Acoustic monitoring of damages in cemented granular materials under uniaxial loading

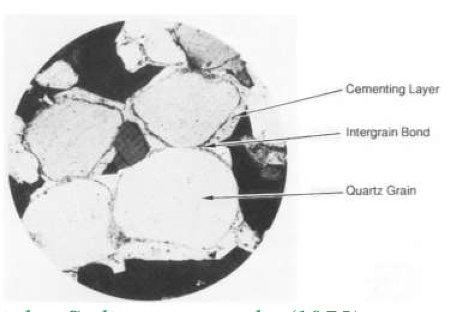
V. CANEL[1,2], X.JIA[1], M. CAMPILLO[2], I.R. IONESCU[3]

[1] Institut Langevin, ESPCI Paris – [2] ISTerre, UGA Grenoble – [3] LSPM, Univ. Paris 13 – email : vincent.canel@espci.fr

I. Context

From the Earth…

Schlumberger, Charac. of fractured reservoirs

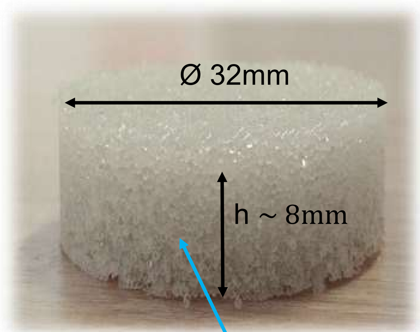


Damaged porous heterogeneous rocks under stress

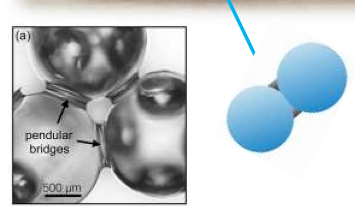
Pettijohn, Sedimentary rocks (1975)

… to the lab.

Cemented granular material



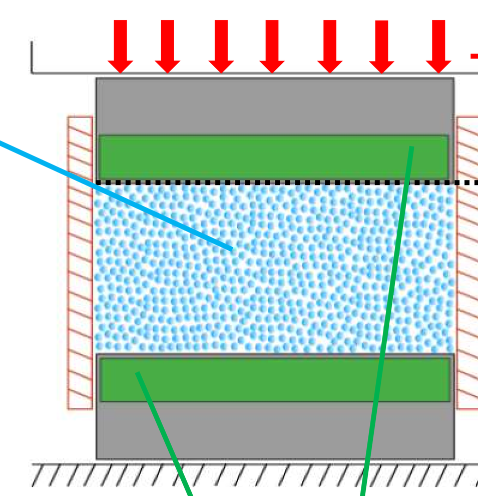
Polydisperse beads
$400\ \mu m < \varnothing_{bead} < 800\ \mu m$
Never broken !
$\varphi = V_{beads} / V_{tot} \sim 60\%$



Hemmerle et al., Scient. Reports (2016)

Two kinds of cement :
- **brittle** (salol)
- **ductile** (eicosane)

$V_{cement} / V_{beads} \sim 2.5\%$



PZT transducers

for active or passive acoustic monitoring

Automatic press

Records displacement and load L during **strain driven** test at load speed 50 μm/s

Up to 10^4 N ~ 12 MPa

Rigid cell

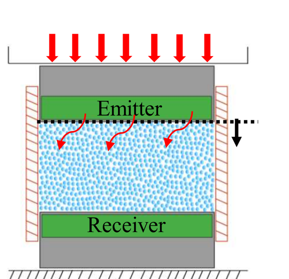
oedometric conditions (lateral boundary not free)

II. Experiments

a) Active probe : longitudinal coherent wave velocity

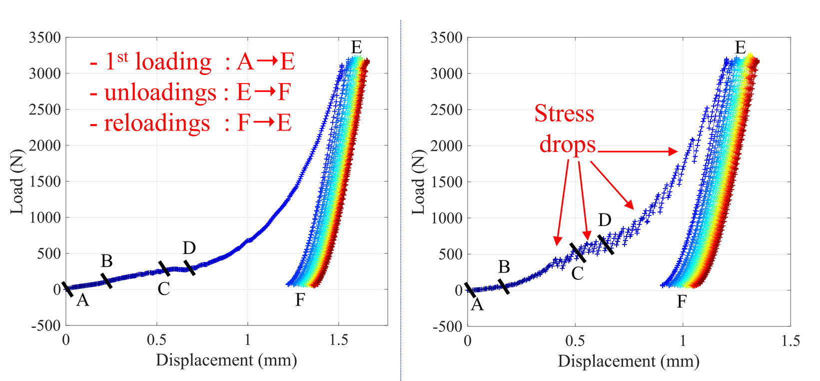
Following Langlois & Jia, PRE (2014), Khidas & Jia, PRE (2012)

1) Set up



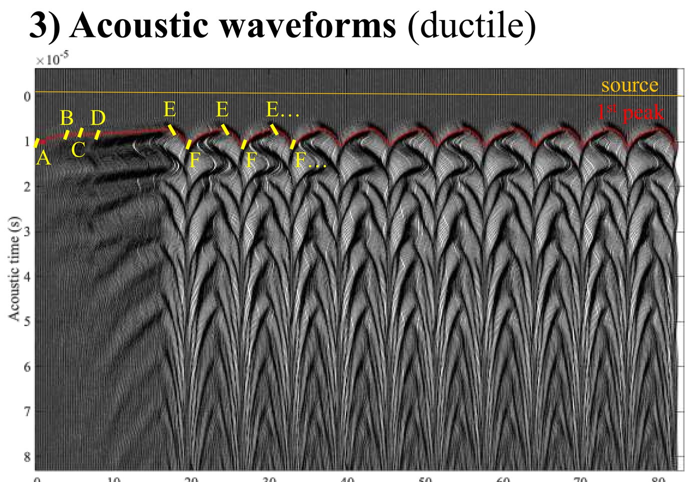
Pulses at 100 kHz generate coherent waves : $\lambda >> \varnothing_{bead}$

2) Mechanical response

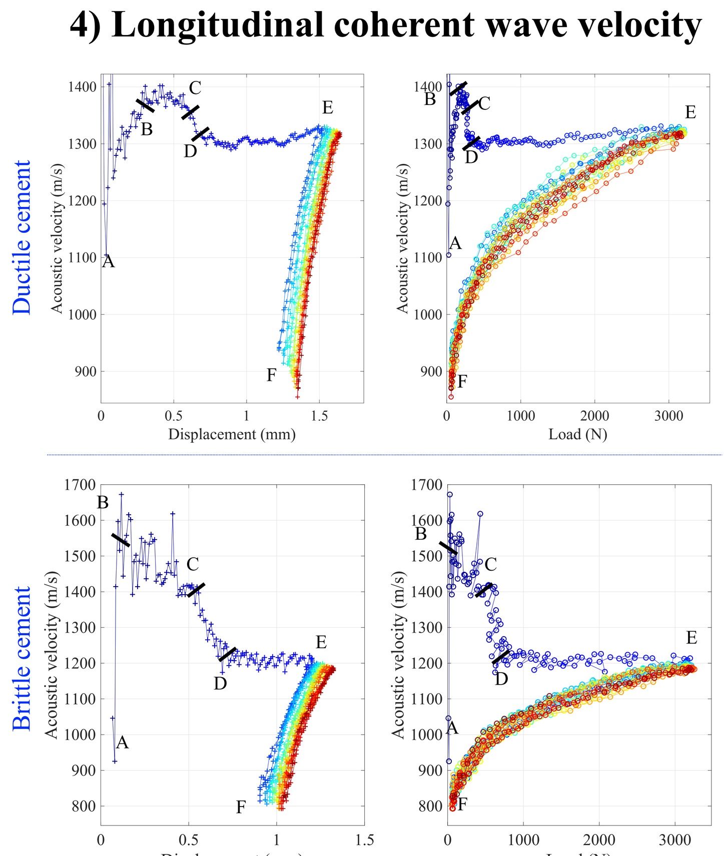


Ductile cement — Brittle cement

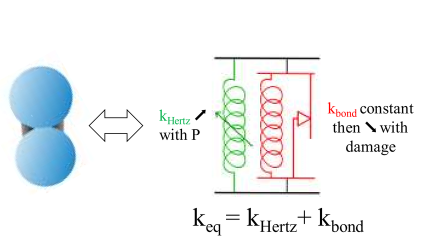
3) Acoustic waveforms (ductile)



4) Longitudinal coherent wave velocity



5) Modeling



$k_{eq} = k_{Hertz} + k_{bond}$

Effective Medium Theory
From micro to macro by homogenization < >

$v_p^2 = \rho_{glass}\ \varphi < k_{eq} > = v_{Hertz}^2 + v_{bond}^2$

with $v_{Hertz} = aL^b$ and v_{bond} ↘ with damage

Digby, J. of App. Mech. (1981)

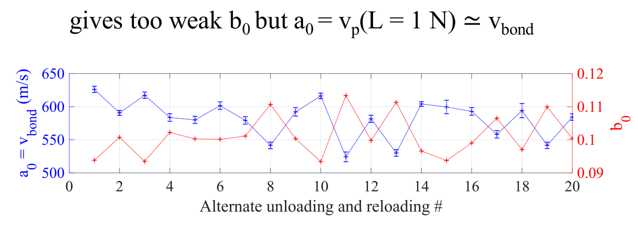
Theoritical b = 1/6

Goddard, Proc. R. Soc. Lon. A 430 (1990)

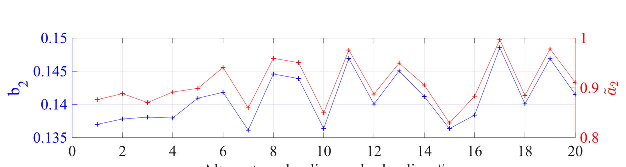
6) Verification of the model (ductile)

- A → E : damage ↗ and v_{bond} ↘ while v_{Hertz} ↗
- E ↔ F : damage and v_{bond} ~ fixed, v_{Hertz} evolves

- 1st fit : $\log(v_p) = \log(a_0 L^{b0})$
gives too weak b_0 but $a_0 = v_p(L = 1\ N) \simeq v_{bond}$



- 2nd fit : $\log(v_p^2 - v_{bond}^2) = \log(a_2 L^{b2})$
gives b_2 closer to 1/6



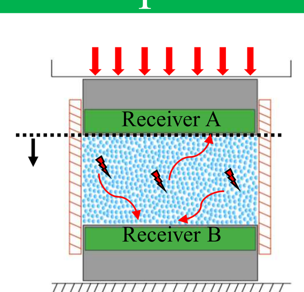
- Similar results for brittle cement

Validation of $v_p^2 = (aL^b)^2 + v_{bond}^2$

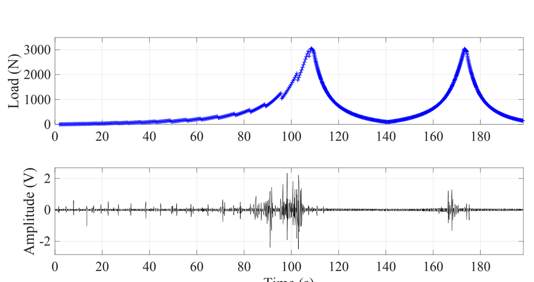
b) Passive probe : acoustic emissions (AE)

1) Set up

More emissions with brittle cement



2) Measurements



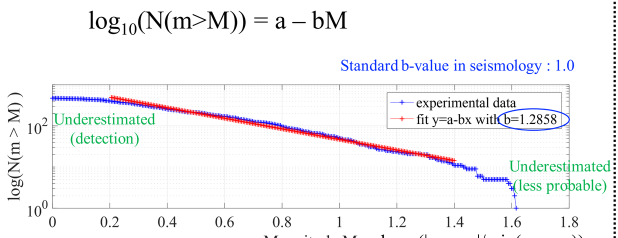
3) AE detection over 1st loading

Classical methods :
- threshold
- STA/LTA
- kurtosis, etc.

More sophisticated :
- SVD, ICA, NNMF
- kmeans ⟶ ~ 500 events
- machine learning, etc.

4) Gutenberg-Richter law

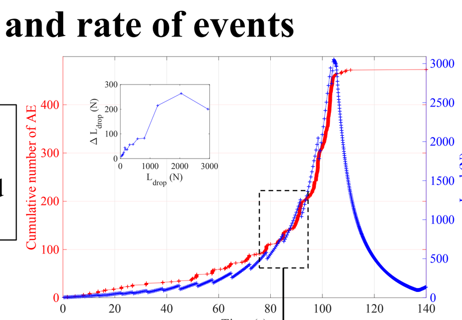
$\log_{10}(N(m>M)) = a - bM$

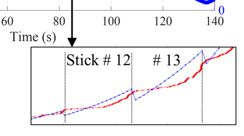


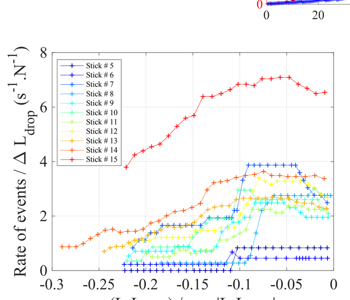
AE behave like earthquakes

5) Number and rate of events

Stress drops : stick-slip-like behavior correlated by AE number





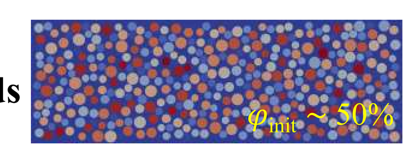


AE rate seems to follow a scale law as the slip approaches

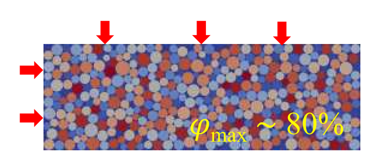
III. 2D FEM simulations

a) Geometrical modeling

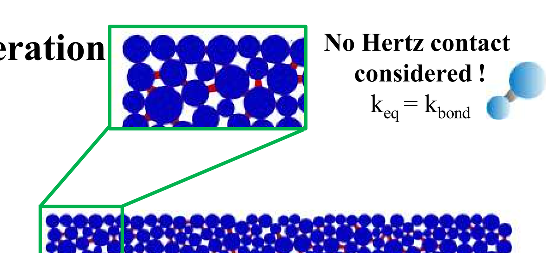
1) Generation of beads



2) Compaction

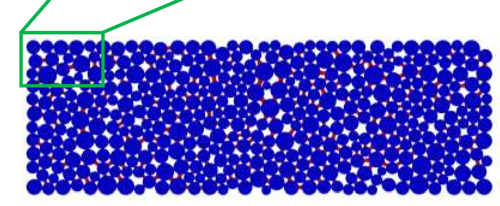


3) Bonds generation



No Hertz contact considered !
$k_{eq} = k_{bond}$

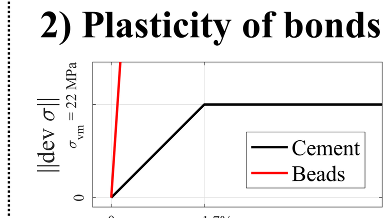
4) Final mesh



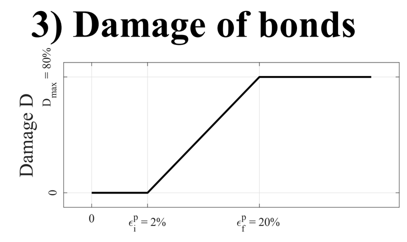
b) Large deformation of a bond

1) Considered deformations
compression / traction / shear / rotation

2) Plasticity of bonds

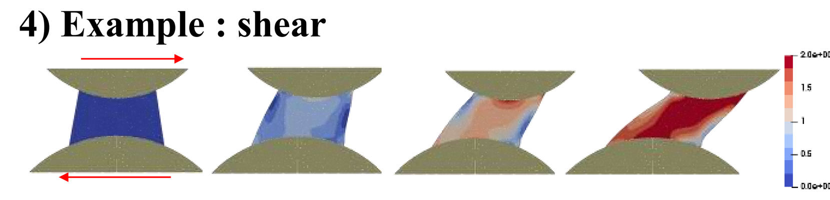


3) Damage of bonds

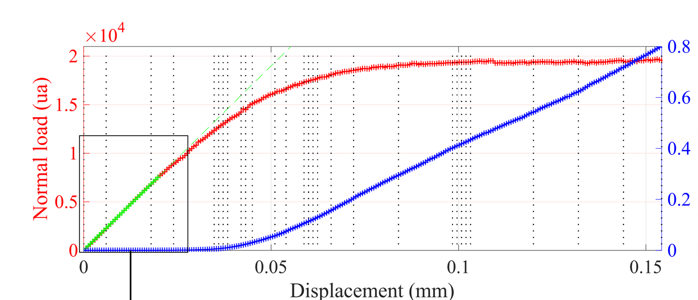


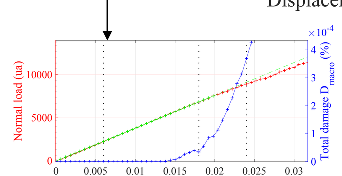
$\lambda = \lambda_0\ (1\text{-}D)$ and $\mu = \mu_0\ (1\text{-}D)$

4) Example : shear



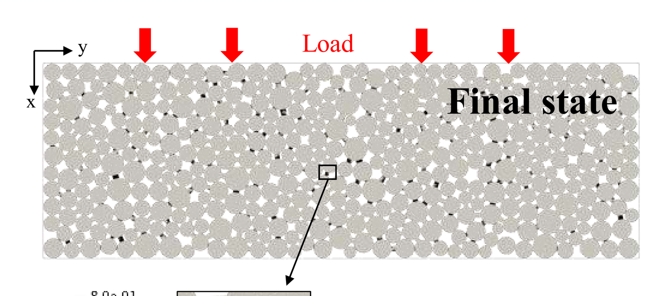
c) Quasistatic macroscopic deformation, load and damage

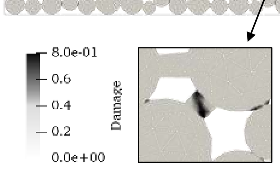




Elastic response before damage

Chosen states for dynamic problem

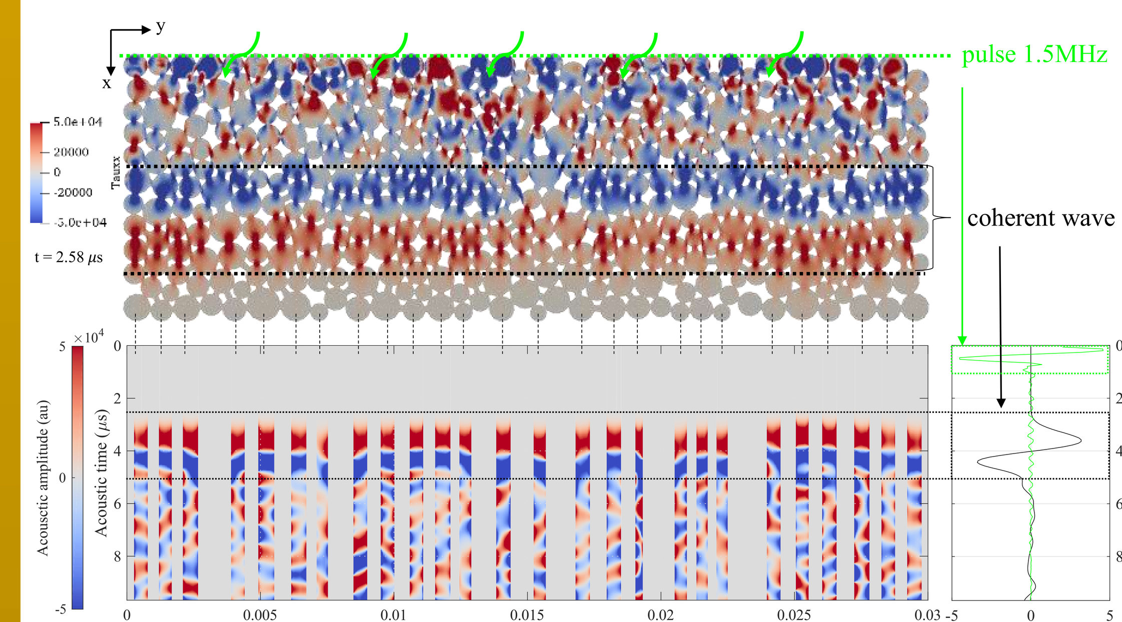


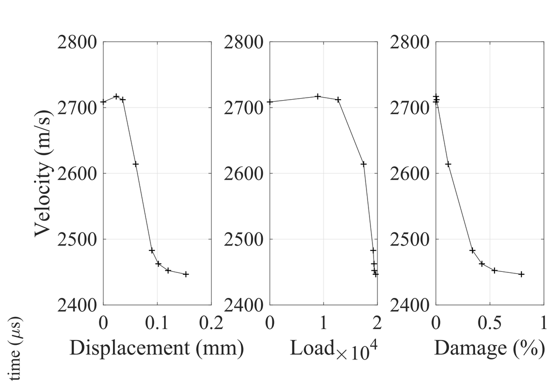


40% of damaged bonds
0.8% of total damage

Heterogeneous damage

d) Dynamic wave propagation and velocity





Small damage ⟹ coherent longitudinal velocity loss

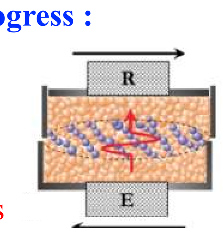
IV. Conclusions and perspectives

Take home messages :

- Efficient active monitoring of acoustic velocity during damaging process and link with microscopic granular physics
- Brittle cement with stick-slip-like stress drops and AE ~ "labquakes"
- Simulations show that a very heterogeneous and small damage implies a dramatic loss of wave velocity

Work in progress :

Study of shear band and fault dynamics



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