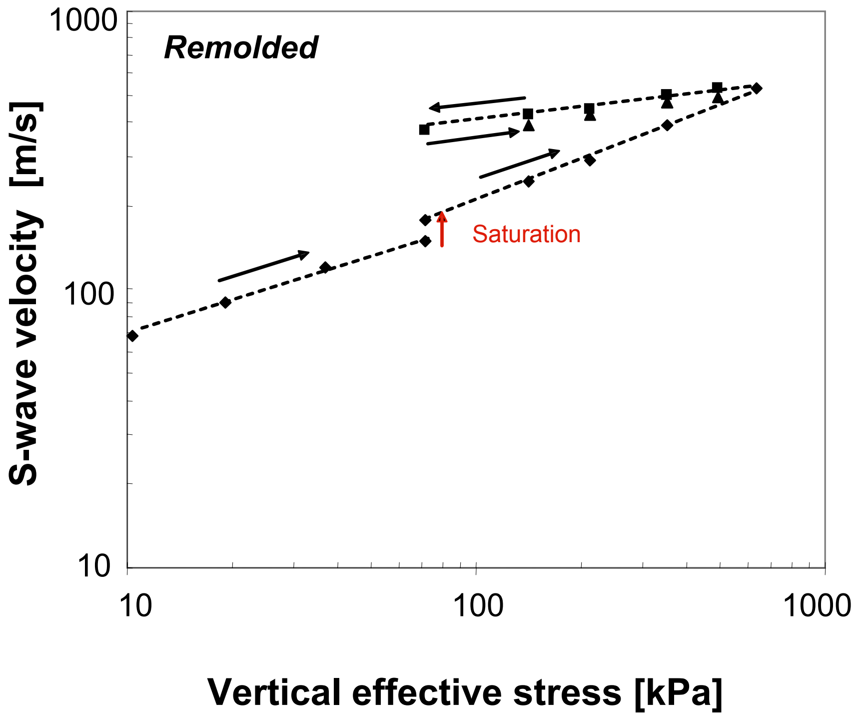


Pampean Loess: saturation

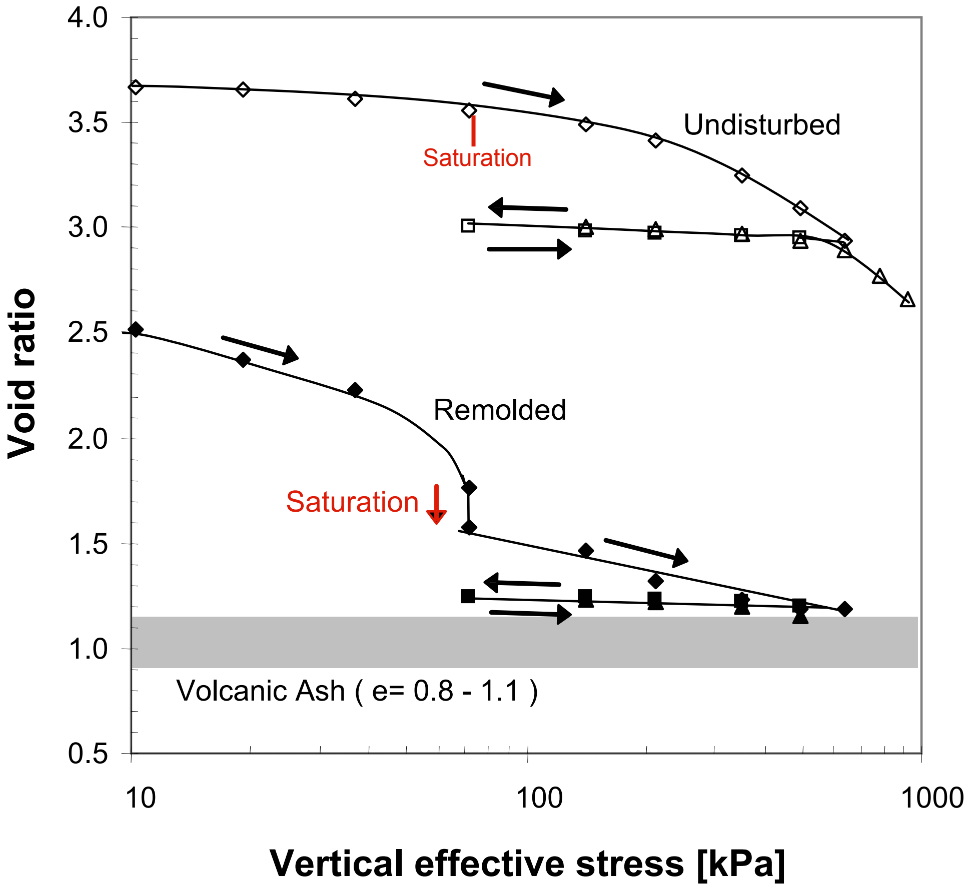


Colombian Volcanic Ash Soils



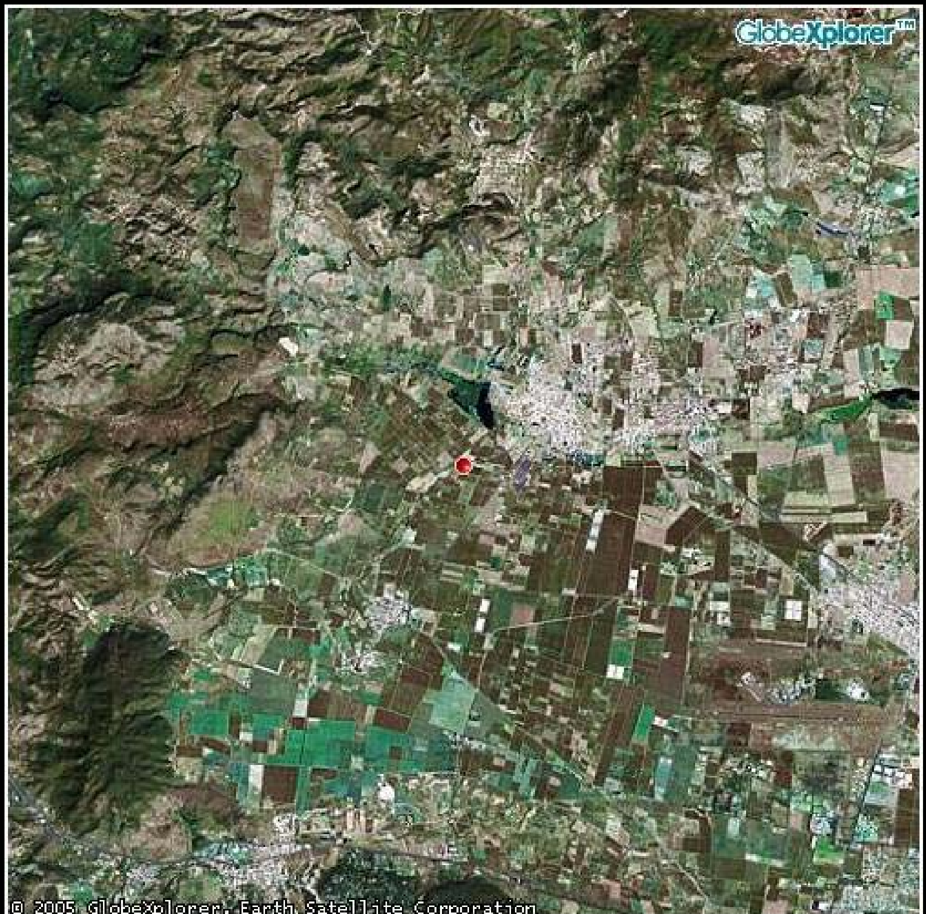


Colombian Volcanic Ash Soils



MACRO IMPLICATIONS…

Giant Desiccation Cracks

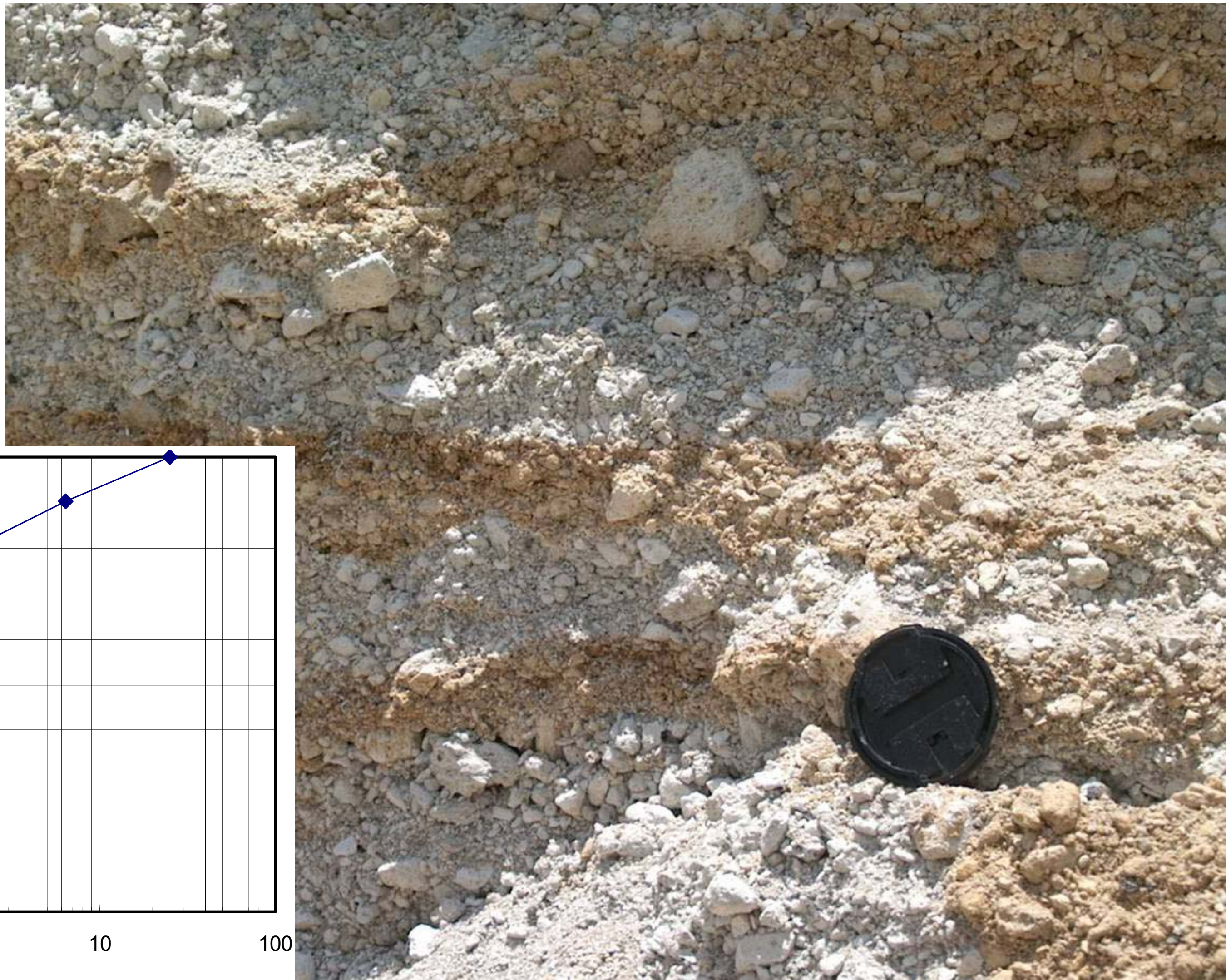


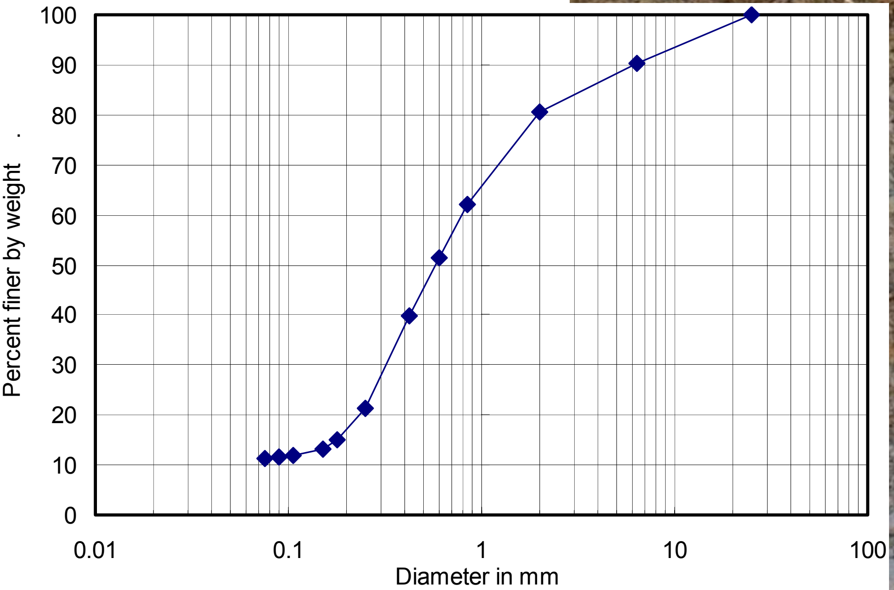
Nextipac - MX

Moisture Content w= 13% - exposed

Shear Wave velocity V_s= 144-to-158 m/s

Grain Size Distribution:





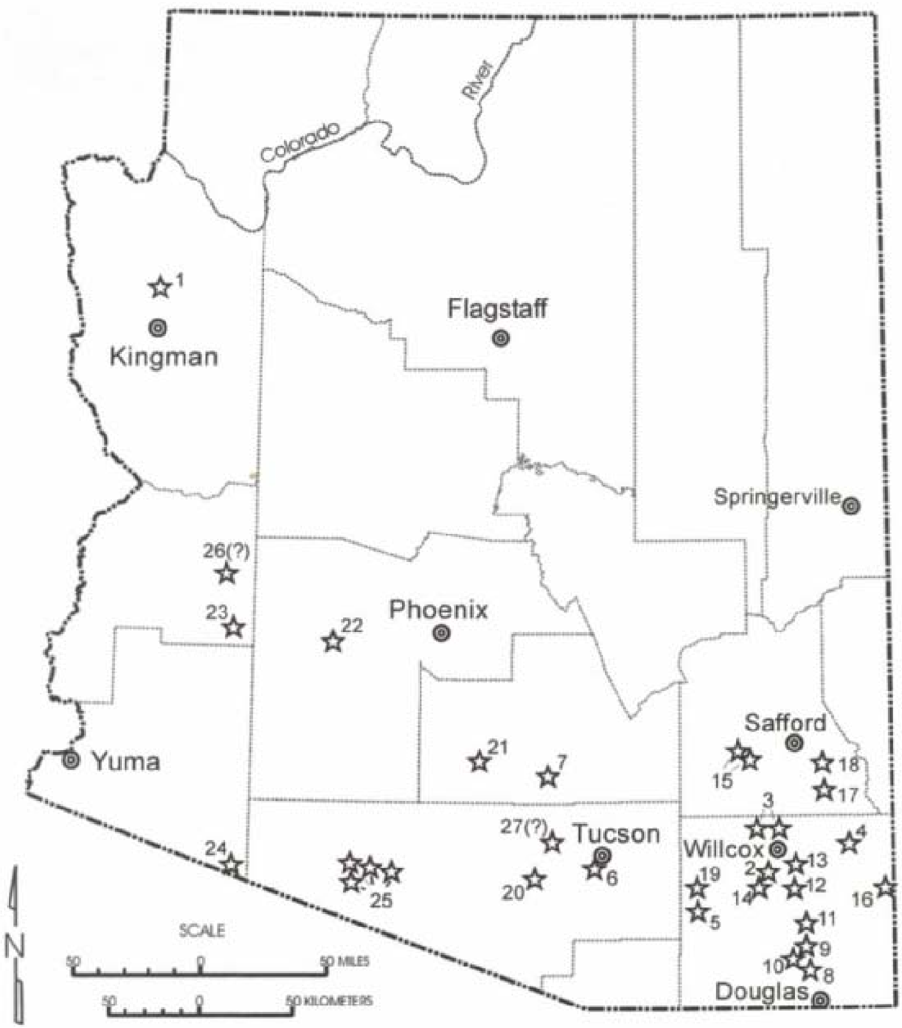
Crumb test:

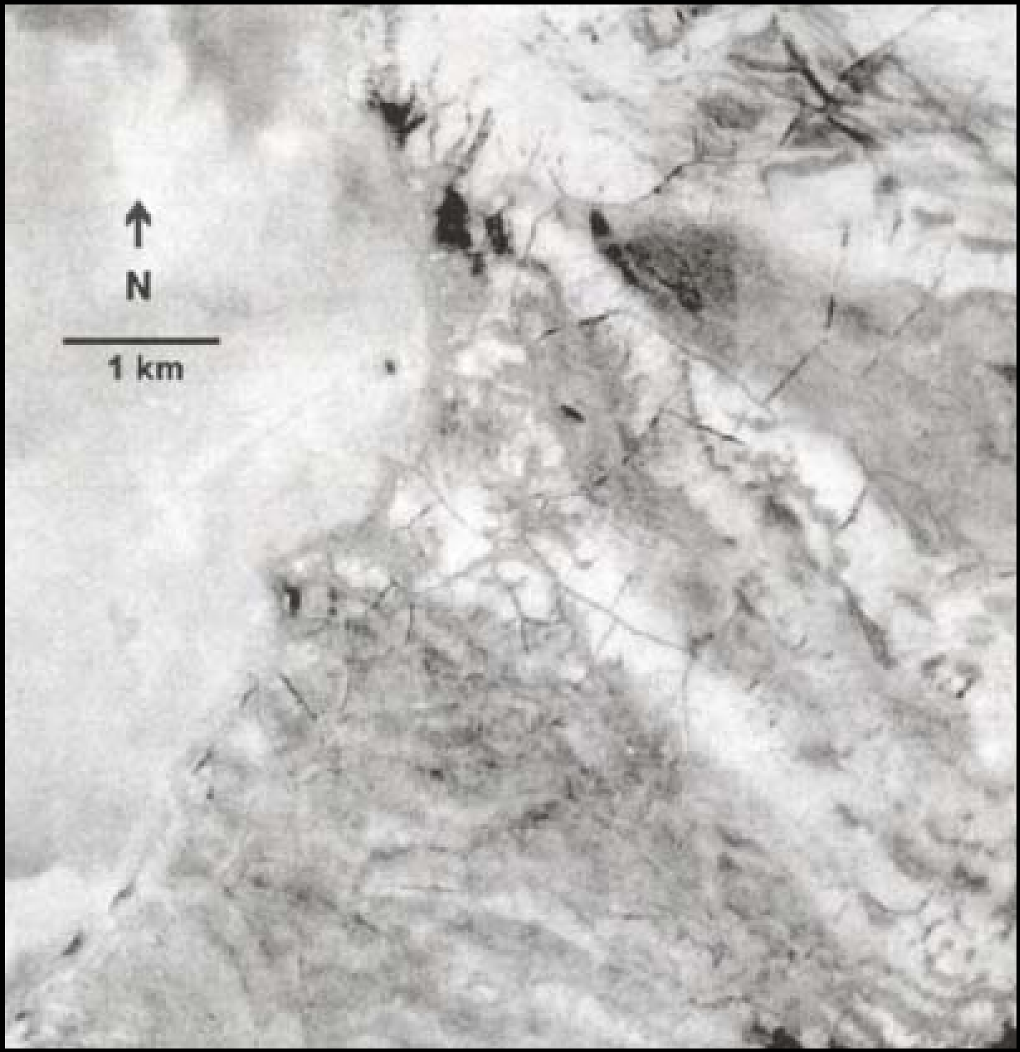
it breaks down when submerged (not completely)

it releases colloidal cloud => dispersion

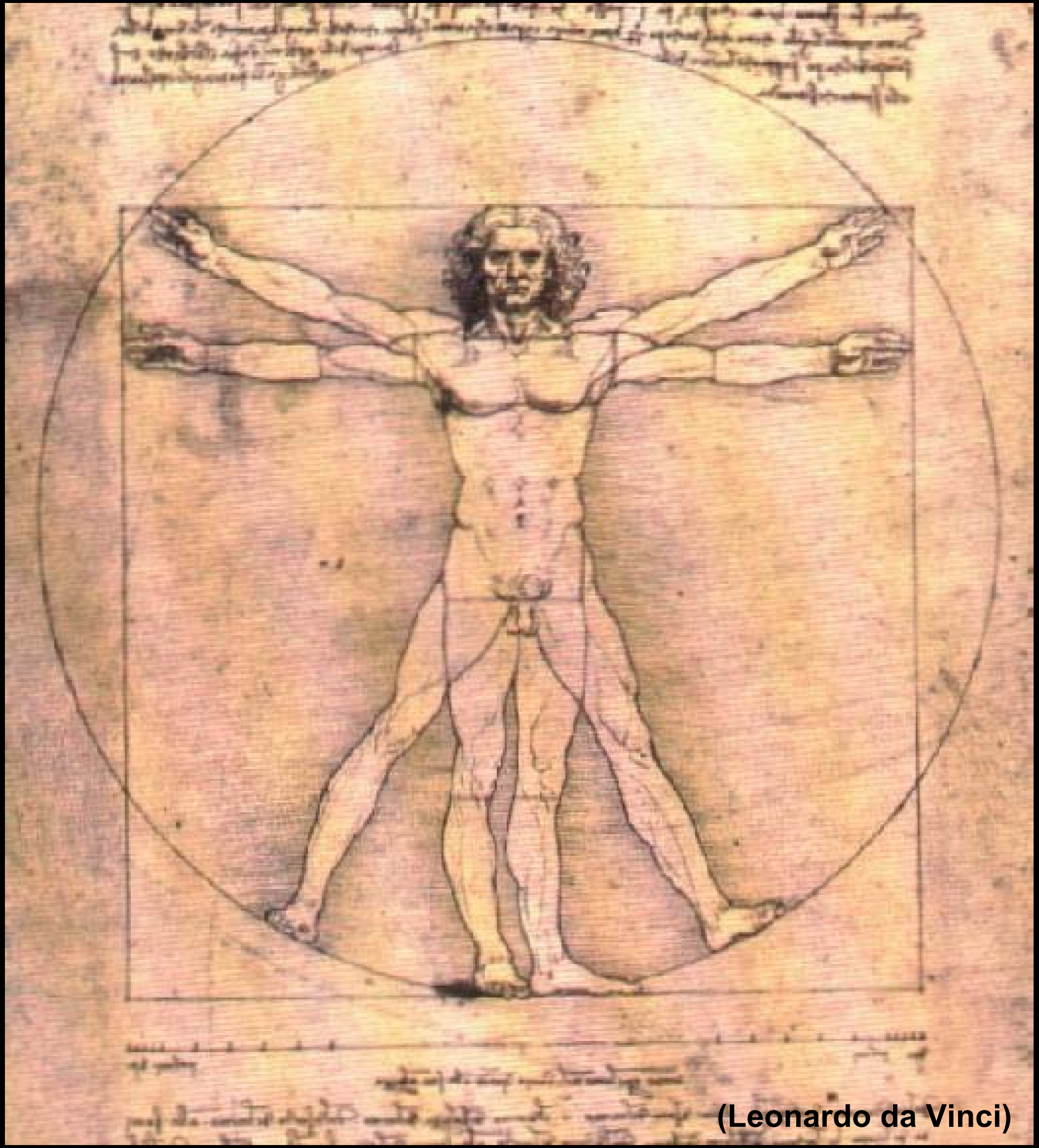
crumb test

GDC in Texas


Colorado
River
Kingman
Flagstaff
Springerville
Phoenix
Safford
Yuma
Tucson
Willcox
Douglas
SCALE
50 0 50 MILES
50 0 50 KILOMETERS
N
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26(?)
27(?)


N
1 km

and God made man of mud…



(Leonardo da Vinci)

unsaturated !

and God made man of mud…

Thank you

unsaturated !

(Leonardo da Vinci)