Seminar, UMPA ENS Lyon, October 7, 2022

Multiscale & Nonlinear **Acoustics in Granular Media**

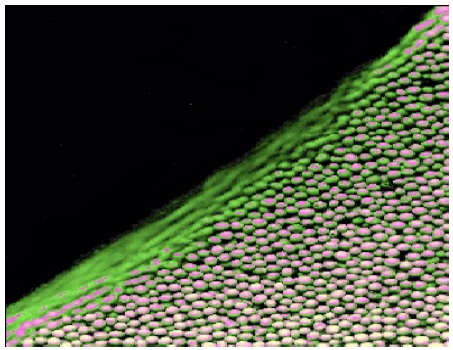
Geophysical Implications:

Earthquake *(stick-slip) and* ***Landslide*** *(granular avalanche)*

Xiaoping JIA

Institut Langevin, ESPCI Paris -PSL, France

San Andreas fault (stick-slip)



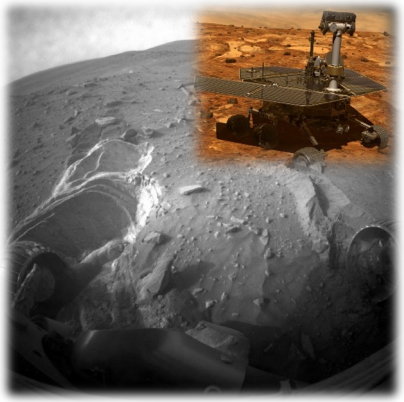
Landslides (Granular avalanches)

Quicksands (Liquefaction)

Granular media

"If we measure it by tons, the material most manipulated by man is water; **the second-most-manipulated is granular matter.**"

de Gennes (1999)



Mars Spirit (2004-2011)
~825 M$

Taiwan (April 25th 2010)
4 deaths

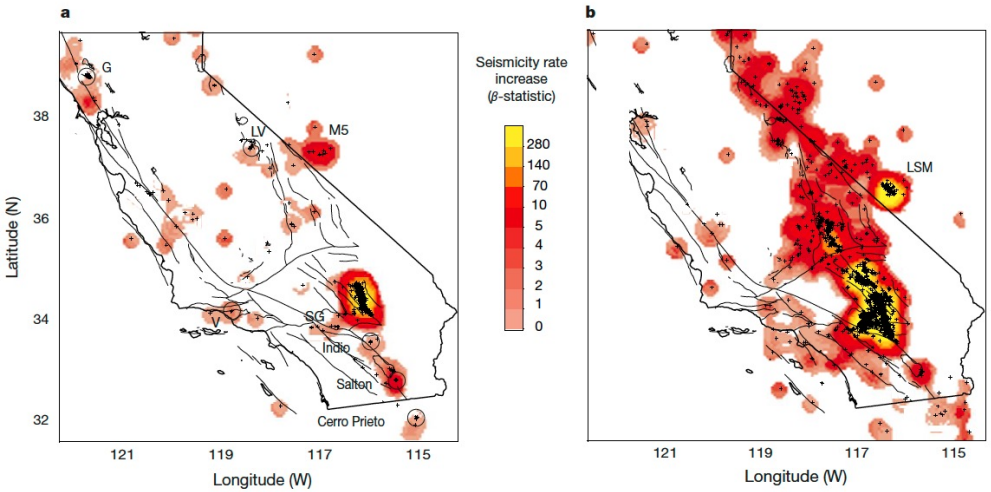
From ~10 microns

To meter

How do small-amplitude seismic waves trigger natural hazards: EQ & Landslides

- Earthquakes triggered by other large earthquakes at remote distances (dynamic strain < 10^{-6})

J. Gomberg et al, Nature 2001; Hill et al et , Science 1993



Hector Mine 1999 Landers 1992

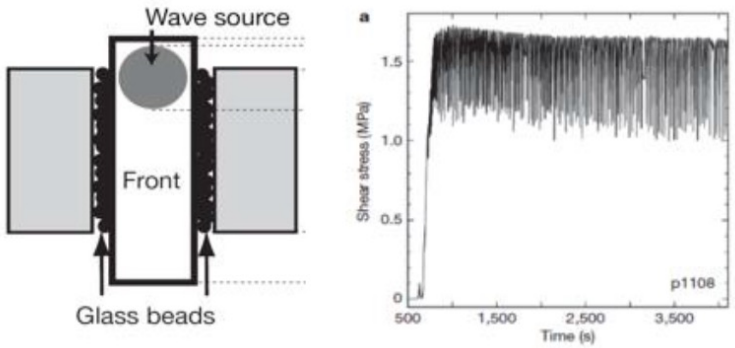
- Rockfalls (landslides /granular avalanches) triggered by small seismicity (local)

- *V. Durand, A. Mangeney et al, JGR* 2019
- *E. Larose et al*, Nat. Com. 2019

Dolomieu crater at Piton de la Fournaise (La Réunion)

- Friction in granular fault gouge (labquakes)

- ***C. Marone*, Annu. Rev. Earth Planet. Sci. (1998)**
- J.H. Dieterich (1992)
- *C.H., Scholz* (Cambridge Press, 2002 & 2010)
- J. Gollub et al, Phy. Rev. Lett (1997)



Johnson et al, Nature 2008

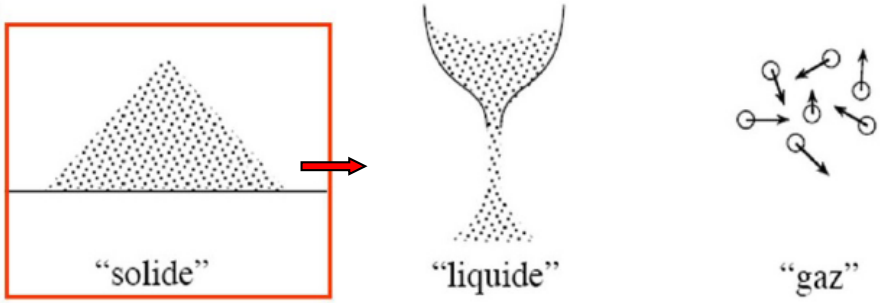
- Possible mechanisms:

→ Acoustic fluidization (Melosh 1996)
→ Opening mode waves (Madariaga 1994)
??? (D. Sornette 1998)
→ Acoustic noise (Brodsky 2013)

→ Granular rotation friction (Scott 1996)
→ Unjamming transition (Liu & Nagel, 1998)

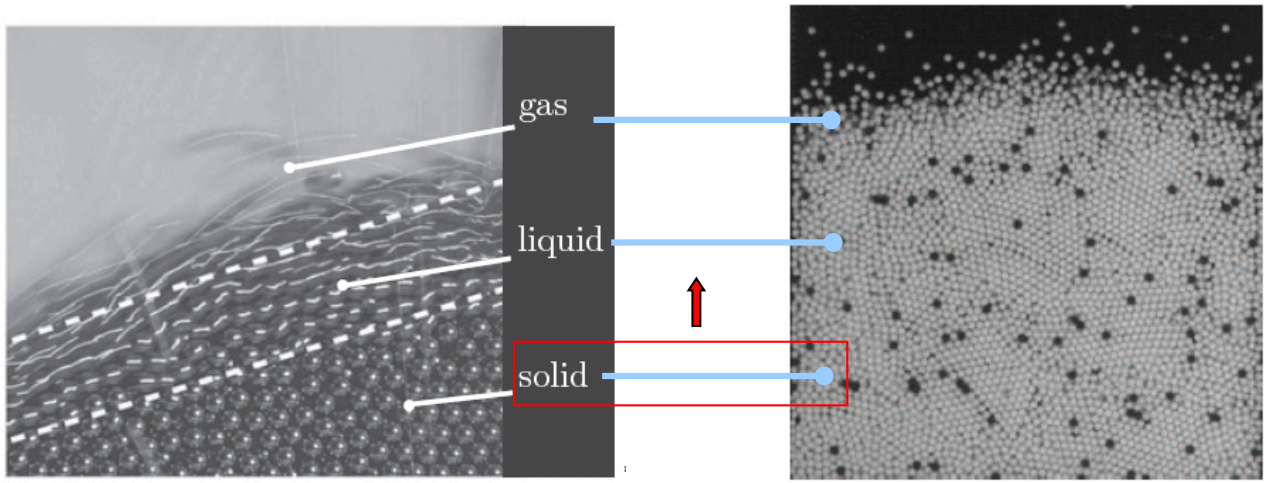
Background

Granular Matter
athermal
(Andreotti, Forterre, Pouliquen, 2011)



Avalanche experiments

- Jaeger et al 1996
- Rajchenbach 2000
-GDR MIDI 2004
- …



Shaking

- Duran et al 1996
- Jaeger, Liu & Nagel 1990
- D' Anna et al 2001
- Marchal et al 2009
- van Hecke et al 2011
- Kolb, Clément et al 2011
- Lastakowski et al 2015

Oscillation

Investigation of the transition from solid to liquid states using sound waves:

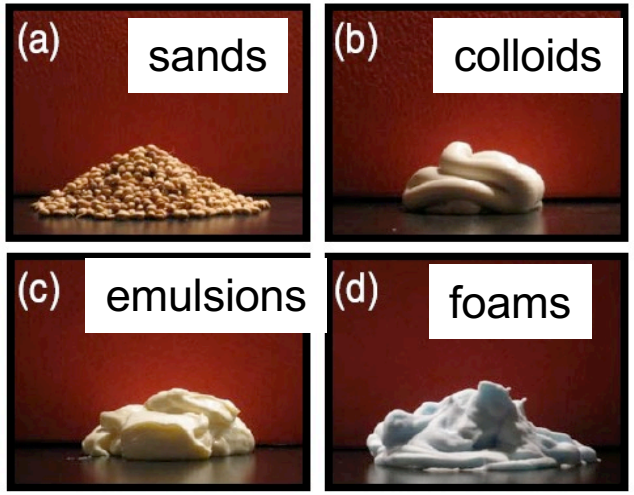
- ♦ Nondestructive ***probing*** (u_{ac} < 1 nm)
- ♦ Controlled ***pumping*** (u_{ac} ~ 0.01– 10µm): *NL responses & shear modulus softenning*

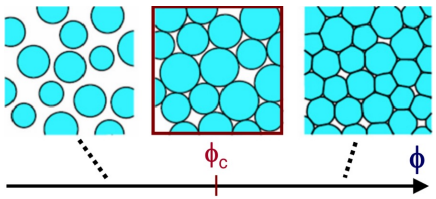
$u_{ac} < d$: no rearrangement !
(micro-plasticity !!)
for d = 50µm - 1mm
(f_{ac} = 0.1-100 kHz)

Unjamming transition (1/2): *from solid to liquid states*

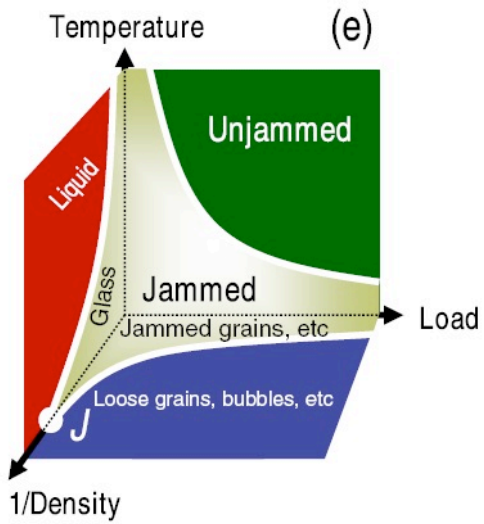
- Jamming transition in soft matter (→ yield stress fluids)

- Liu and Nagel, Nature (1998)
- van Hecke, J. Phys.:Condens.Matter (2010)



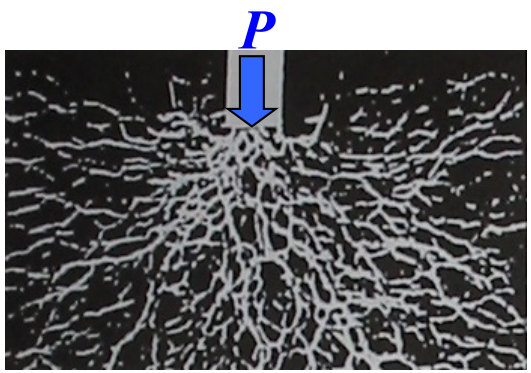


$\phi_c \sim 0.64$



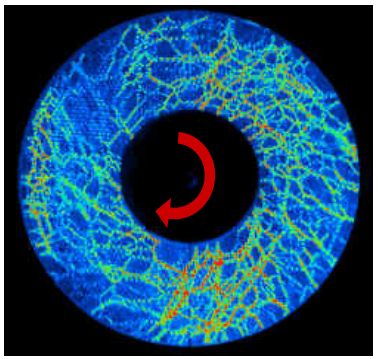
- Frictional contact force networks in dense granular packings
(photoelastic visualization)

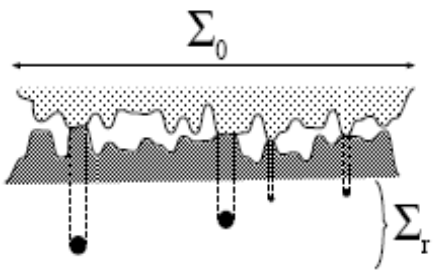
under ***compression***
(Dantu ,1957)



Force chains ξ***:***
5-10 d
*(**d** grain size)*

Dynamical heterogeneity



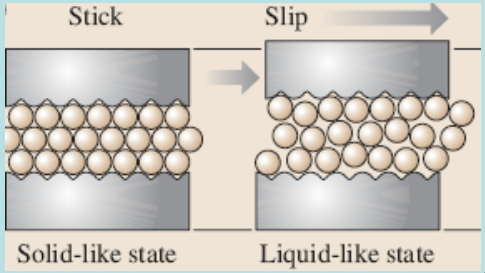


under ***shear***
(Behringer et al, 1999)

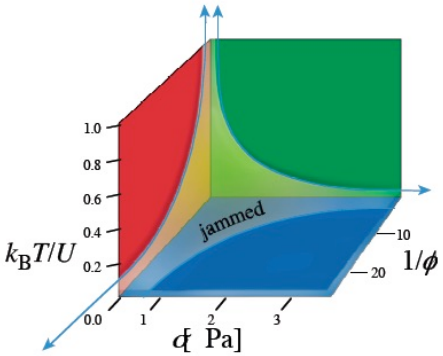
Unjamming transition (2/2): *from stick to slip*

$10^{-9} – 10^{-6}$ m

Boundary Lubrication



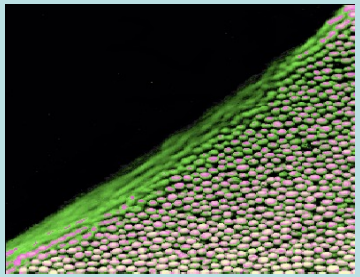
Robbins 1990; Israelachvili 1994



Liu, Nagel, 1998

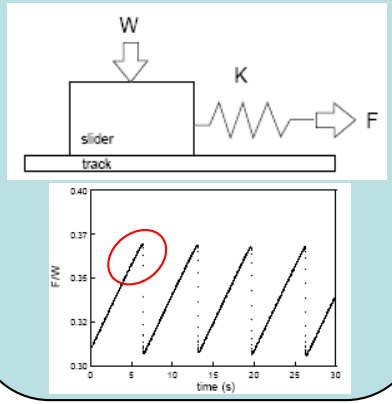
$10^{-4} – 10^{-2}$ m

Granular Flow



Jaeger, Nagel & Behringer, 1996

Stick-Slip Motion

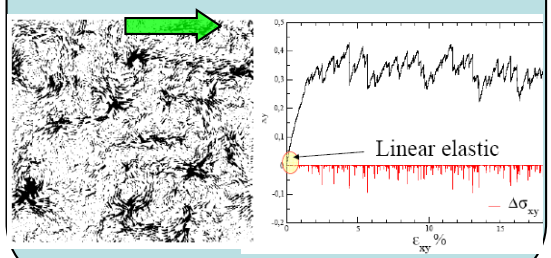


- ***Threshold rheology of jammed systems***
- ***Plasticity of amorphous materials***

- Persson 1998
- Baumberger & Caroli 2006

$10^{-9} – 10^{-6}$ m

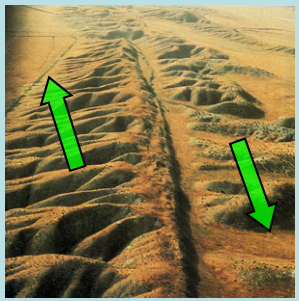
Glassy Rheology



Barrat, Tanguy et al 1999
Maloney & Lemaitre 2000

10^{-3} - 10^{5} m

Landsliding



Marone 1998; Scholz, 2002

Outline

1. Ultrasound propagation in *heterogeneous* granular solid

1.1 Linear propagation

- coherent waves (elastic heterogeneity)
- multiple scattering (dissipations & mean free path)

1.2 Nonlinear propagation

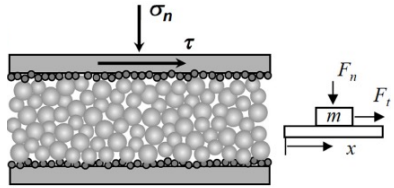
- elastic softening (hysteretic nonlinearity)
- slowdown of shear wave velocity (unjamming)

Probe-pump
(micro-plasticity)

2. Acoustic montoring and triggering of *shear instability* in confined granular media

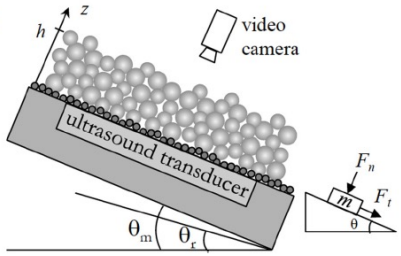
2.1 Shear band formation and failure (labquakes)

- shear-induced wave velocity weakening
- probing precusor events with scattered coda waves



2.2 Ultrasonic triggering of granular avalanches

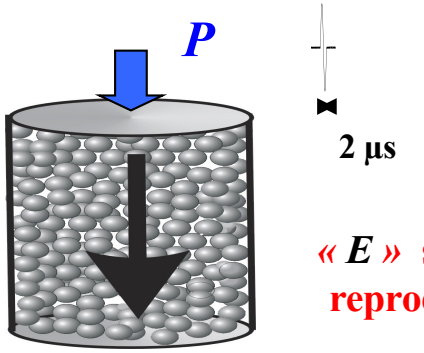
- bifurcation between jamming creep self-accelerated flows
- granular avalanches triggered by acoustic lubrication of contacts



1.1 Linear sound propagation in heterogeneous granular solid (1/4)

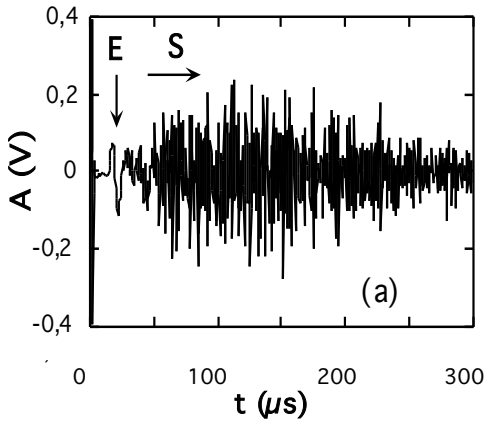
Jia, Caroli and Velicky, Phys. Rev. Lett. 82 (1999)

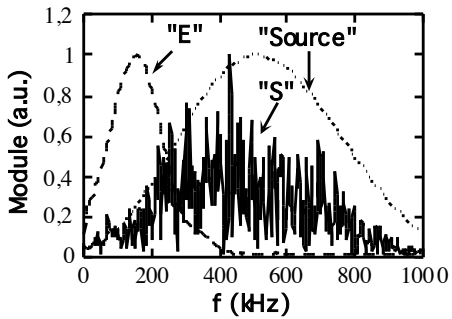
- $\lambda_E \geq 10\,d$: coherent waves (*E*)



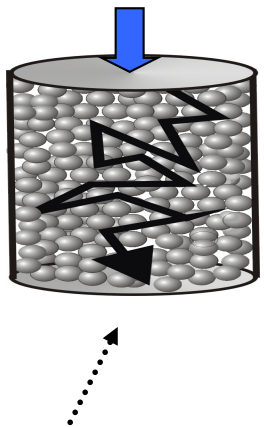
P = 0.75 MPa

« *E* » signal is reproducible

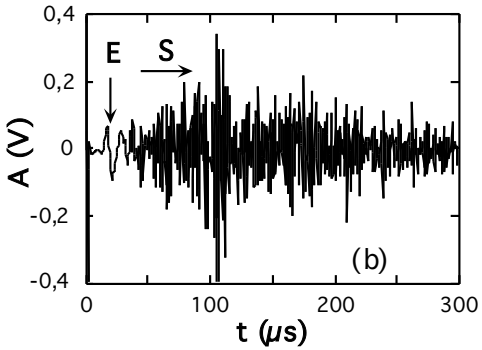




- $\lambda_S \sim 2d$: multiply scattered waves (*S*)



« *S* » signal is configuration specific



glass beads *d*: 600-800 µm

Physical Review Focus

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Ultrasound Propagation in Externally Stressed Granular Media
X. Jia, C. Caroli, and B. Velicky
Phys. Rev. Lett. **82**, 1863 (1 March 1999)

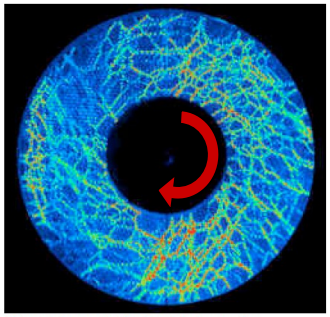
Probing a Sandpile with Sound

1 March 1999

Alexander Hellemans

Dunes blow in the Sahara, cereal shifts in its box, and wheat falls in a silo. Physicists have a hard time describing the complex motions of such "granular materials" because they don't fit neatly into categories like solids or liquids. Just characterizing the state of a bag of sand is challenging without a complete picture of the widely varying forces on each grain. In the 1 March *PRL* a group of physicists in France demonstrates that ultrasound pulses can probe the detailed structure of a granular material. They found that sound waves that scatter many times inside a collection of beads carry information on the distribution of forces on the particles.

Xiaoping Jia and his colleagues at the University of Paris placed glass beads ranging from 0.2 to 1.5 mm in size (depending on the experiment) in 3 cm diameter cylinders. The beads were squeezed by pistons pressing with seven times atmospheric pressure. Just inside the pistons they placed an ultrasound transmitter on top of the beads and a detector underneath. When they



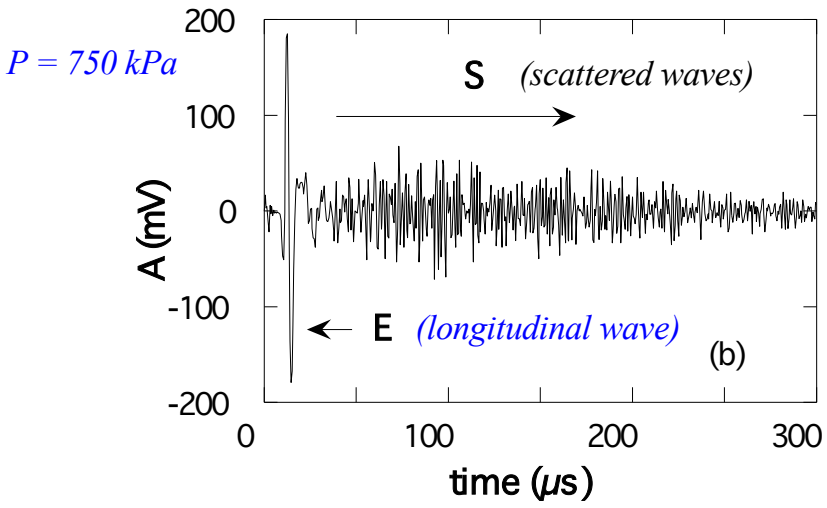
Dan Howell/Duke University

Web of forces. As a granular material is squeezed, a complicated structure of force "chains" is set up, where the

Coherent sound velocity *V* versus pressure and particle shape: EMT (2/4)

♦ Velocities of coherent waves

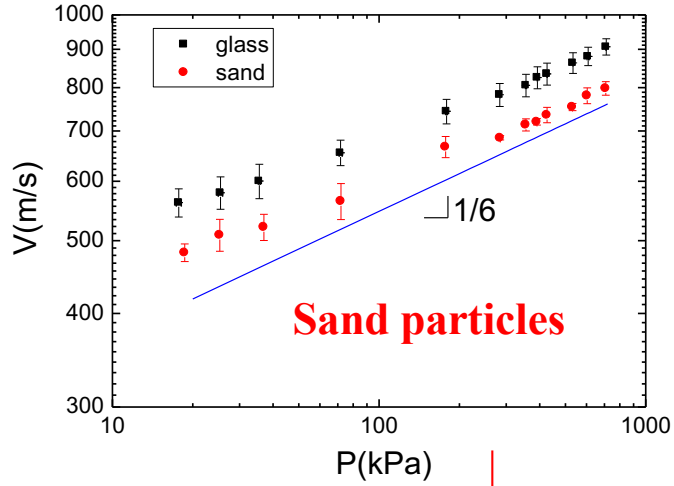
- *Jia, Caroli, Velicky, Phys. Rev. Lett. 82 (1999)*
- *Jia, Mills, Powders & Grains (2001)*



Glass beads
d: 0.4 -0.8 mm

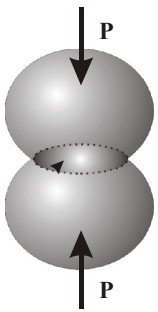
$$V_L = \sqrt{(K + 4/3G)/\rho}$$

$$V_T = \sqrt{G/\rho}$$

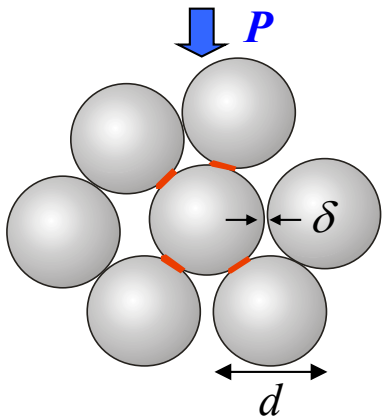


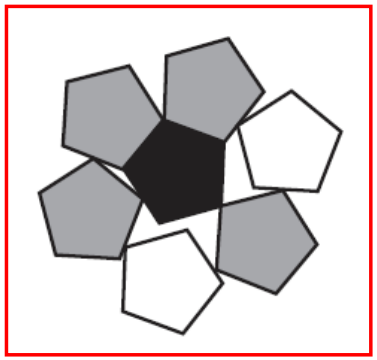
♦ Effective medium theory (affine approximation) *(Duffty & Mindlin 1957; Digby 1981)*

$$V_{L,T}(P) \propto (Z)^{1/3}.[k(P)]^{1/2} \propto P^{1/6}$$



Hertzian contact :
$k \sim P^{1/3}$





$Z_{bead} \approx 6$
$Z_{sand} \approx 4$

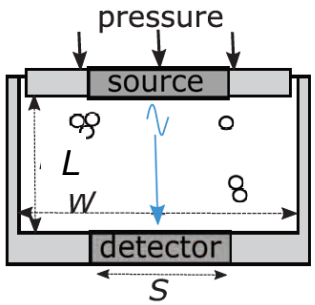
Wildenberg, Yang & Jia
Granular Matter 17 (2015)

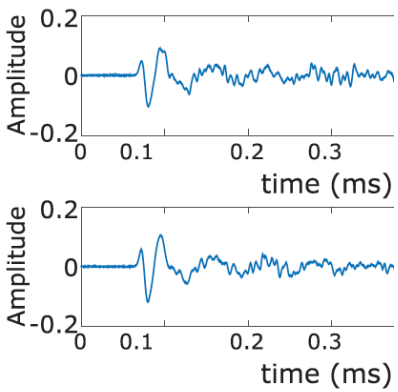
- *Goddard (1990)*
- *de Gennes (1999)*
- *Makse, Johnson, Schwartz (2000)*
- *Velicky, Caroli (2002)*
- *Coste, Gilles (2003); Roux (2000)*

Sound wave velocity V_P fluctuation in granular layers (3/4)

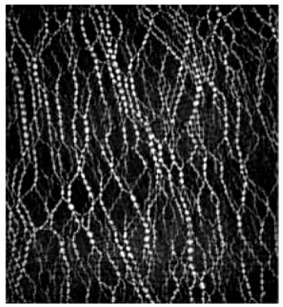
Wildenberg, Tourin, and Jia , Europhys. Lett. 115 (2016)

♦ Set-up



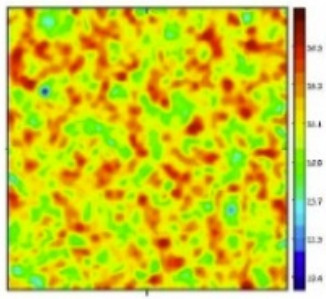


▸ **Elastic anisotropy**



Majmudar, Behringer Nature (2005)

▸ **Shear modulus fluctuation**



Barrat et al, PNAS (2014)

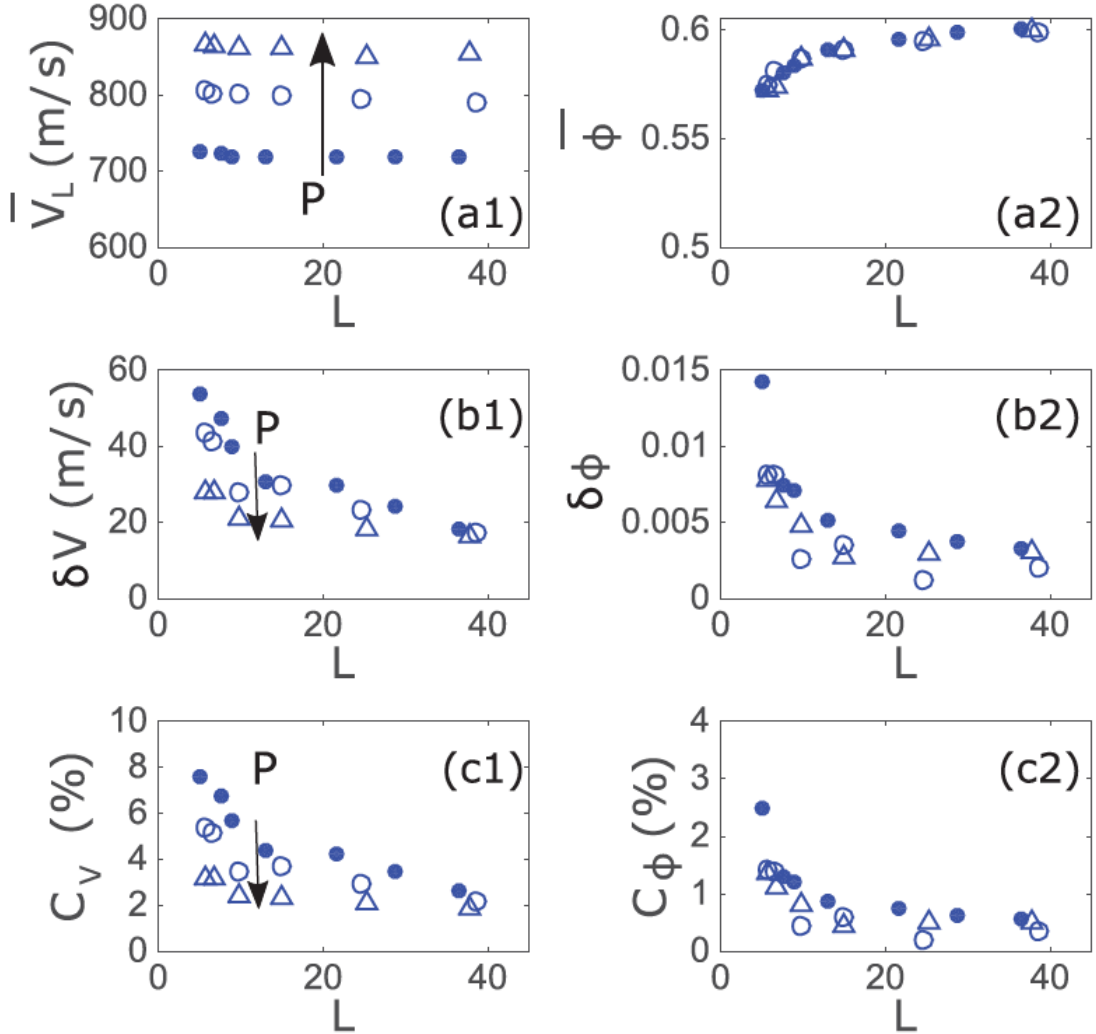
$$V_L = \sqrt{(K + 4/3G)/\rho}$$

with $\bar{V}_L/\bar{V}_T \approx 1.8$

one has $\delta G/\bar{G} \sim 5\,\overline{\delta V_L}/\bar{V}_L \sim 40\%$

for coarse graning length $w = L\ (= H/d) < 5$

Spherical glass beads *(d = 1.5 mm)*



Wave speed fluctuation:

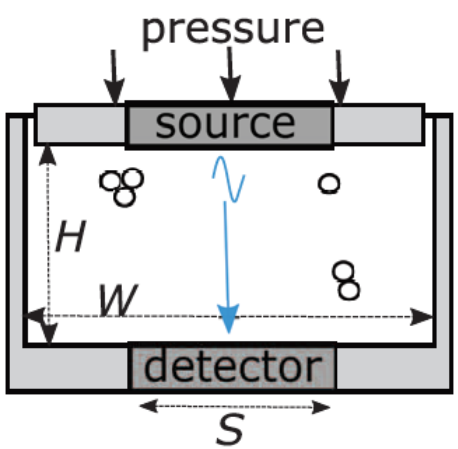
$C_V = \delta V_L/\bar{V}_L$

Packing density fluctuation:

$C_\phi = \delta\phi/\bar{\phi}$

Sound wave velocity V_P fluctuation in granular layers (4/4)

♦ **Set-up**



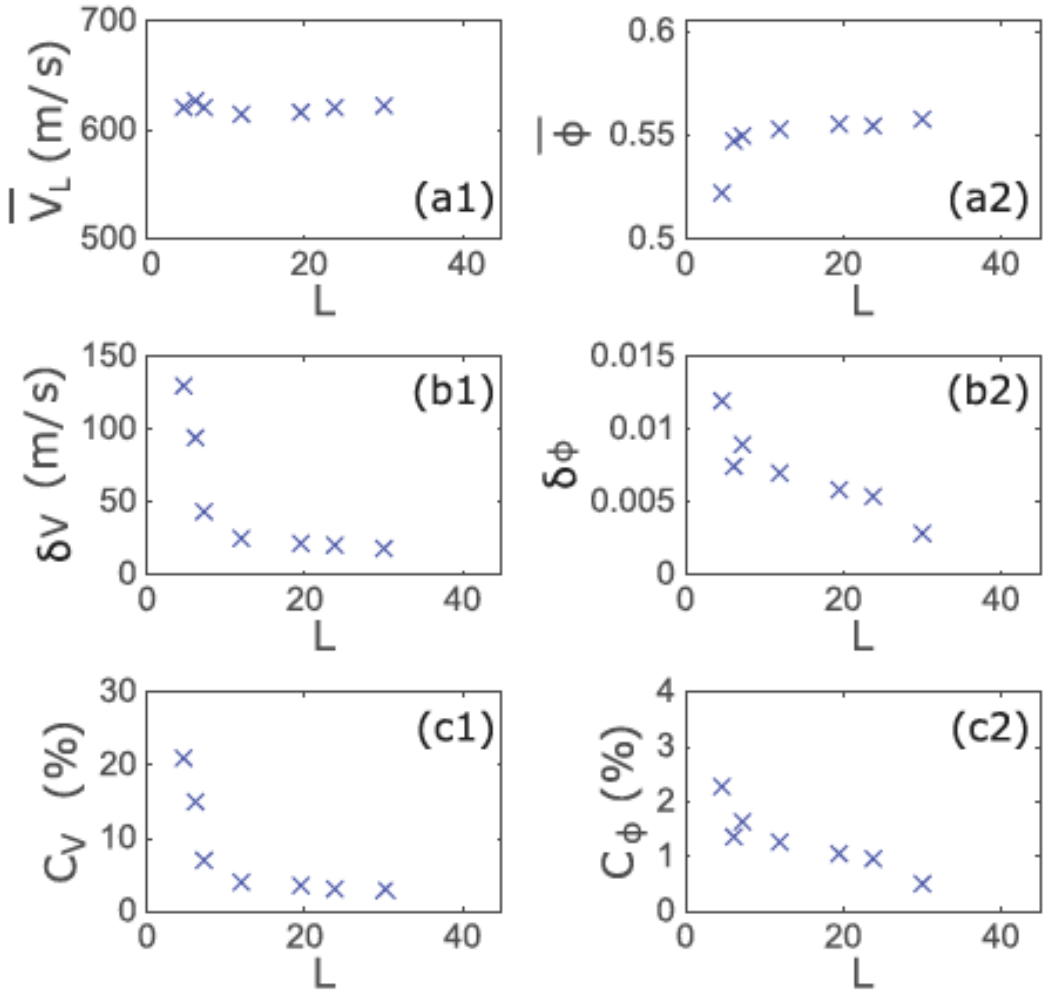
$$V_L = \sqrt{(K + 4/3G)/\rho}$$

with $\bar{V}_L/\bar{V}_T \approx 1.8$

one has $\delta G/\bar{G} \sim 5\,\overline{\delta V_L}/\bar{V}_L \sim 100\%$

for coarse graning length $w = L\,(= H/d) < 5$

Irregular sand particles *(d = 1.8 mm): (micro)-**ballasts***



Wave speed fluctuation:

$$C_V = \delta V_L/\bar{V}_L$$

Packing density fluctuation:

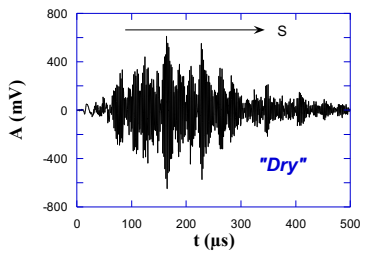
$$C_\phi = \delta\phi/\bar{\phi}$$

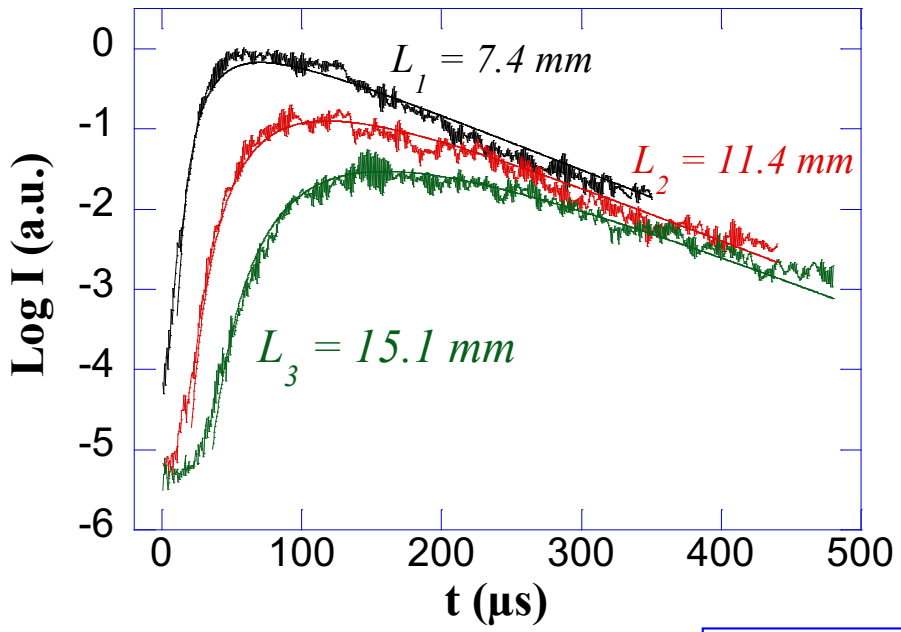
Codalike multiple scattering of *shear* waves in granular media (1/4)

Jia, Phys. Rev. Lett. 93 (2004)

$$\partial_t I - D\nabla^2 I + \frac{I}{\tau_a} = \delta(z)\delta(t)$$

with $D = (1/3)\, v_e\, l^*$ the diffusion coefficient and τ_a the inelastic absorption time





- *Page, Weitz et al, PRE (1995)*
- *Weaver, Sachse, JASA (1995)*
- *Tourin, Derode, Fink, Random Media (2000)*

$D \approx 0.13$ mm²/µs

$\tau_a \approx 64$ µs

→ $Q^{-1} = (2\pi f \tau_a)^{-1} \approx 0.005$

Theorem of energy equipartition :

$N_T / N_L \propto 2\,(v_L/v_T)^3 \approx 16$

Weaver, JASA (1982)

$l^* \approx 0.87$ mm $\sim d$

→ $\xi \leq l^* \sim d$ (not 5-10 d !)

Short-range correlation of the force chain !

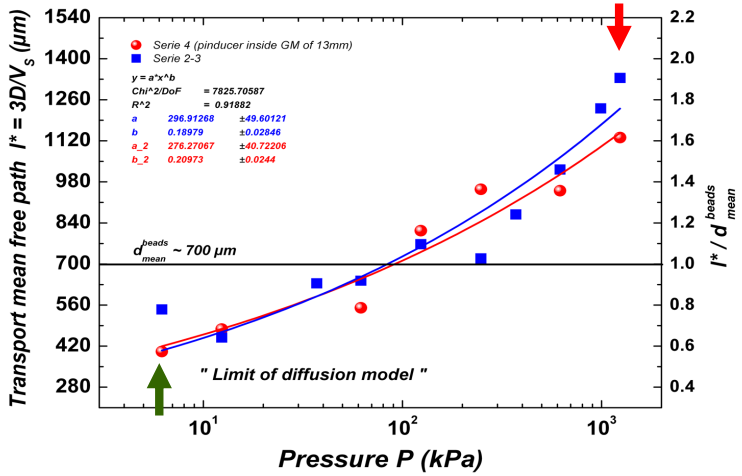
Evolution of transport mean free path l^* vs pressure P (2/4)

Laurent, Yang & Jia (in preparation)

$l^* = 3D / v_e$

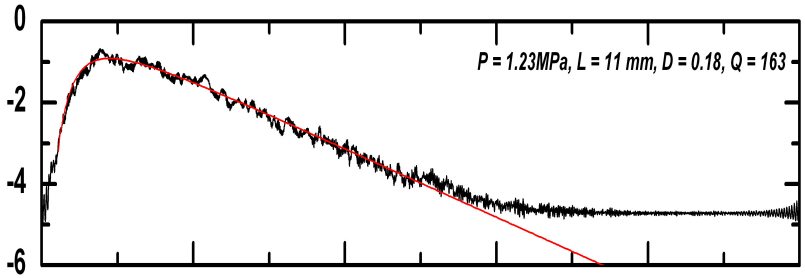
with $v_e = v_{shear}$ (?)

cf Sound scattering in granular suspensions (A. Le Ber, ongoing work)



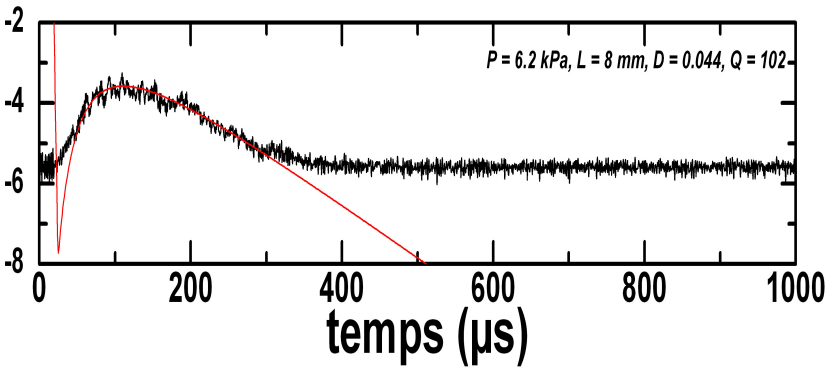
← *Sub- or Super-diffusion ?*
← *Anderson localization ?*

◆ *Strong stress P*

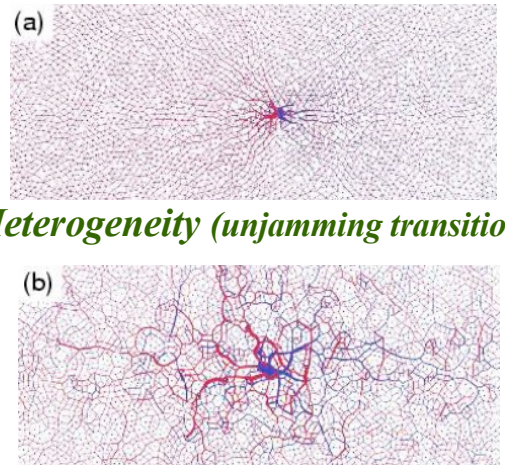


Breakdown of a diffusion model for weakly stressed media ?

◆ *Weak stress P*



◆ **Response to a point force**



Heterogeneity *(unjamming transition)*

P

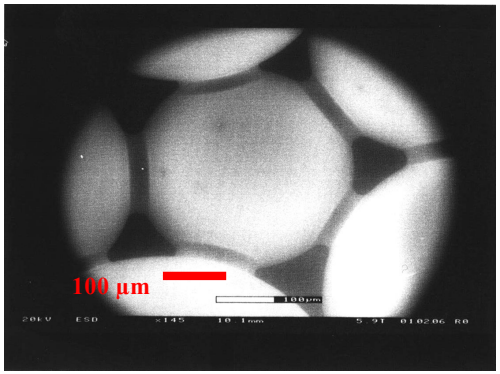
Ellenbroek, van Hecke, van Saarloos, PRE (2009)

Continuum, homogeneous elasticity not applicable at small scales !

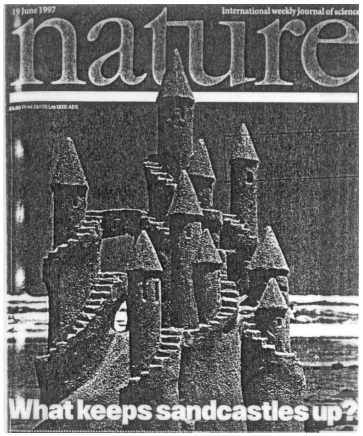
- *Barrat, Tanguy et al*
- *Goldenberg & Goldhirsch*

Probing the internal dissipation in dry and wet granular media with diffusively scattered waves (3/4)

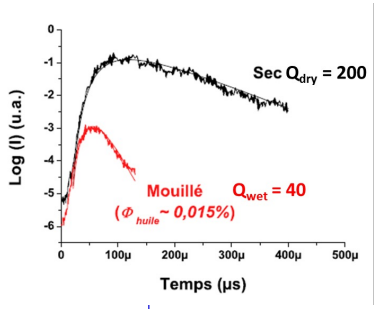
Liquid Bridges



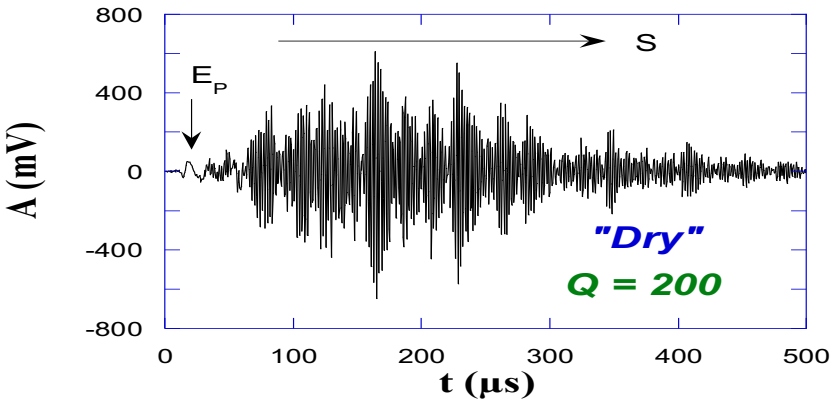
$\Phi_{oil} = 1\%$

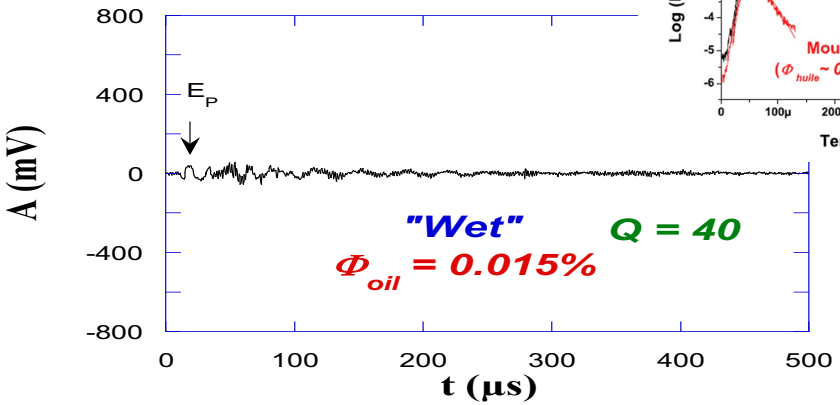


-Bocquet, Charlaix, Crassous, Ciliberto, 1998
- Halsey & Levine, 1998
- Schiffer et al, 1999
- Herminghaus et al, 2005



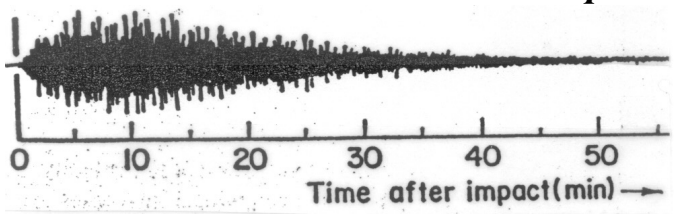
- **Absorption of multiply scattered waves by added liquids**



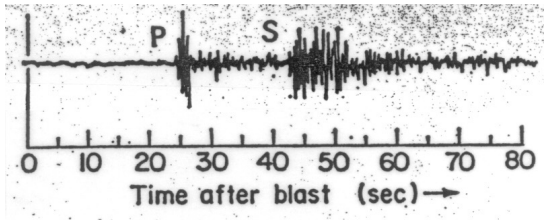


- **Similitude with the seismograms (« coda »)**

« Lunar » *Apollo 12*



« Terrestrial »

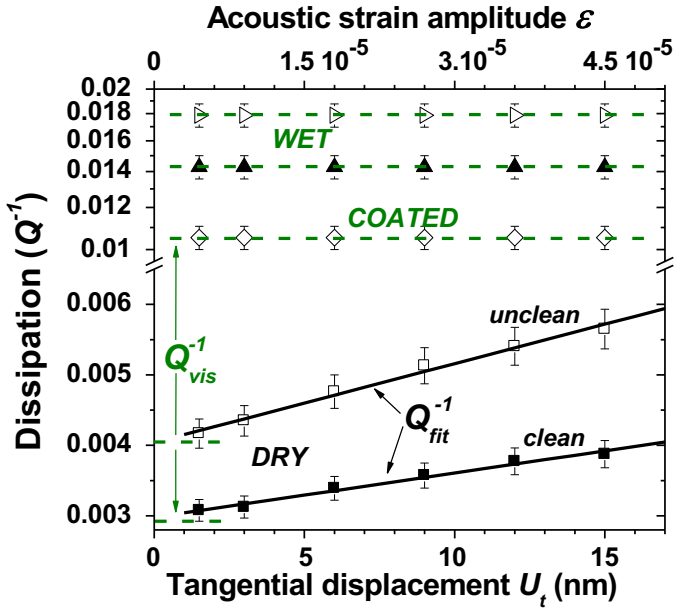


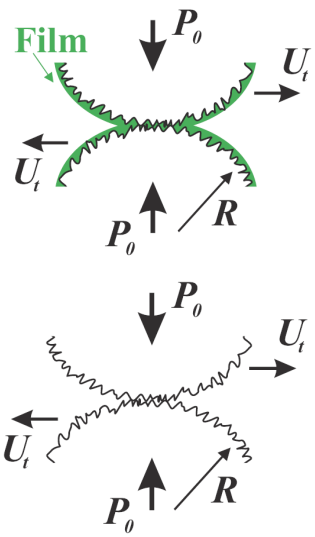
$Q_{moon} \cong 500\ Q_{earth}$

Latham et al ***Science****, 1969*

Interfacial dissipation mechanisms in glass bead packings (4/4)

Brunet, Jia & Mills, Phys. Rev. Lett. 101 (2008)





$$Q^{-1} = \frac{\Delta W_{loss}}{W_{stored}} = Q^{-1}_{vis} + Q^{-1}_{fric}$$

♦ ***Linear* viscoelastic** dissipation (***asperities*** *or* ***films***) (Johnson, 1955; Baumberger et al 1998)

♦ ***Nonlinear* frictional** dissipation (Mindlin, 1950)

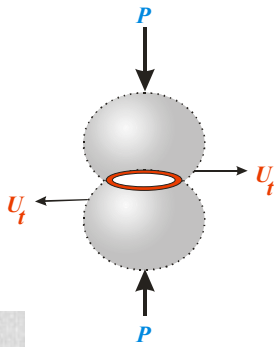
$$Q^{-1}_{fric} \propto \mu^{-1}\ U_t\ P^{-2/3}$$

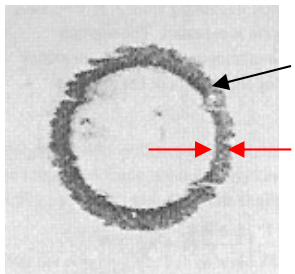
$$Q^{-1}_{unclean} = 0.004 + 112.10^3\ U_t$$

$$\rightarrow \mu_{unclean} = 0.98$$

$$Q^{-1}_{clean} = 0.003 + 63.10^3\ U_t$$

$$\rightarrow \mu_{clean} = 1.75$$

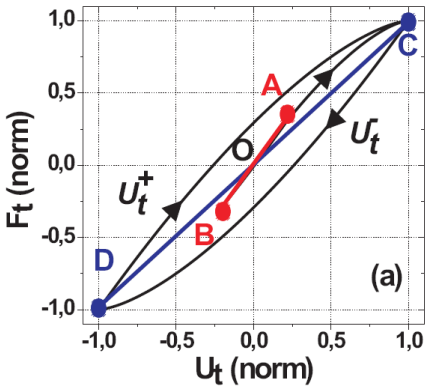




'Microslip'

L >> 100 nm
(valid range)

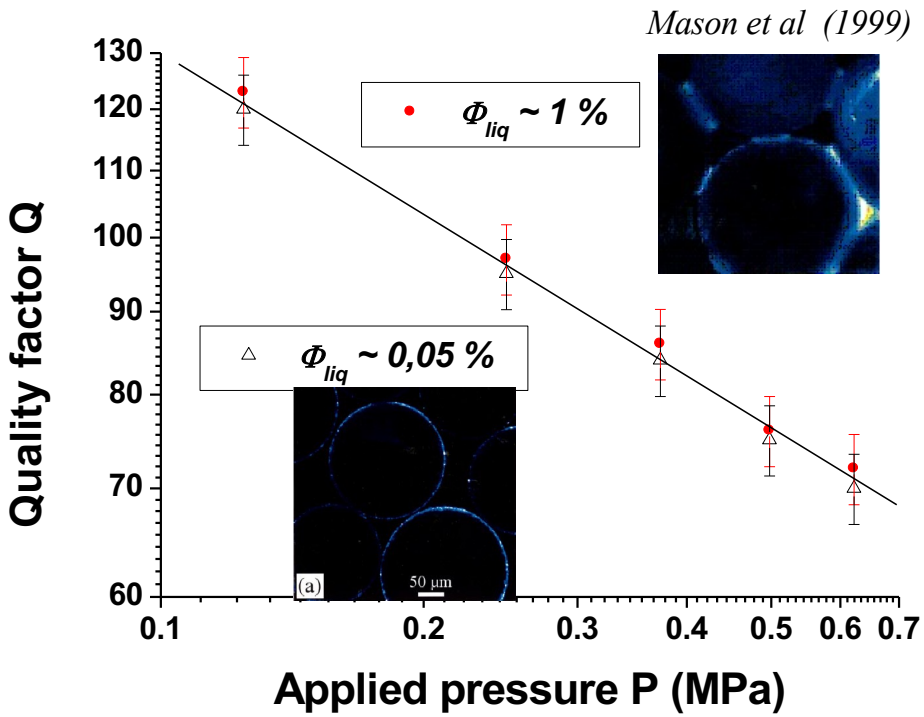
K. Johnson (1961)



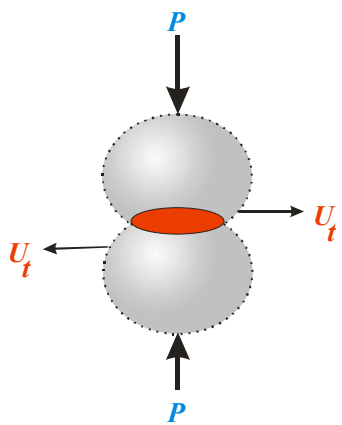
← Breakdown of the Mindlin's model:
***local* Coulomb friction μ not legitimate !**

Bureau, Baumberger, Caroli (2002)

Interfacial dissipation in *wet* glass bead packings (5/5)



$$Q^{-1} \simeq Q_{liq}^{-1} \quad (\gg Q_{fric}^{-1})$$

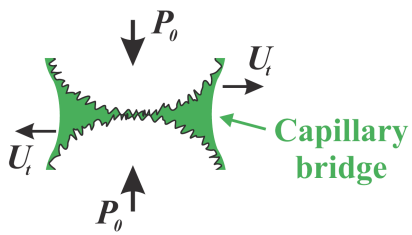


$$Q_{liq}^{-1} \propto \nu \; \delta_{liq}^{-1} \; P^{1/3}$$

$(\nu$: vis cos ity; δ_{liq} : film thickness$)$

$$10cSt \le \nu \le 100cSt$$

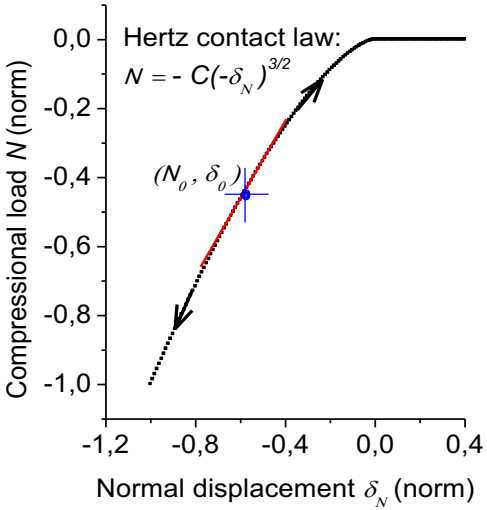
$$10nm \le \delta_{liq} \le 100nm$$



→ ***Viscous dissipation** occurs primarily in **liquid films** trapped at contact zones, but **NOT** in **bulk** capillary **meniscii**.*

1.2 Nonlinear ultrasound propagation in *fragile* granular solid

♦ Hertzian nonlinearity:



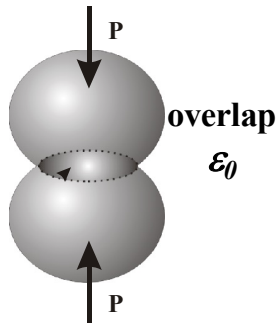
▸ **weakly nonlinear regime:** $\varepsilon_a \ll \varepsilon_0$

$$\sigma_a = M_0 \varepsilon_a (1 + \beta \varepsilon_a + \ldots)$$

$\beta = -1/(4\varepsilon_0)$ is third-order elastic constant

(Norris & Johnson, 1997)

→ harmonics generation (reversible interaction)



▸ **strongly nonlinear regime:** $\varepsilon_a > \varepsilon_0$

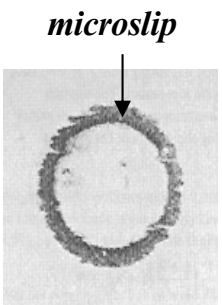
Soliton-like shock waves : 1D ordered granular chains

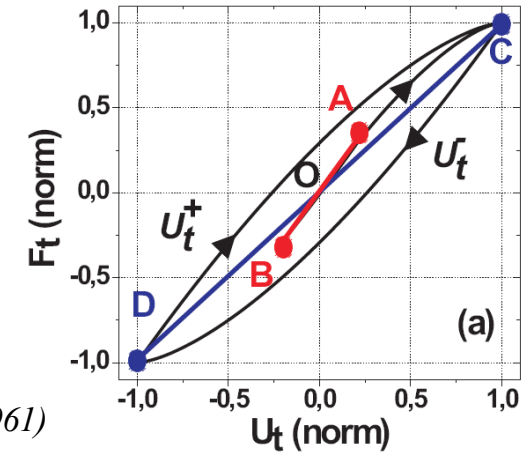
-**Nesterenko** (1983); Coste, Falcon, Fauve (1997); Sen et al, 2008

- Dario, Nesterenko et al (2006); Huillard, Noblin, Rajchenbach (2011)

- Gomez, Wildenberg, van Hecke, Vitelli (2011): 2D/3D disordered packs

♦ Frictional nonlinearity: *micro-plasticity* (« slipping micro-fissure»)
(Mindlin model)





K.L. Johnson (1961)

in weakly nonlinear regime, $\varepsilon_a < 0.1\varepsilon_0$

▸ **Frictional (hysteretic) dissipation**

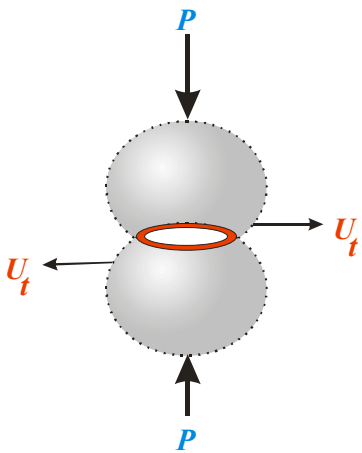
Brunet, Jia, Mills, PRL 101 (2008)

▸ **Shear stiffness weakening**

$U_t{}^*$ increases

$k_t = dF_t/dU_t$ decreases

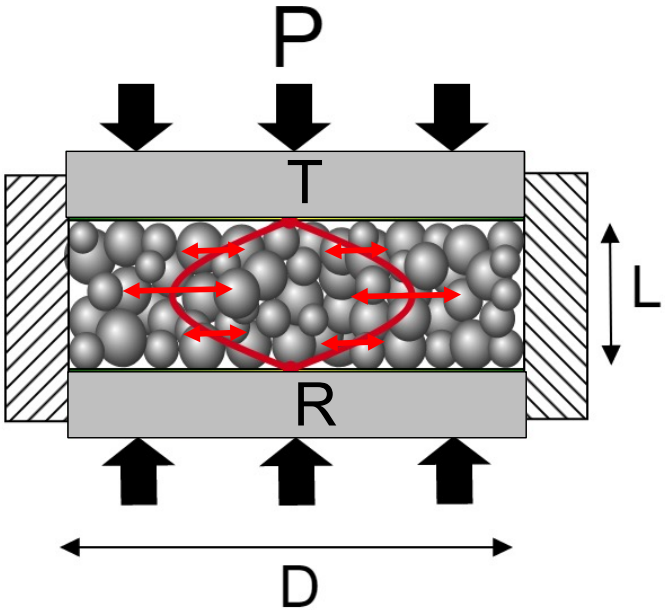
Jia, Brunet, Laurent, PRE 84(R) (2011)



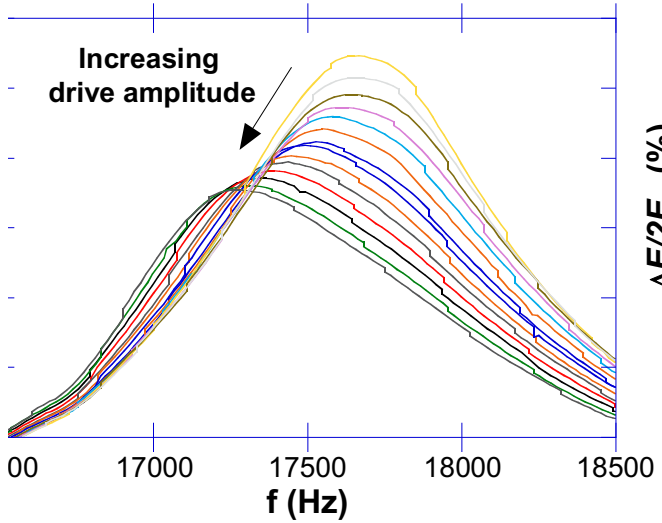
Nonlinear acoustic resonance in granular solids (1/2): *P- modes*

♦ **Compressional mode**

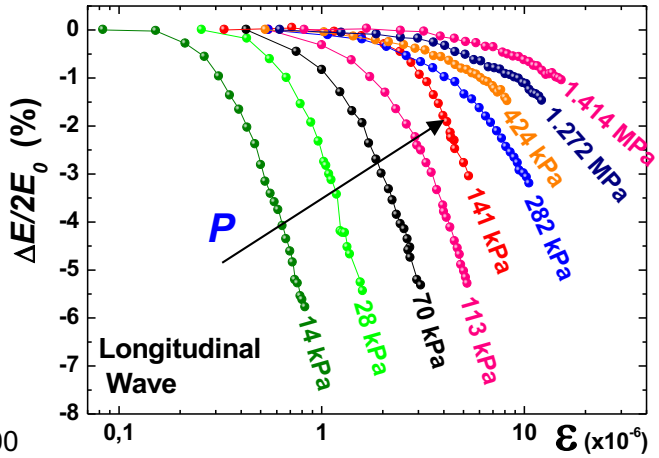
Johnson & Jia, Nature 437 (2005)



P = 0.11 MPa and *L = 18.5 mm*

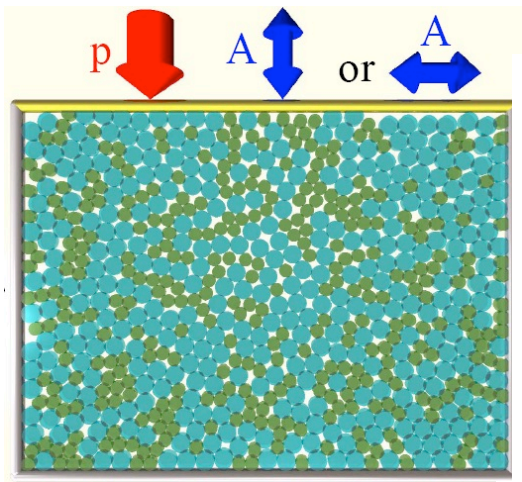


Young modulus weakening: $E = \rho V^2$

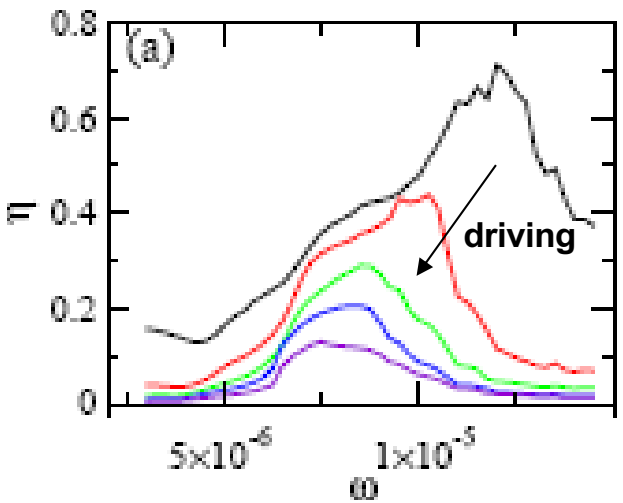


♦ **MD simulation in 2D frictionless disk packs**

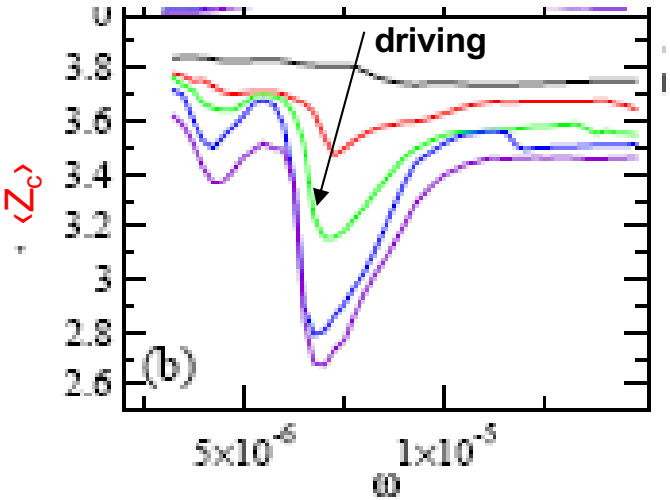
$$V(P) \propto (Z)^{1/3}.[k(P)]^{1/2} (\propto P^{1/6})$$



Olson, Lopatina, Jia, Johnson
PRE 92 (2015)



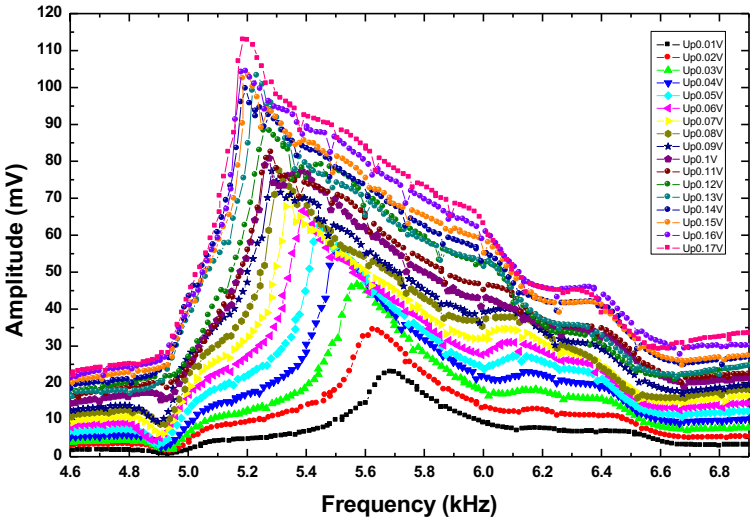
Dilatancy ?



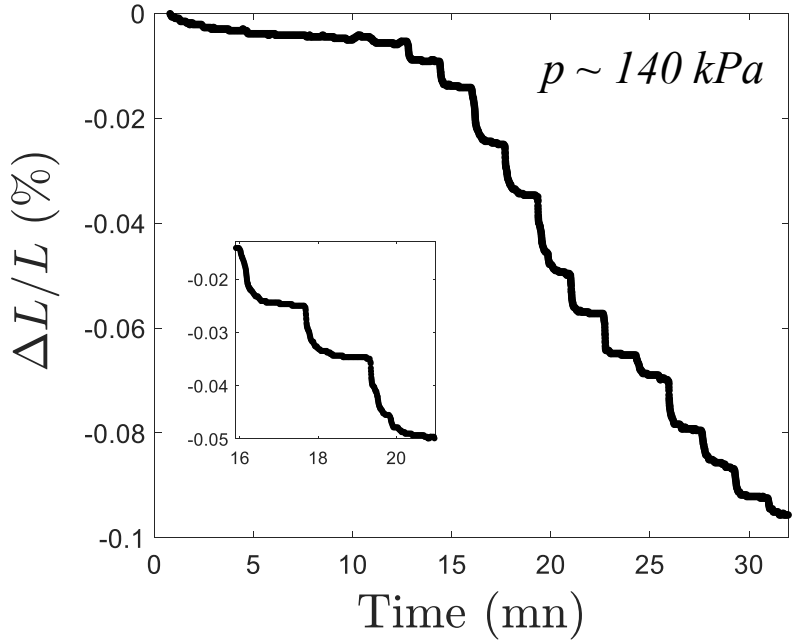
Nonlinear acoustic resonance in granular media (2/2): *shear modes*

Lieou, Laurent, Johnson, and Jia, arXiv (2022))

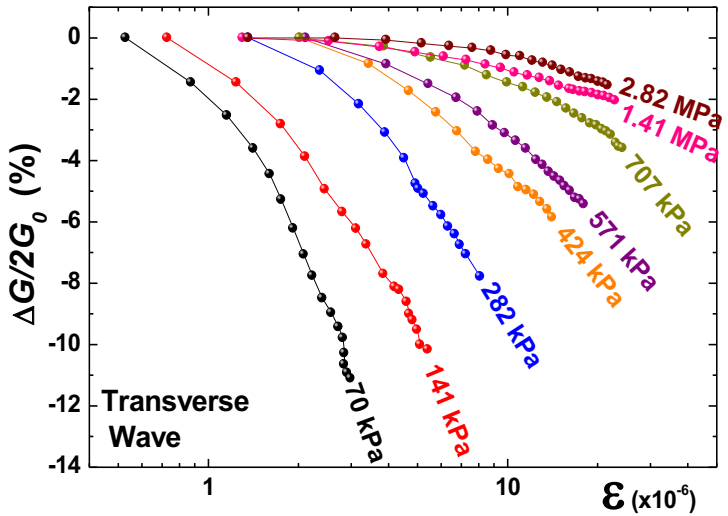
♦ Resonance curves vs amplitude



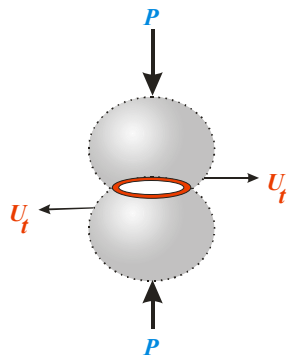
♦ Activated-like (logarithmic) compaction



♦ Shear modulus weakening



Micro-slip (plasticity)* by the *acoustic lubrication*, *leading to the «adhesion decrease» and compaction !



$$c_L \propto (Z / R\rho_0)^{1/3} (k_n)^{1/2}$$

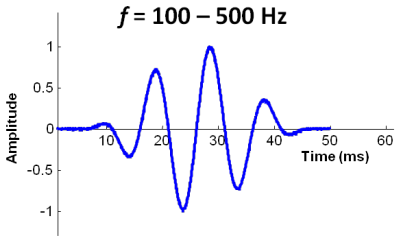
with Z slipping!

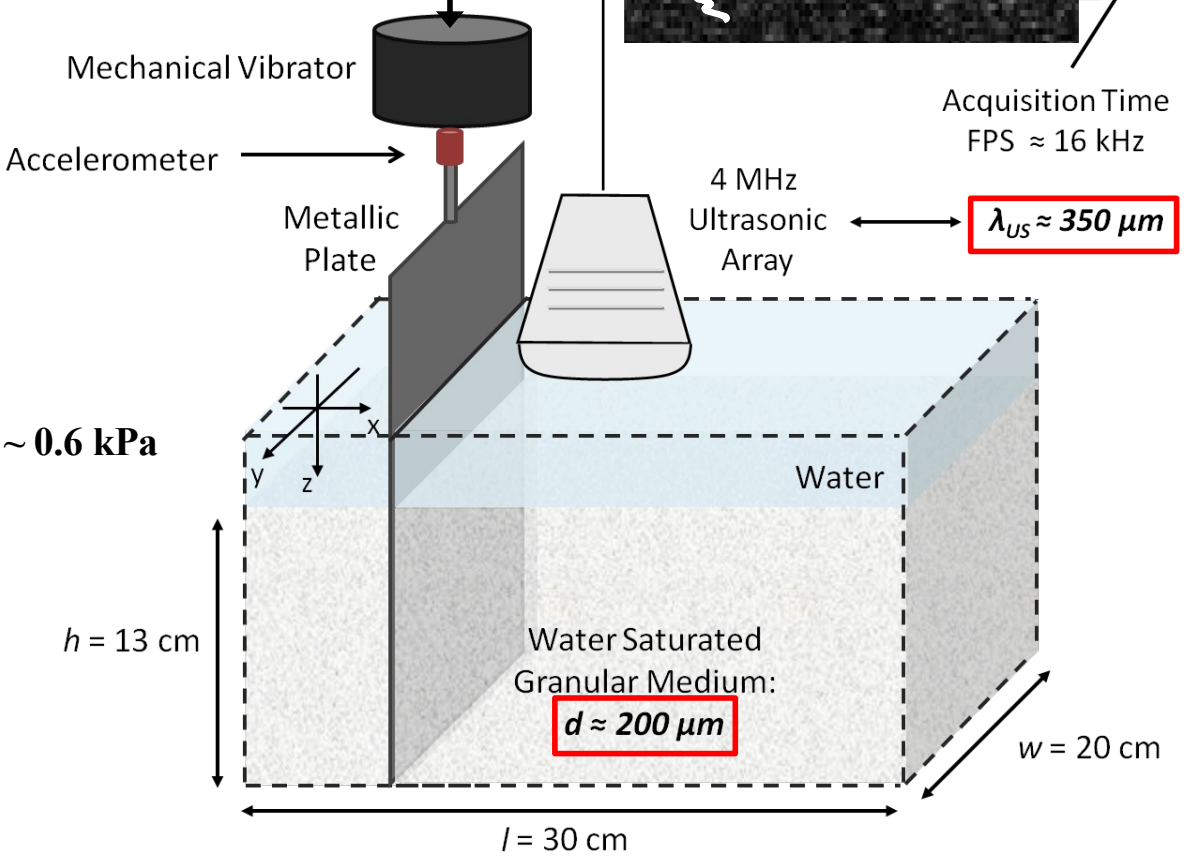
Shear wave velocity softening in granular sediments (1/3)

♦ **Elastography using ultrasonic speckle interferometry**

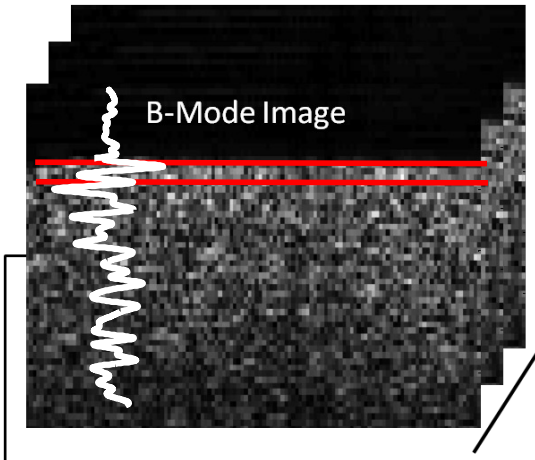
Brum, Gennisson, Fink, Tourin & Jia , PRE 99 (2019)

- Catheline, Gennisson, Tanter, Fink, *PRL* 91 (2003)
- Maneville et al, PRA (2013)



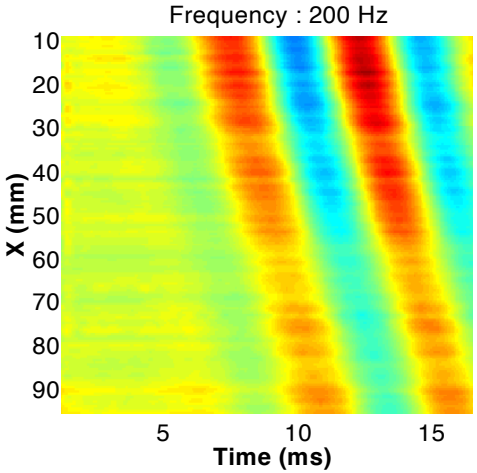


"PIV"



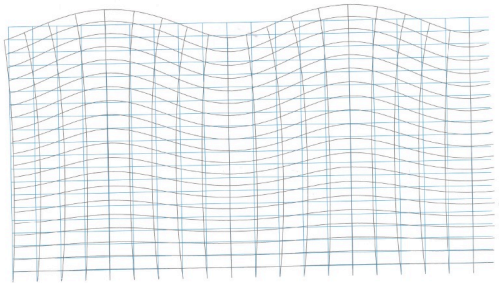
Correlation Algorithm

- **Out-of-plane *surface vibration* in the linear regime**



- **Rayleigh-like surface acosutic wave**

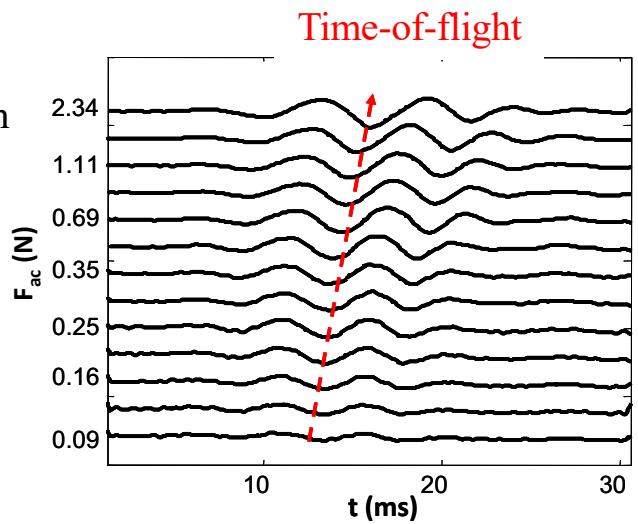
$V_S \approx 28$ m/s and $l_{LF} \sim 10$ cm

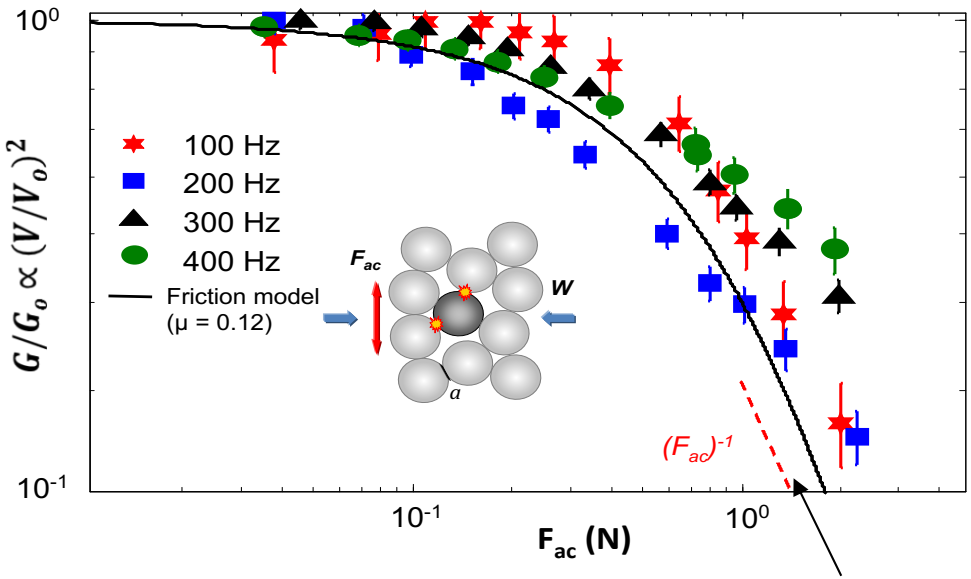


- *Bonneau et al, PRL 101(2008)*
- *Jacob et al, PRL 100 (2008)*

Shear wave velocity softening (2/3): transition from jammed to unjammed states

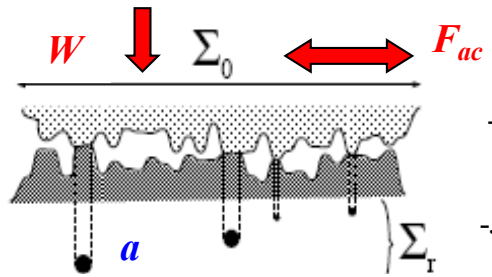
Distance:
$x = 95.5$ mm





Otsuki & Haykawa (2014)
(with dilatancy !)

♦ **Multi-contact interface** (Mindlin friction model)



-Bureau, Caroli, Baumberger *R. Soc.Proc.* (2003)

-Jia, Brunet, Laurent, *PRE* (2011)

$\rho(a) \sim \exp(-a/a_0)$ à la Greenwood

→ Contact slipping by oscillatory shear leads to the softening of interfacial shear stiffness k !

♦ **Mean-field theory of granular media:**

$$V_S^2 \propto G \propto Z_0 * k * \Delta Z \quad (\propto P^{2/3} \text{ frictionless spheres})$$

Z_0: mean coordination number
Δz: excess number (to isostatic limit)

Wyart, Nagel, Witten *PRE* (2005)

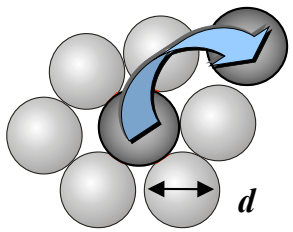
$$G/G_0 (= \mu_s/\mu_{s0}) = 1/\left[1 + F_{ac}/2\mu W + (5/4)(F_{ac}/2\mu W)^2\right]$$

Shear modulus softening (& **yield deccrase**) are due to contact slipping between grains (local-avalanche process).

jammed → unjammed states: without packing density change $\Delta\phi$!

Shear wave velocity softening: jammed → unjammed/flowing states (3/3)

$f_{LF} = 100\ Hz$



$V_S^2 \sim G(Z, \gamma_0)$

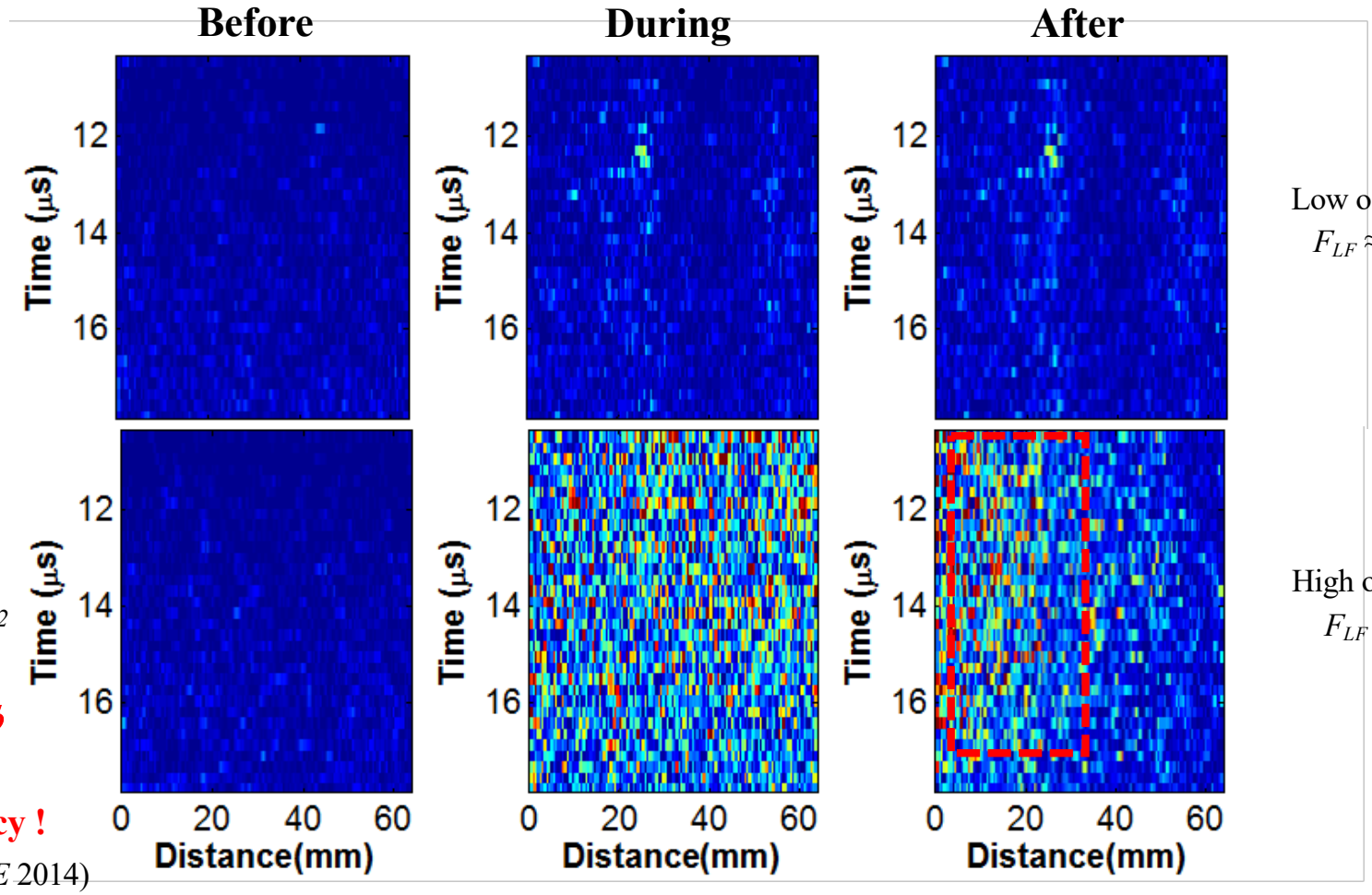
$\sim K(\Delta Z)^2 \gamma_0^{-1/2}$

ΔZ & packing ***Δϕ***

are decreased

due to shear **dilatancy !**

(Otsuki,& Haykawa *PRE* 2014)



Low oscillation:

$F_{LF} \approx 0.03\ N$

High oscillation:

$F_{LF} \approx 2.7\ N$

Nonlinear elasticity is coupled with plasticity in amorphous media !

Procaccia et al, *PRE* (2011)

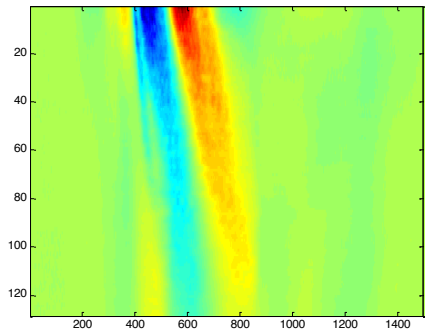
The shear velocity is $V_S \approx 6.8\ m/s$

→ $\Delta V_S / V_S$ (≈ 10/17) ≈ 55%

→ the shear modulus

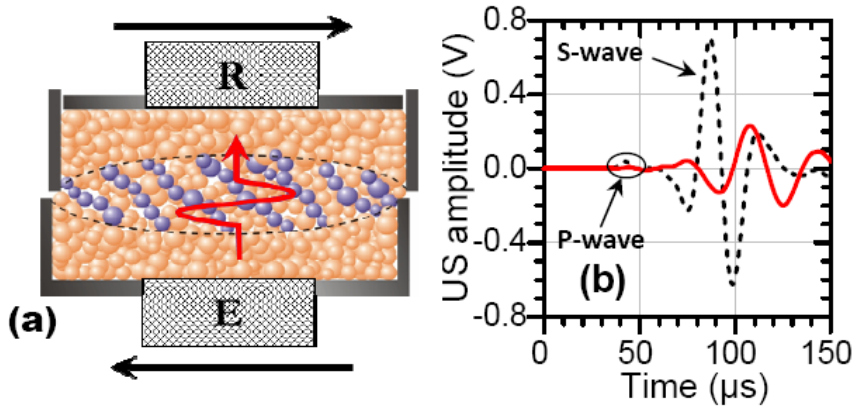
$\Delta G/G \sim 85\%$!!

during unjamming transition !

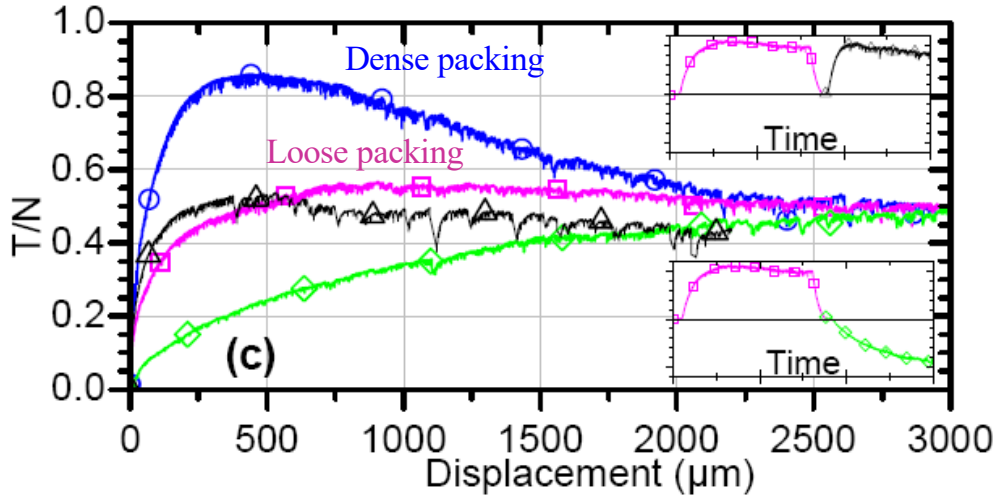


2.1 Probing the shear band formation with shear wave (1/3)

Khidas & Jia, PRE 85 (2012)

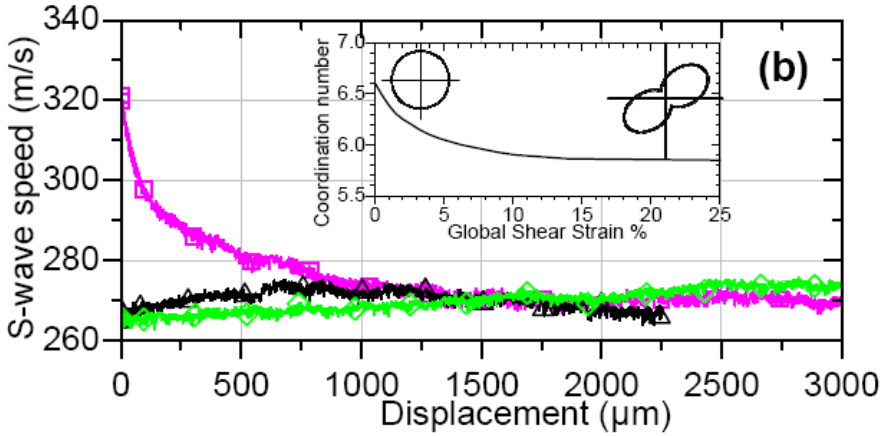


♦ **Mechanical response**

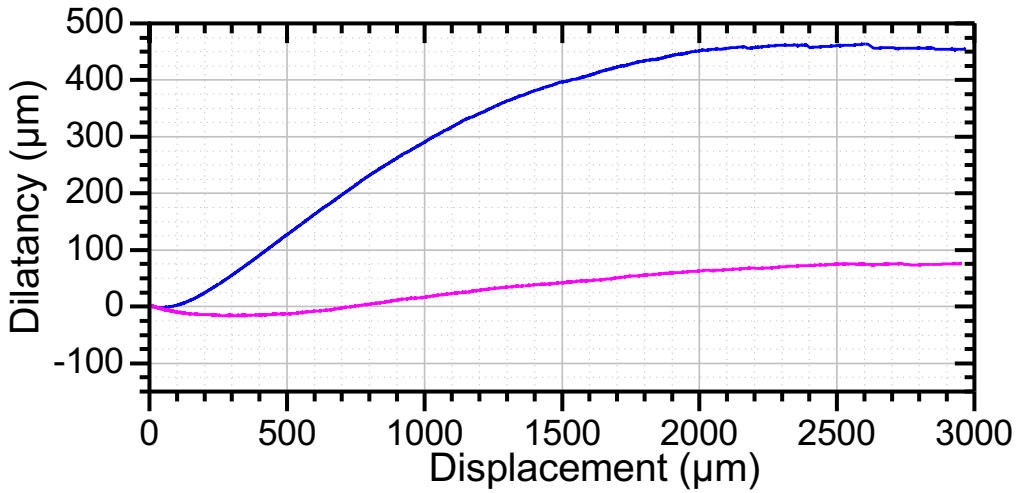


♦ **Shear wave velocity weakening before failure**

Loose packing



Reynolds' Dilatancy



Outline

1. Ultrasound propagation in *heterogeneous* granular solid

1.1 Linear propagation

- coherent waves (elastic heterogeneity)
- multiple scattering (dissipations & mean free path)

1.2 Nonlinear propagation

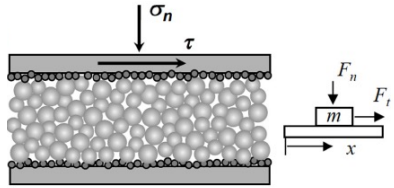
- elastic softening (hysteretic nonlinearity)
- slowdown of shear wave velocity (unjamming)

Probe-pump (micro-plasticity)

2. Acoustic montoring and triggering of *shear instability* in confined granular media

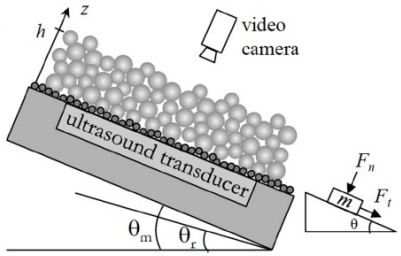
2.1 Shear band formation and failure (labquakes)

- shear-induced wave velocity weakening
- probing precusor events with scattered coda waves



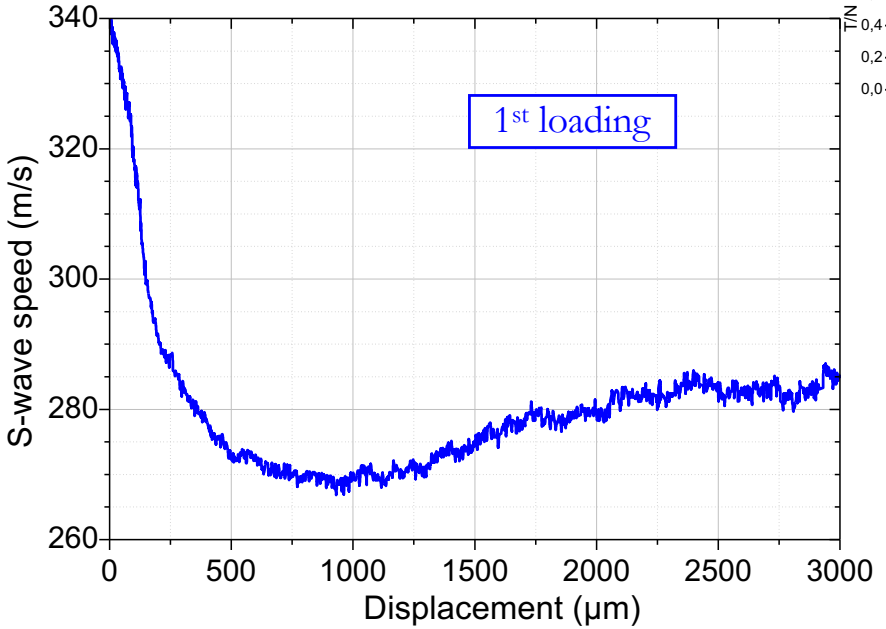
2.2 Ultrasonic triggering of granular avalanches

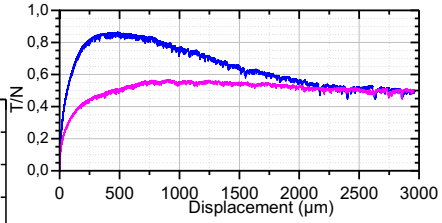
- bifurcation between jamming creep self-accelerated flows
- granular avalanches triggered by acoustic lubrication of contacts



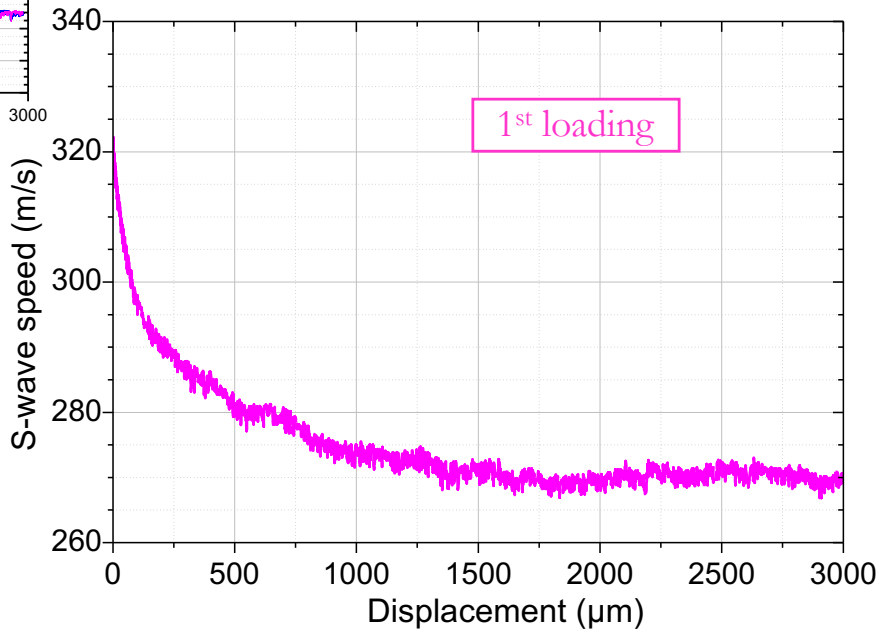
Coherent sound propagation: S-wave speed (2/3)

✓ Initial packing: Dense



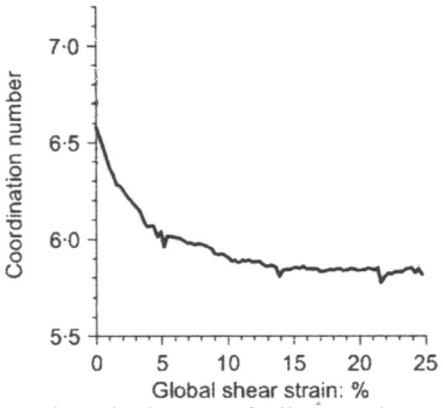


✓ Initial packing: Loose



S-wave speed evolution:

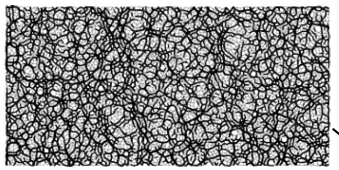
- Decrease of coordination number (z)

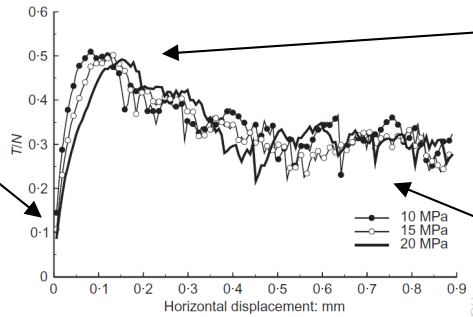


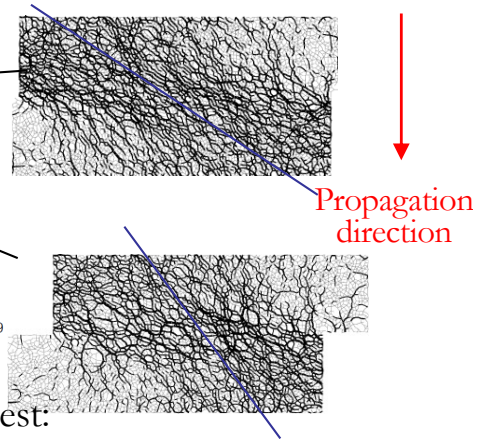
3D DEM simulations of direct shear test:
Cui & O' Sullivan 2006

$$V_S \propto z^{1/3} \cdot \phi^{-1/6} \cdot P^{1/6}$$

- Rotation of principal stress direction







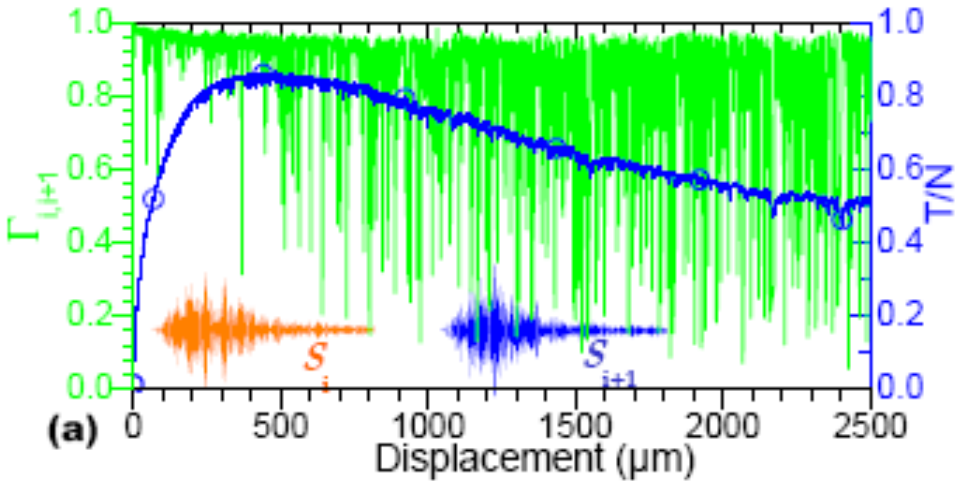
2D DEM simulations of direct shear test:
Zhang & Thornton 2007

Probing intermittent behavior with scattered waves (3/3)

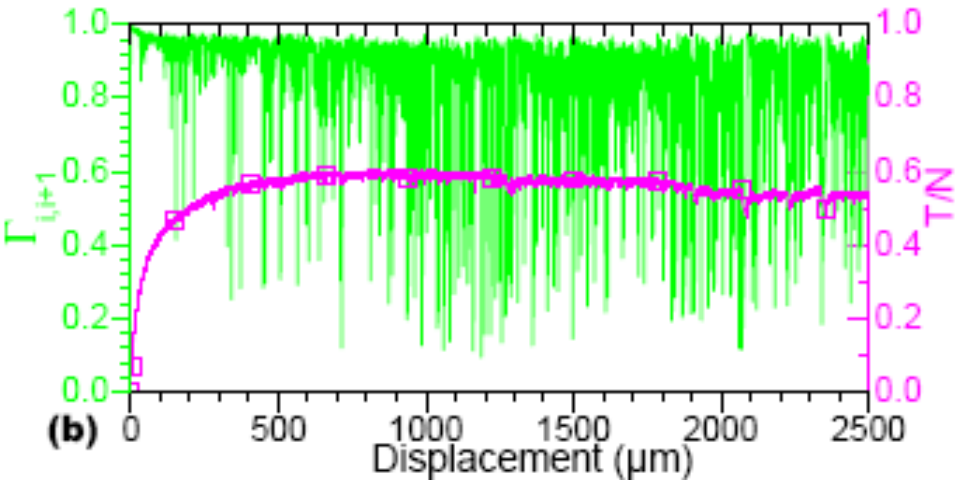
♦ Cross-correlation of scattered waves (i.e., acoustic speckles or coda): cf *DWS*

$$\Gamma_{ij}(\tau=0) \propto \int S_i(t) \cdot S_j(t+\tau)\, dt$$

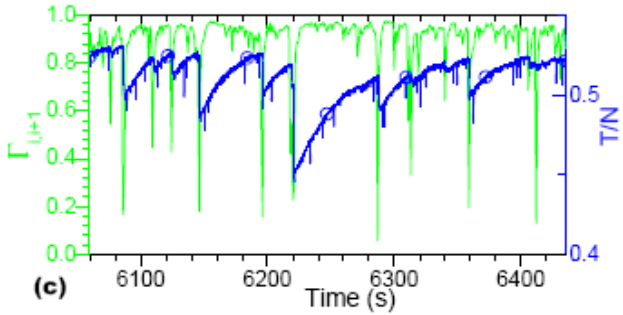
Dense packing



Loose packing



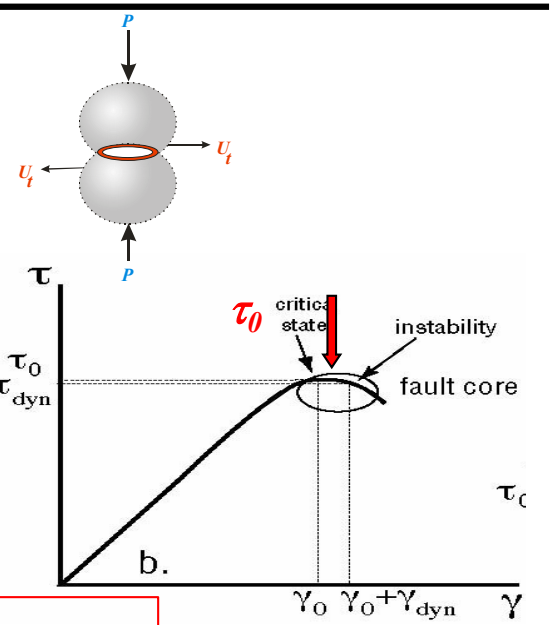
Zoom



Intermittent dynamics !
("stick-slip" events)

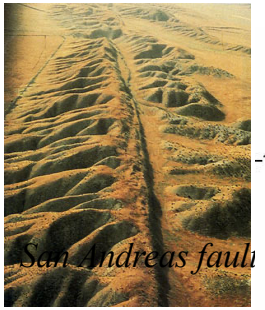
2. Triggering of shear instability via *shear* acoustic lubrication at contacts (micro-palsticity) / T_{eff}

J. Gomberg et al, Nature 2001; Hill et al et , Science 1993



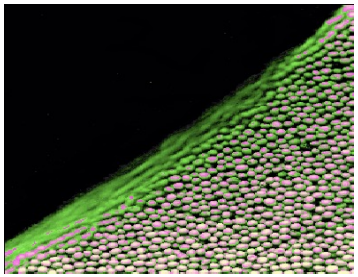
→ Earthquake triggering / dynamical weakening

- *Melosh, Nature (1996)*
- *J. Gomberg et al, Nature 2001*
- *Johnson, Jia, Nature (2005)*
- *Johnson, Gomberg, Marone et al, Nature (2008)*
- *Jia, Brunet, Laurent PRE (2011)*



→ Avalanche/Rheology of vibrated granular media

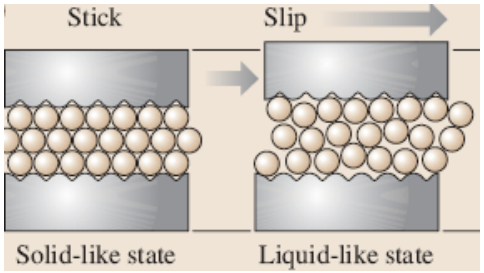
- *Jaeger, Liu, Nagel, PRL (1989)*
- *Dijksman, van Hecks et al, PRL (2011)*
- *Léopoldès, Jia, Tourin, Mangeney, PRE (2020)*



Lowering the yield stress!

→ Sliding triggering of a glassy interface

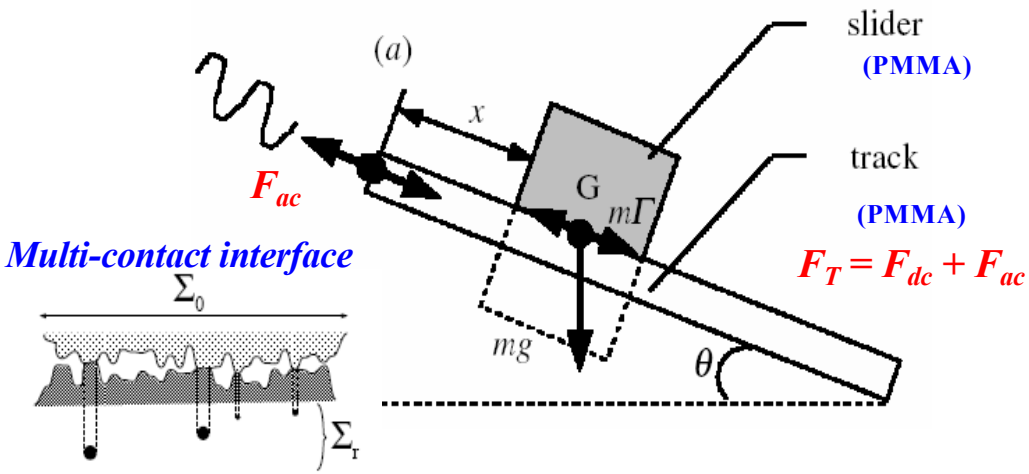
- *Heuberger, Drummond, Israelachvili, J. Phys Chem. (1998)*
- *Bureau, Baumberger, Caroli, PRE (2001)*
- *Léopoldès, Conrad, Jia, PRL (2013)*



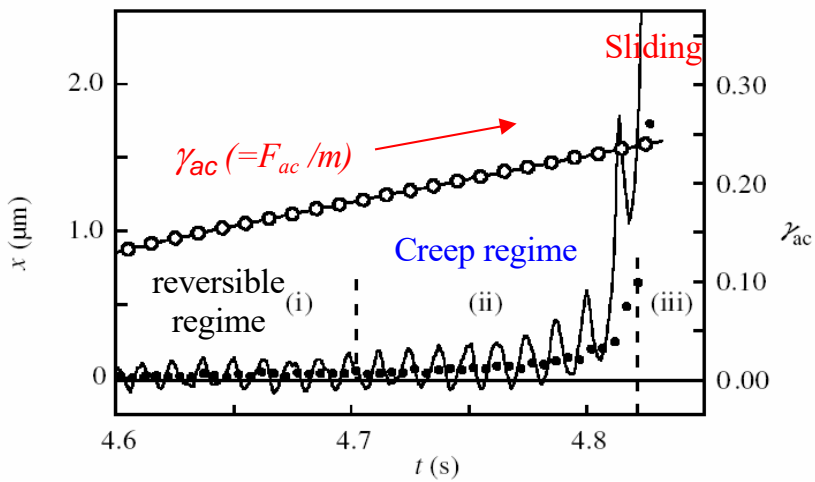
2.2 Sliding triggered by shear oscillation (1/3): sliding at rough interface

Bureau, Baumberger & Caroli, PRE 64 (2001)

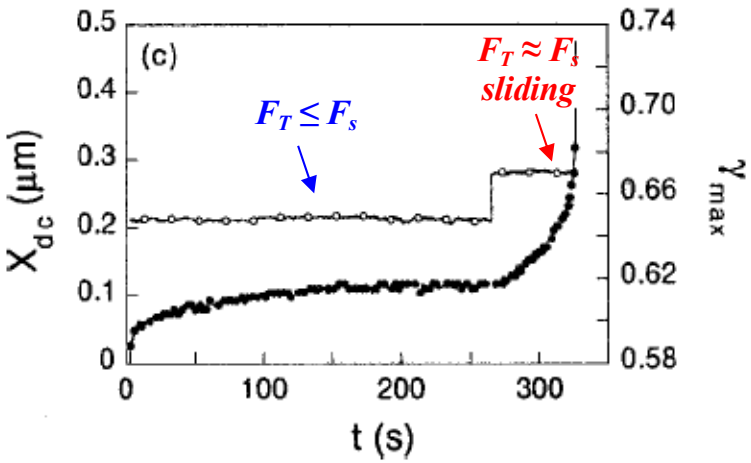
$\omega \ll \omega_0 = \sqrt{k/m}$ (*quasistatic limit: $f = 100$ Hz*)



♦ **Displacement *x(t)* vs biased oscillating shear force (F_{ac})**



♦ **Birfucation: from jamming creep to sliding**

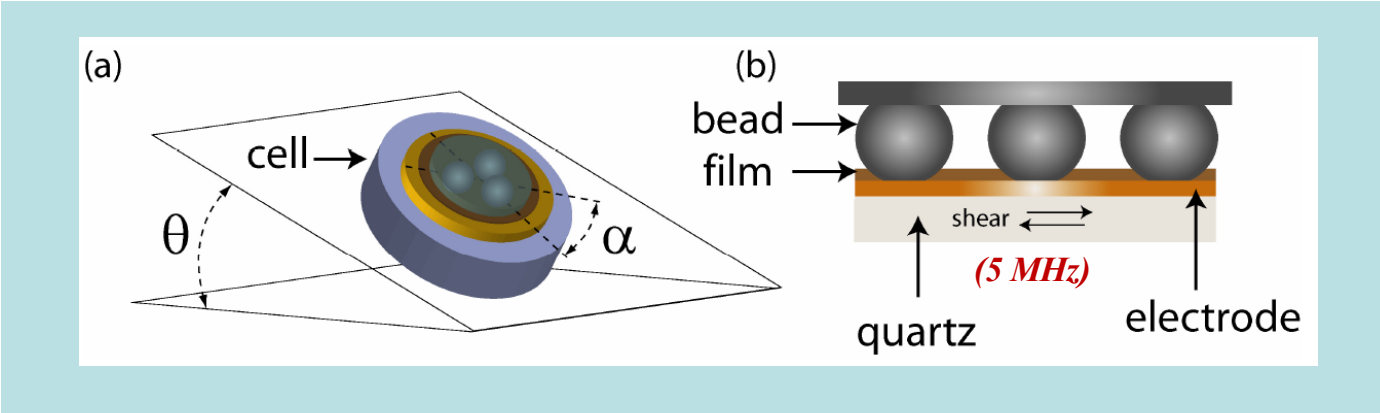


Rate- ($\dot{x}$) and State- (ϕ) constitutive law (Rice-Ruina model):

$$\mu = F_T / F_N = \mu_0 + A\ln(\dot{x}/V_0) + B\ln(\phi V_0 / D_0) \quad \text{with } \phi: \text{ age of contact}$$

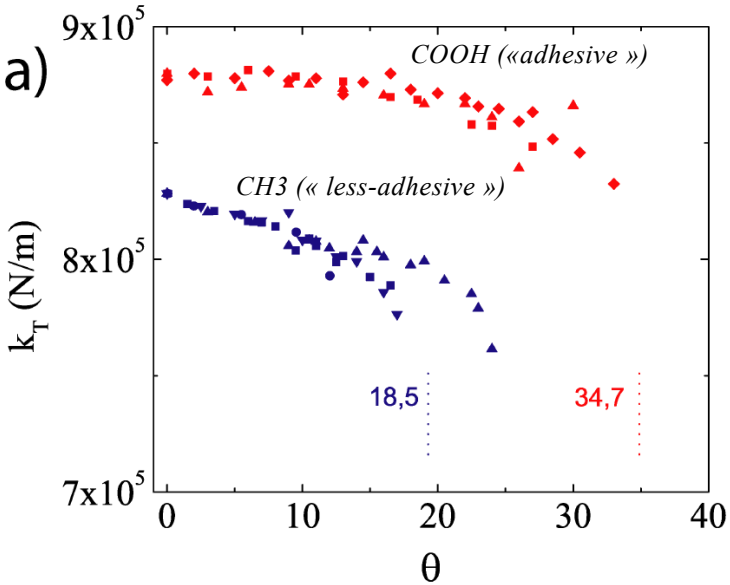
Sliding triggered via acoustic lubrication (2/3): mono-contact sliding

Léopoldès, Conrad & Jia, PRL 110 (2013)

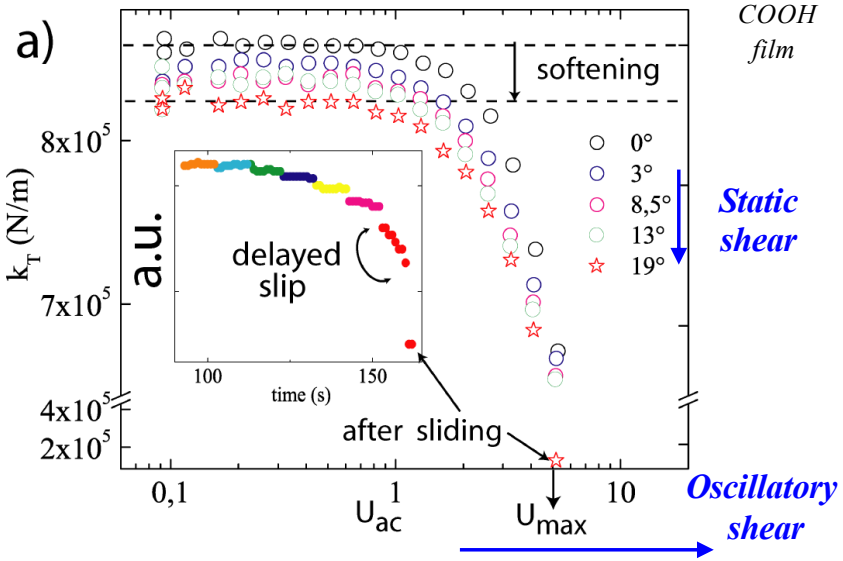


Monolayers (~ 1 nm)

- **Elastic softening k_T (interfacial stifness) under *static* shear**



- **k_T softening under *oscillatory* shear and triggering of sliding**

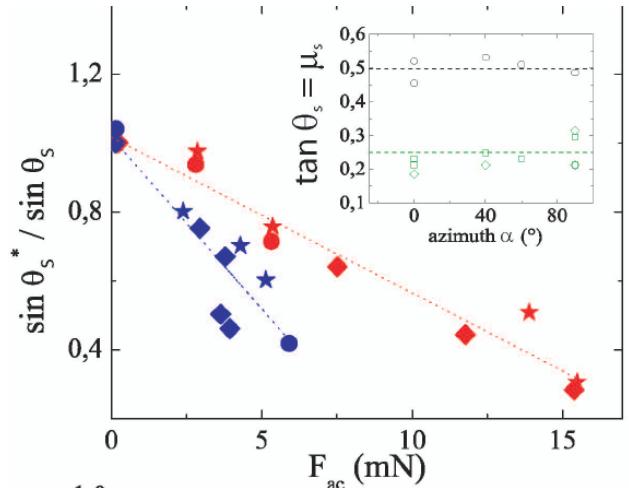


Sliding triggered via *shear* acoustic lubrication (3/3): mono-contact sliding

♦ Sliding triggered below threshold by shear acoustic lubrication

$\omega \gg \omega_0$

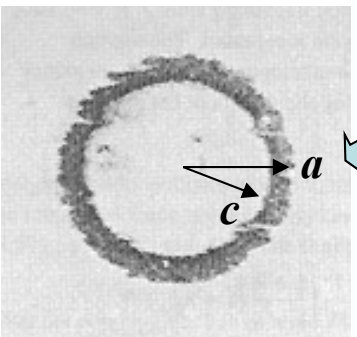
Slider doesn't move!



$\mu_s \approx 2$ *for COOH*
$\mu_s \approx 1$ *for CH3*

$$\sin\theta_s^* / \sin\theta_s = F_s^* / F_s \approx c^2 / a^2 \approx 1 - (2/3) F_{ac} / \mu_s F_N < 1$$

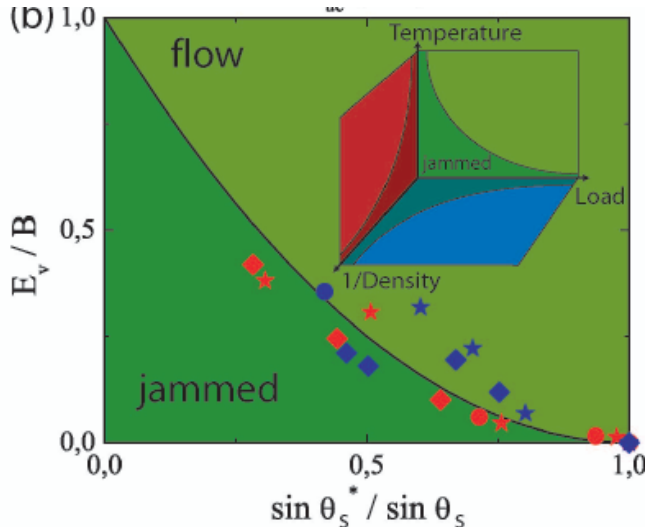
where $F_s = \sigma_s \Sigma_s$ with $\Sigma_s : \pi a^2 \searrow \pi c^2$



Acoustic lubrication *of the* ***stuck area*** (Hertz-Mindlin contact)

♦ Jamming transition diagram

Liu & Nagel (1998)



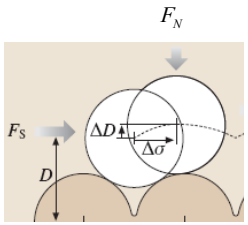
$$E_v / B \approx [1 - (\sin\theta_s^* / \sin\theta_s)]^2 \quad \textbf{(solid line)}$$

with $E_v \approx (A/2) K U_T^2$ *Vibrational energy or* T_{eff}

and $B \sim 10^{10} kT$

Note $E_{jump} \approx F_N \Delta D \sim 10^{12} kT$ with $\Delta D \sim 1\mu m$ (asperity)

$\rightarrow E_{jump} \gg E_v$!!

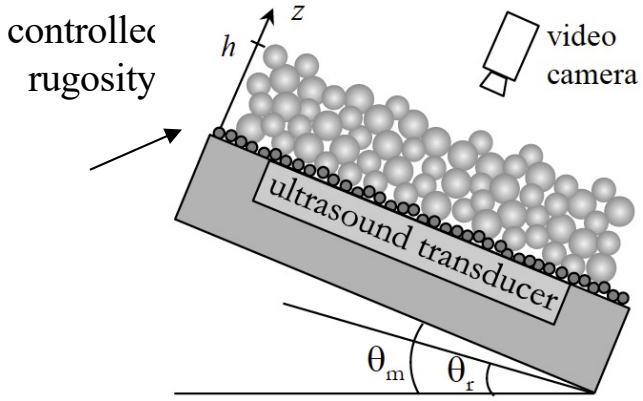


Sliding / failure ***is much easierly triggered by oscillating*** ***shear mode*** ***than by*** ***opening mode*** ***!***

Granular avalanche triggered through acoustic lubrication (1/2)

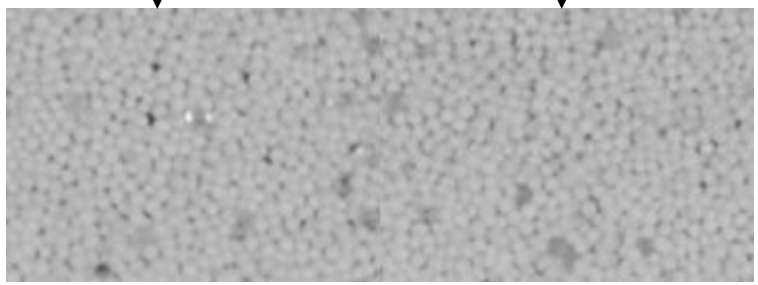
Léopoldès, Jia , Tourin, and Mangeney, PRE 102 (2020)

♦ **Flows triggered below avalanche angle by ultrasound**



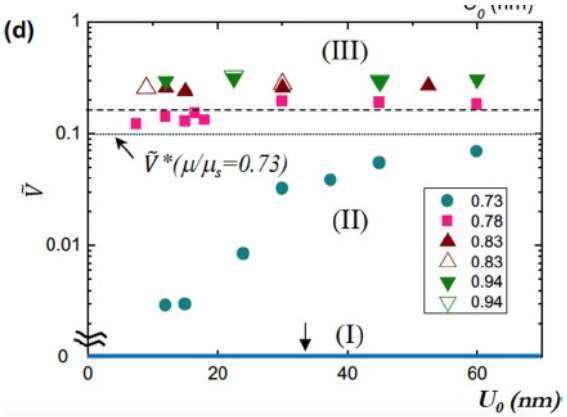
f_{US} = 100 kHz and $U_0 \sim 5$ nm

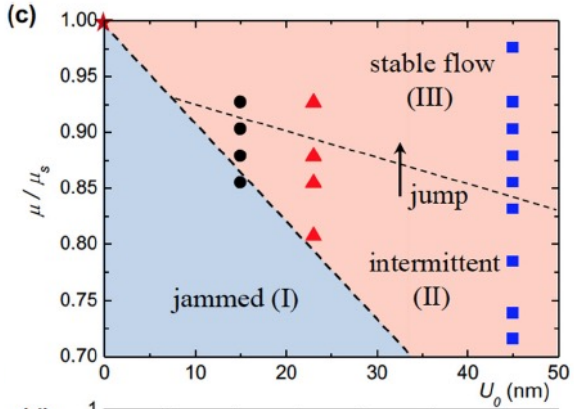
$\theta = 18° < \theta_{max} = 20°$ $\theta = 15° < \theta_r$



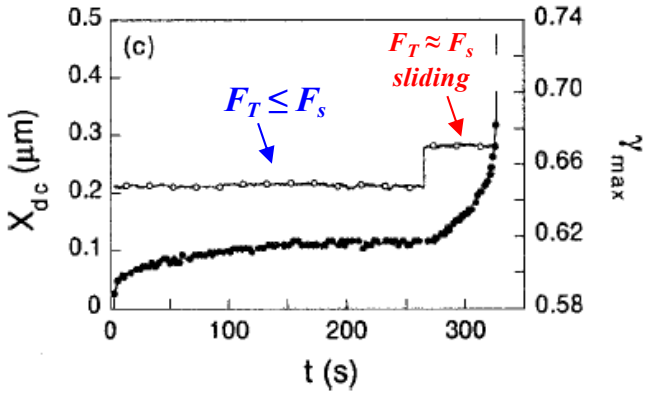
triggered inertial flow (continuous) triggered slower flow (intermittent)

♦ **Bifurcation between intermittent and continuous flows** (analogue to solid friction)





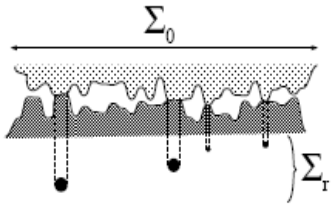
Bureau, Baumberger & Caroli, PRE 64 (2001)



Granular avalanche triggered through acoustic lubrication (2/2)

♦ Frictional velocity weakenig systems: instable (II) & stable flows (III)

➢ Friction at solid interfaces (MCI)



Rate- ($\dot{x}$) and State- (ϕ) constitutive law (Rice-Ruina model):

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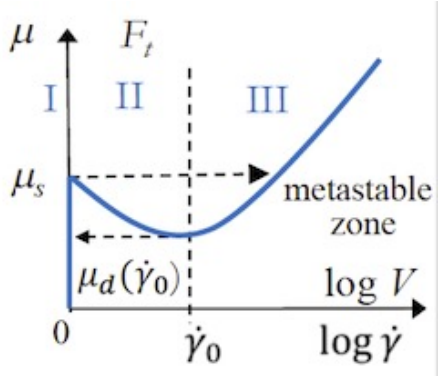
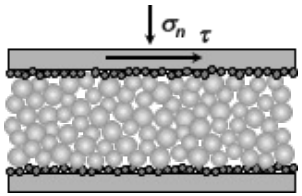


- Gollub et al, PRL (1997)

➢ Friction in granular flows



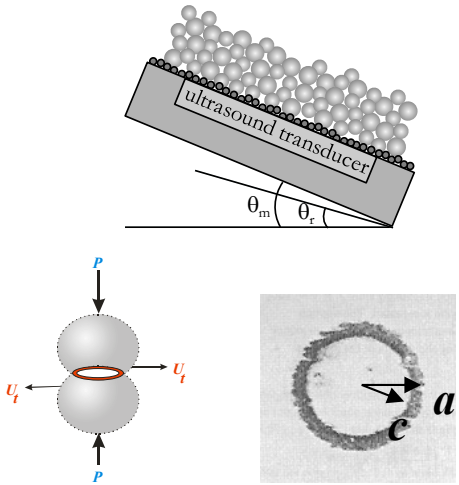
- Heuristic granular friction law
(μ_s : interparticle friction)

$$\mu_{eff} = \frac{\mu_s}{1+\alpha_1\tilde{\dot{\gamma}}^2} + \beta\tilde{\dot{\gamma}}^2$$

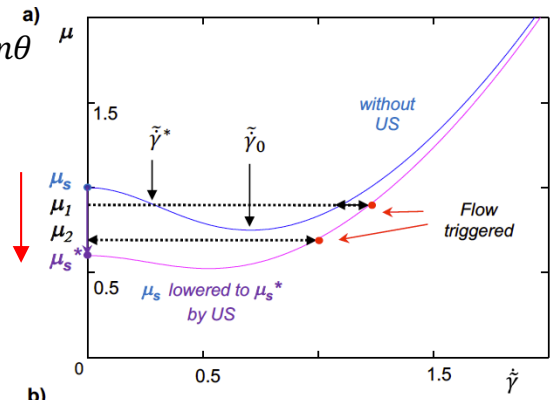
Jaeger, Liu, Nagel & Witten, EPL 11 (1990)

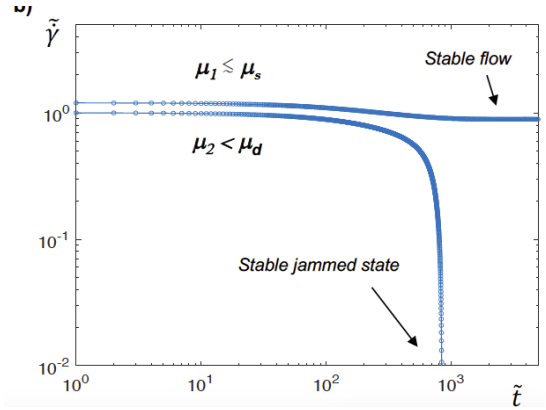
♦ Bifurcation between creep jamming and accelerated flow

Léopoldès, Jia, Tourin, Mangeney, PRE 102 (2020)



$\mu = \tan\theta$



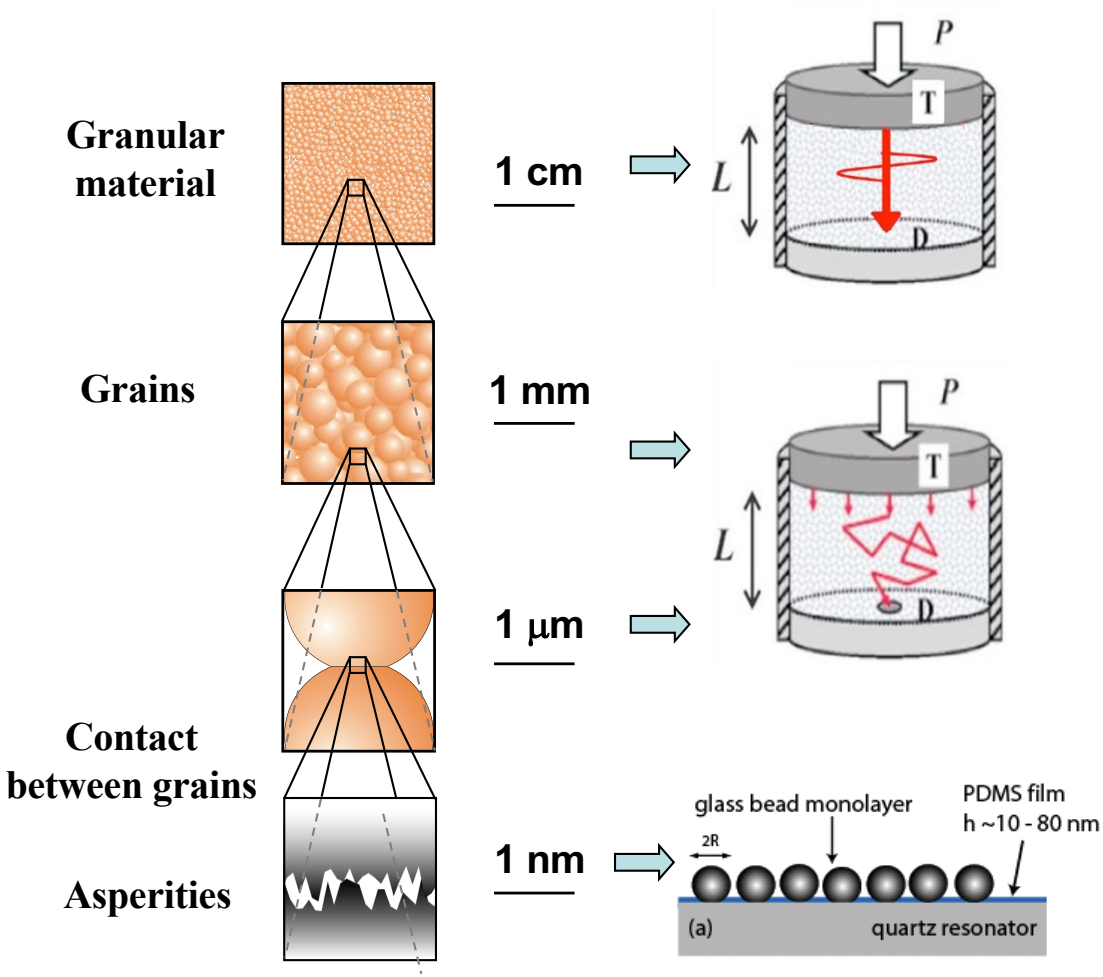


motion equation: $d\tilde{\dot{\gamma}}/d\tilde{t} = \mu - \mu_s/(1+\alpha_1\tilde{\dot{\gamma}}^2) - \beta\tilde{\dot{\gamma}}^2$

Acoustic lubrication of the stuck area ! *(Jia et al, PRE 2011)*

Conclusion (1/2): Acoustic Probing of Granular Media

Multiscale acoustics of dense granular media:



♦ $\lambda_E \geq 10\ d$: **Coherent elastic waves**

- Compressional & shear velocities
  → material elastic moduli K & G

- Jia, Caroli and Velicky, PRL 82 (1999)
- Wildenberge, Tourin, and Jia, EPL 115 (2016)

♦ $\lambda_S \sim d$: **Multiply scattered waves**

- Q-factor → dissipation at the contact
- Mean free path l^* → rearrangements

Jia, PRL 93 (2004); Brunet, Jia and Mills, PRL 101 (2008)

♦ **Ultrasonic interfacial rheology**
shear resonator & a bead layer

- Resonance peaks and width
  → interfacial stiffness & dissipation

Léopoldes & Jia , PRL 105 (2010)

Conclusion (2/2): Acoustic pumping (T_{eff})

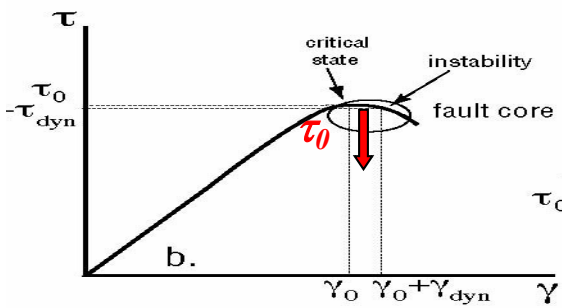
♦ Acoustic fluidization may occur without significant packing density change with shear modulus softening via *micro-plasticity* (contact slipping)

♦ Strong nonlinear elasticity is observed at unjamming transition with macro-rupture (dilatancy) and loss of contact Z

♦ Triggering of granular avalanche (macro-instability) via acoustic lubrication of contacts

→ Dynamic earthquake triggering

→ Rockfalls (landslides) triggered by small seismicity (local)



- *Melosh, Nature (1996)*
- *Gomberg et al, Nature (2001)*
- *Johnson, Jia, Nature (2005)*
- *Johnson, Gomberg, Marone et al, Nature (2008)*

Lowering the yield stress!

Dolomieu crater at Piton de la Fournaise (La Réunion)

- *V. Durand et al, JGR* 2019