YUKAWA INSTITUTE FOR THEORETICAL PHYSICS

Running on liquid: Impact-induced hardening in dense suspensions

Y25.00002

Pradipto and H. Hayakawa, Phys. Rev. Fluids **6**, 033301 (2021).

Pradipto and H. Hayakawa, Phys. Fluids **33**, 093110 (2021).

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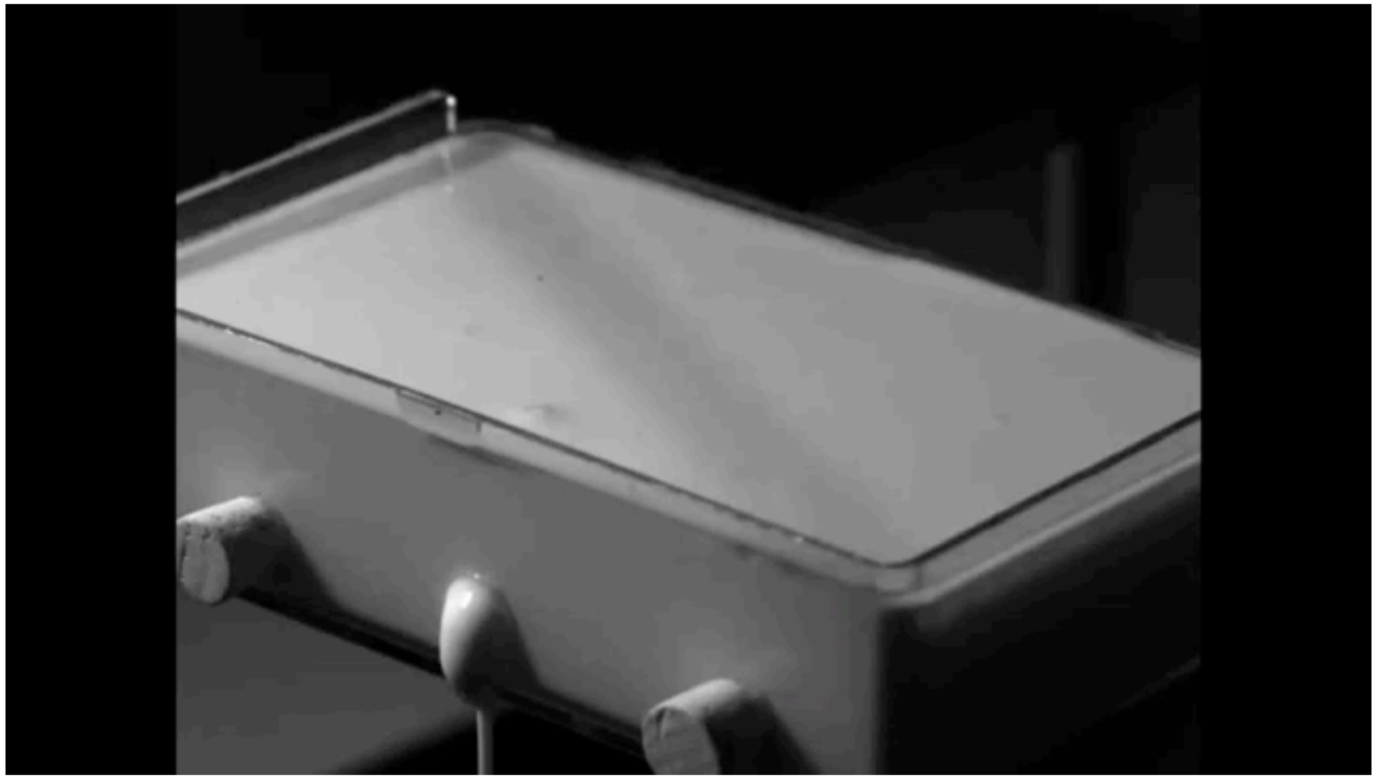
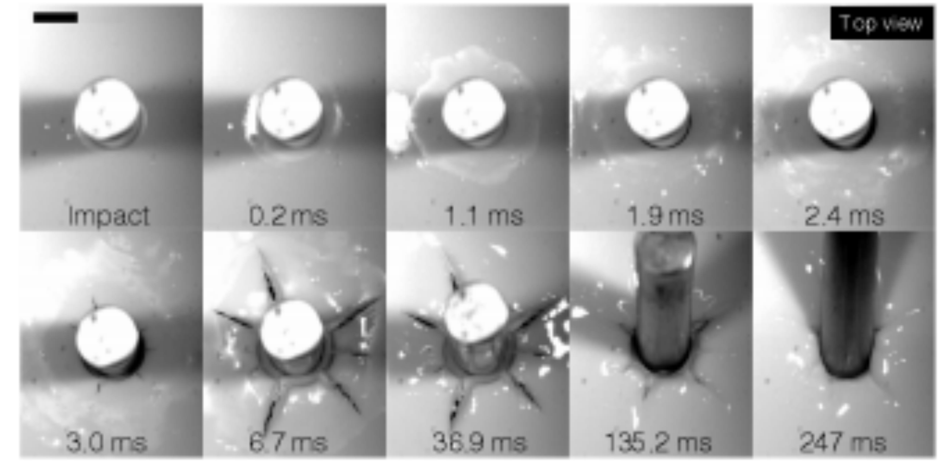
Kyoto University

APS March meeting 2022

Y25 CONSTRAINT-BASED RHEOLOGY OF DENSE SUSPENSIONS AND GRANULAR MATERIALS II

Dense suspensions under impact





Fracture Roche et al, PRL 2013

Source: Itai Cohen Group on YouTube https://youtu.be/hP88C-_LgnE

Impact-induced hardening

Occurs on hard particles suspended in Newtonian solvent

Cannot be observed in fluids or granular particles alone

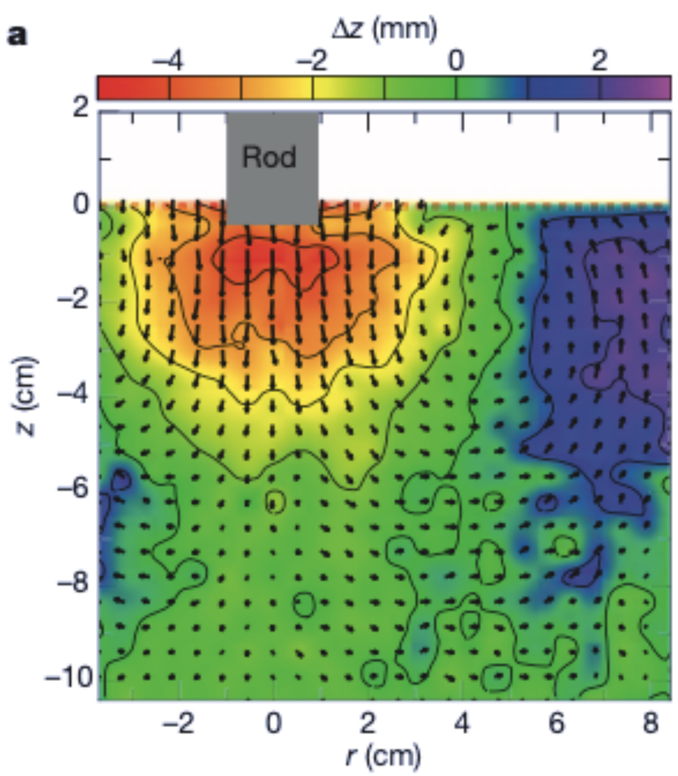
A person can run on top of dense suspensions

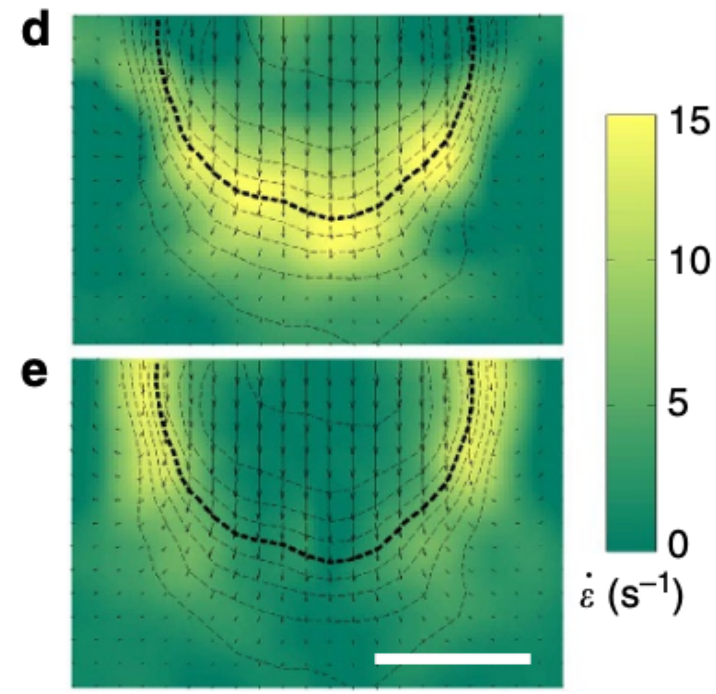
Physical explanations remain elusive

- Inherently far-from-equilibrium
- Highly dissipative —> transient
- **Can shear thickening (CST and DST) explain such strong solidification?**

Dense suspensions under impact have stronger response than the one observed in shear thickening suspensions

Waitukaitis and Jaeger, Nature **487**, 205 (2012)   Han et al, Nat. Comms. 2016

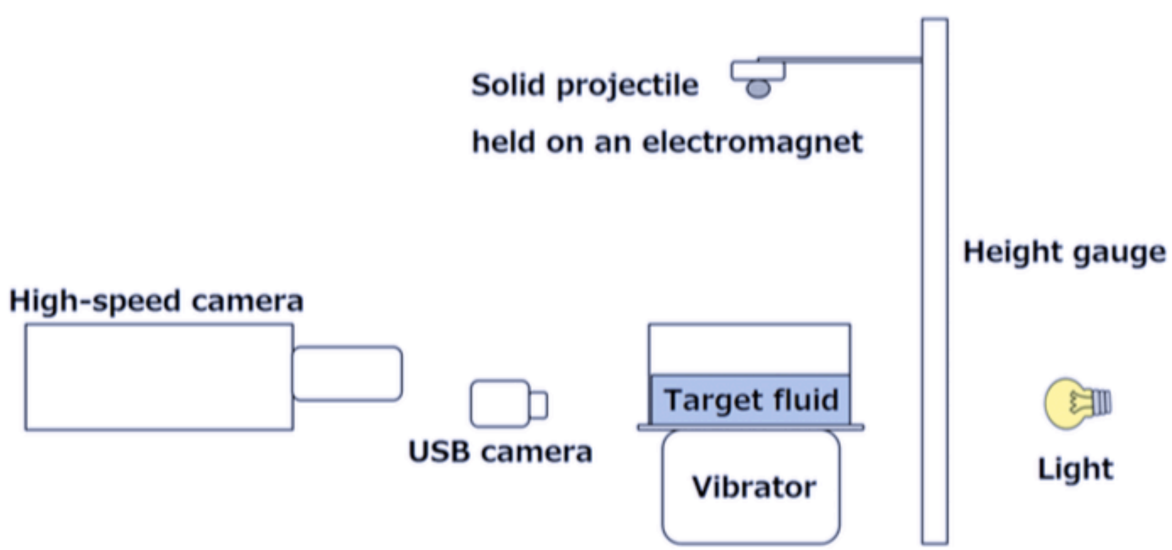


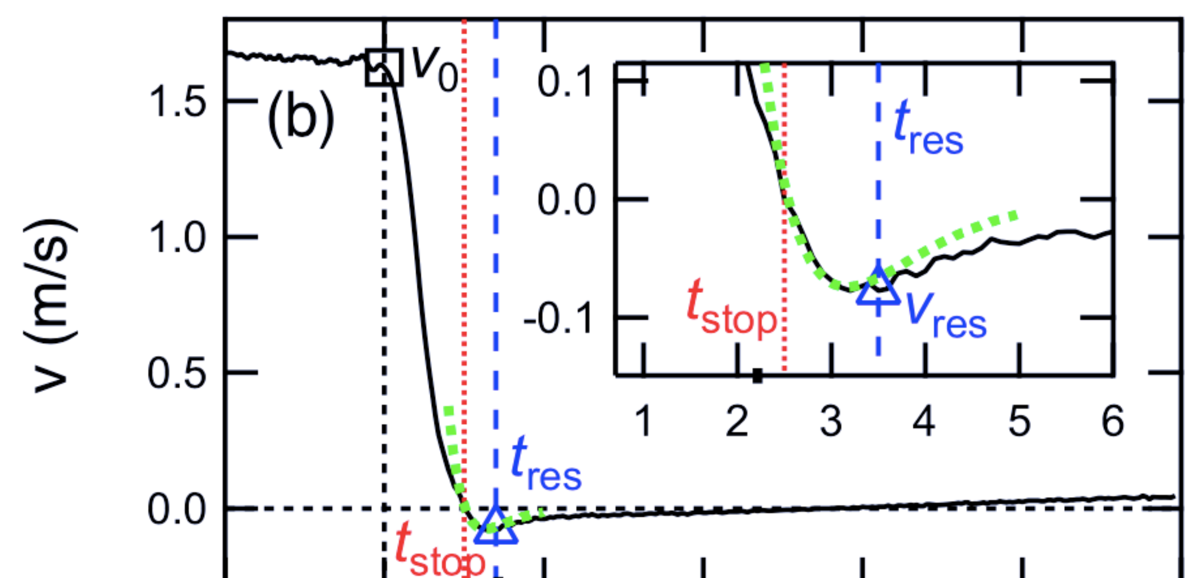


Dynamically Jammed Region

Localized and transient solid-like region beneath the impactor

Elastic rebound Egawa and Katsuragi, Phys. Fluids **31**, 053304 (2019)

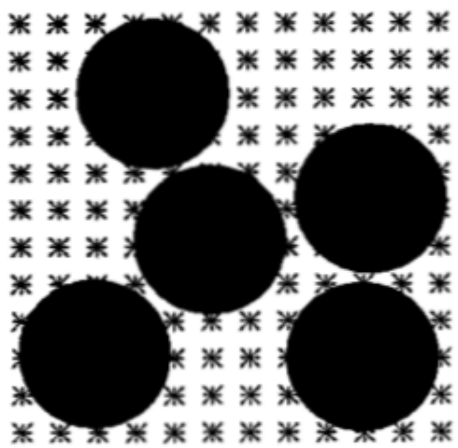




Ingredients of our simulation

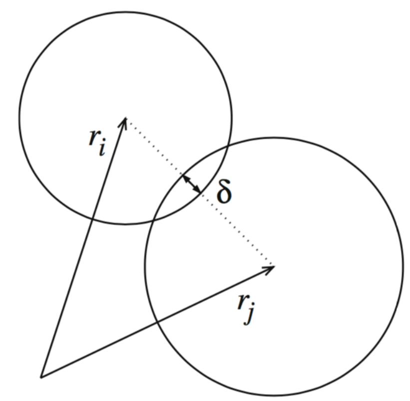
Hydrodynamic interaction

LBM + Lubrication corrections



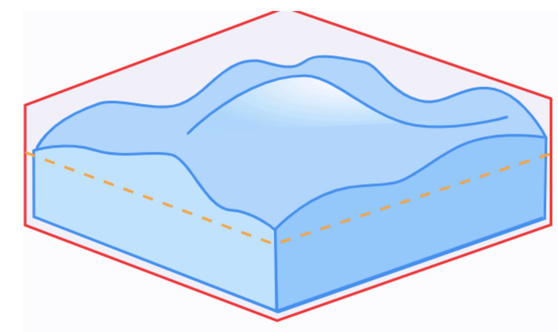
Contact between particles

DEM

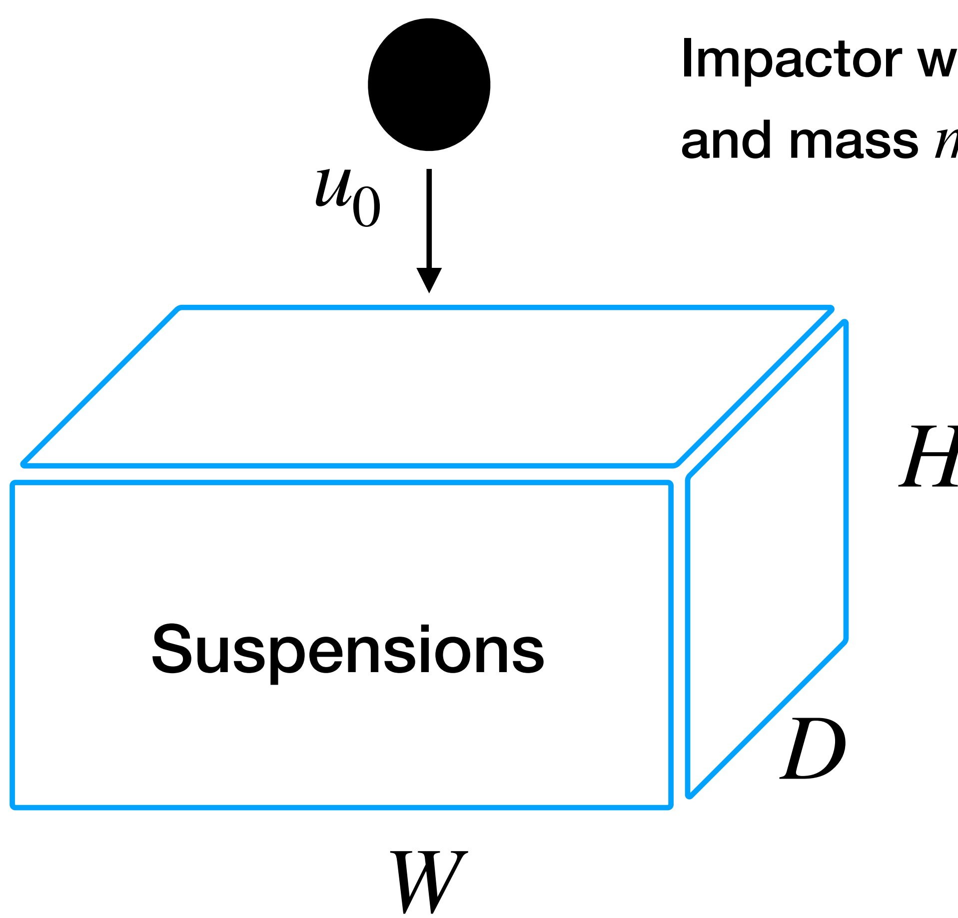


Free surface

LBM



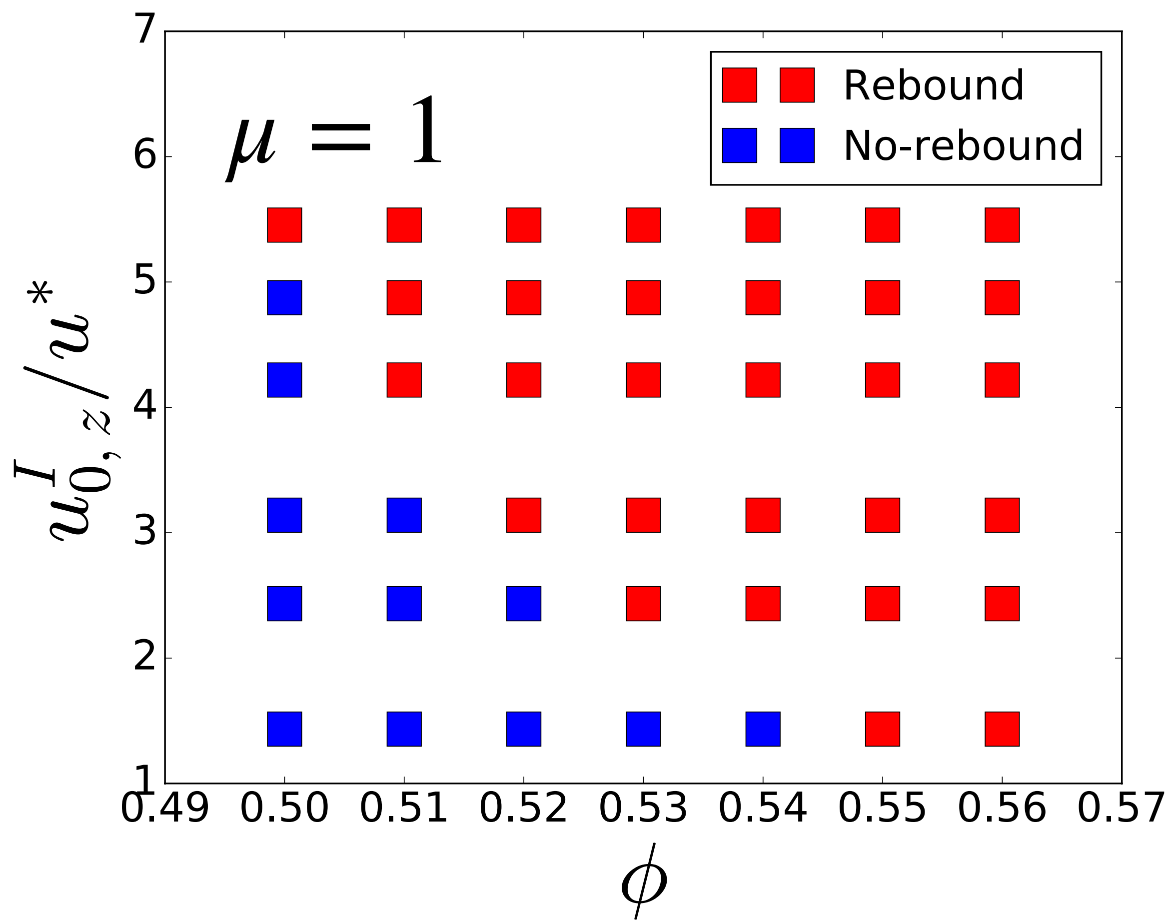
Setup



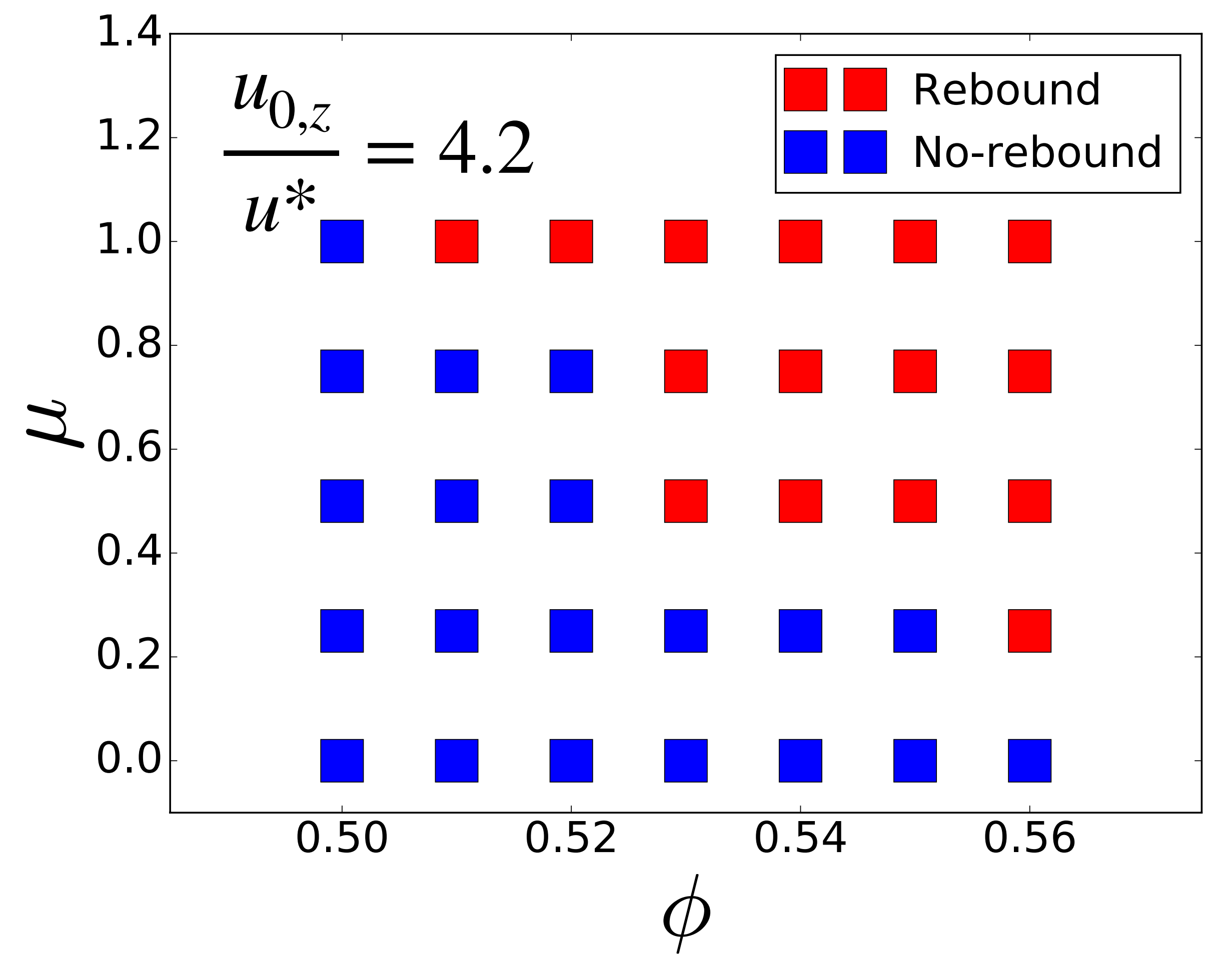
Impactor with radius a_I
and mass m_I

Rebound depends on impact velocity and frictional interactions between particles

Impact velocity



Friction coefficients

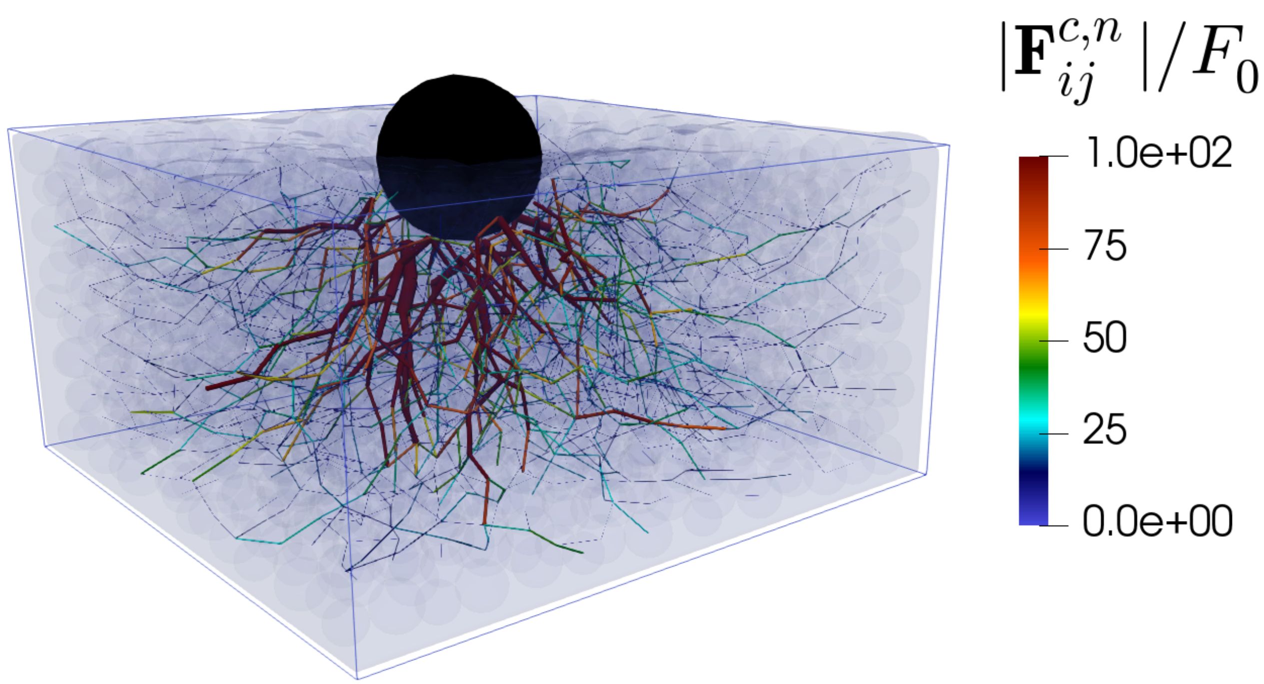


$\phi = \frac{\text{Total solid particles volume}}{\text{Volume of the container}}$

We can run on top suspension but we'll sink if we walk

Frictional interaction increases the contact duration between particles that leads to a stronger hardening

Inside the hardening suspension



Force chains

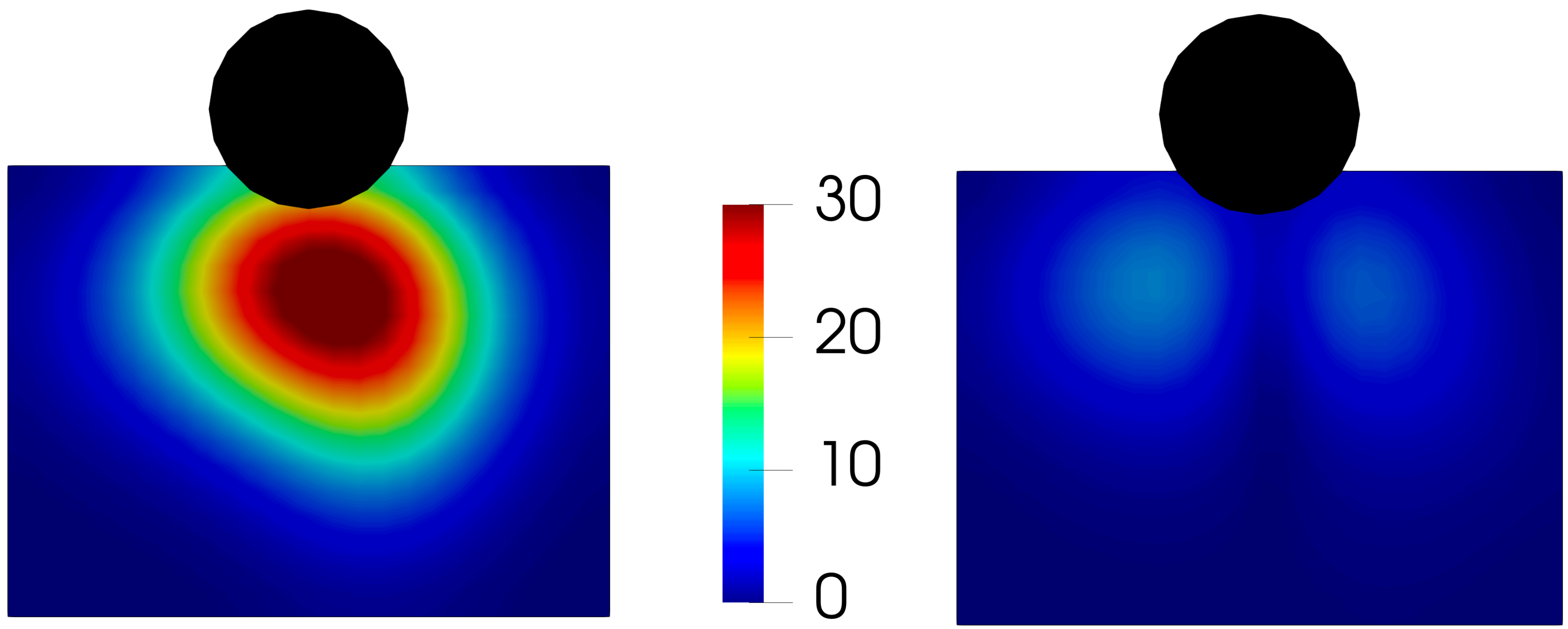
- Formed by contacting suspended particles
- Transmitting force from the impactor to the bottom boundary
- Sustain the impactor → rebound

Coarse-grained fields

J. Zhang, R. P. Behringer, I. Goldhirsch, Prog. Theor. Phys. Supp **184**, 16 (2010)

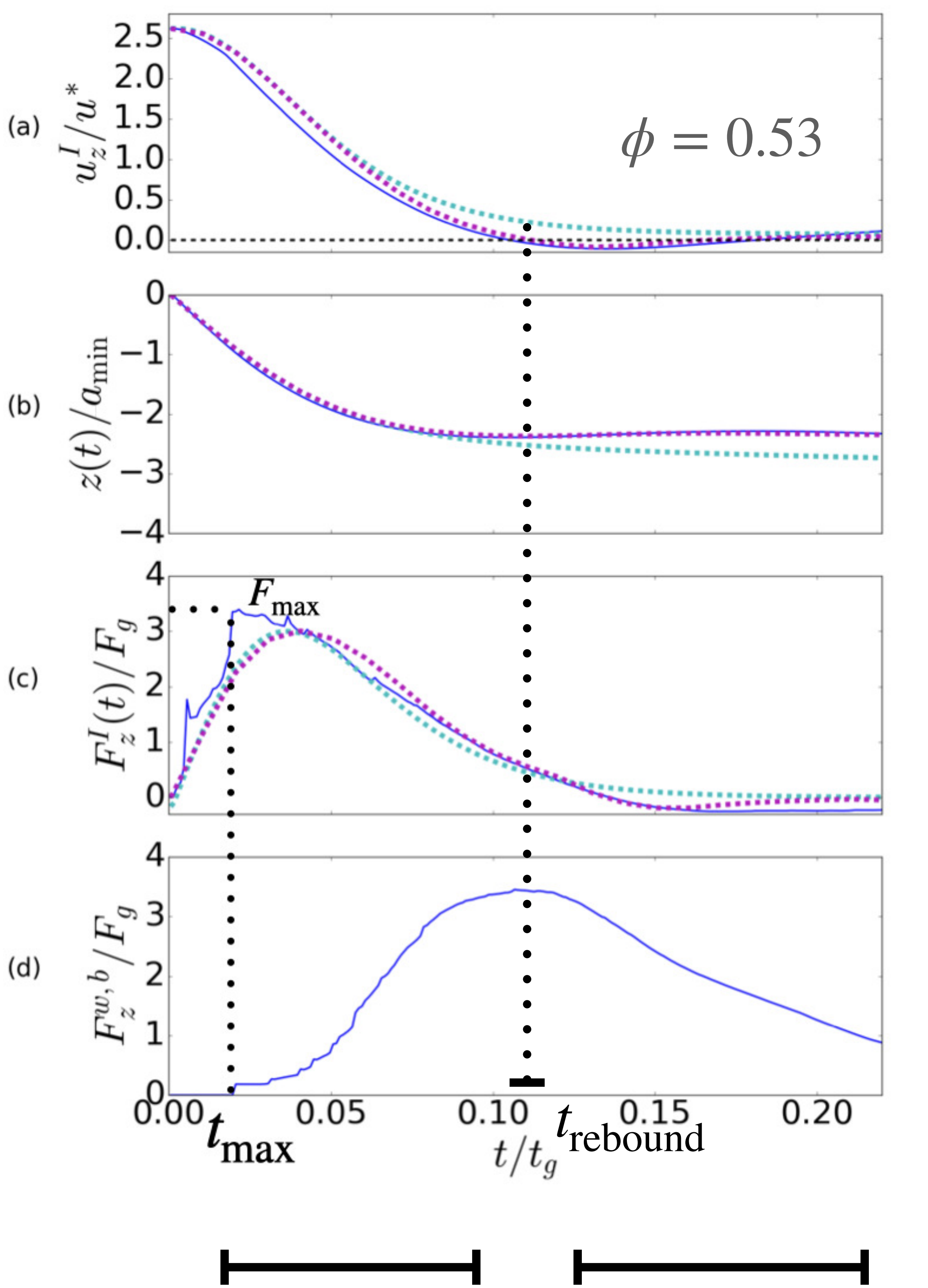
Stress in normal direction σ_{zz}

Stress in shear direction σ_{rz}



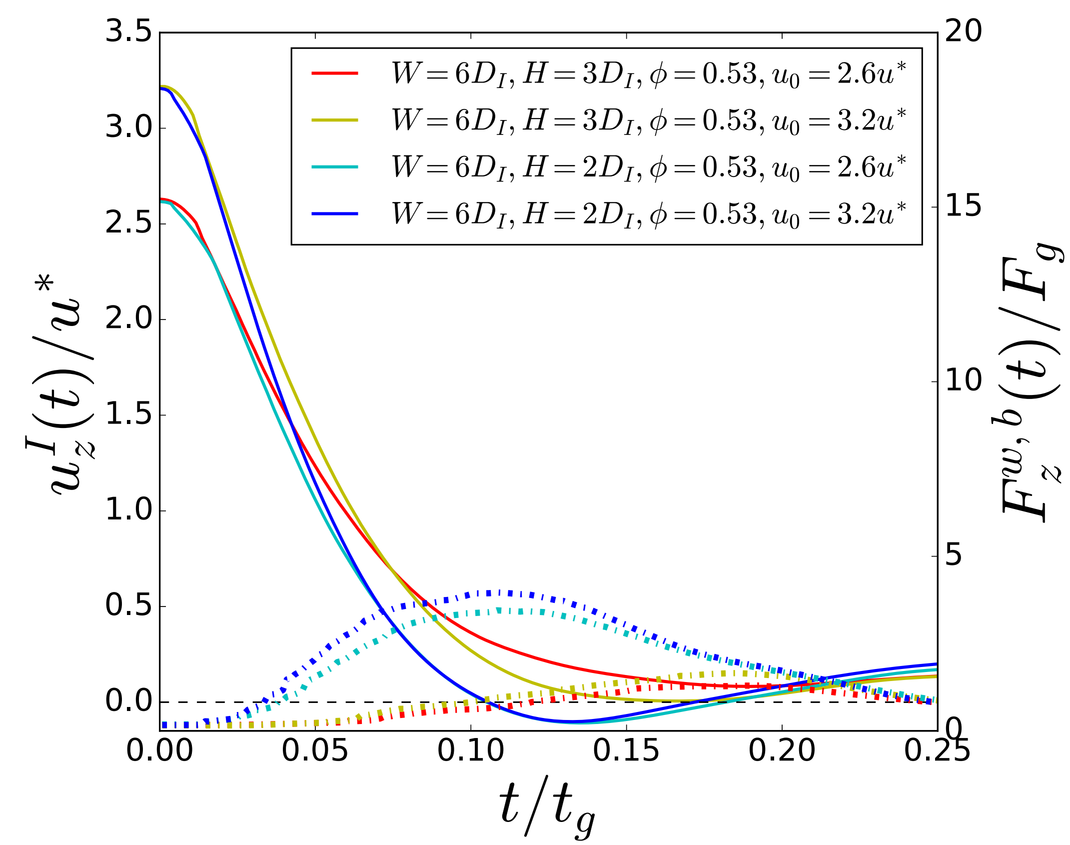
High normal stress instead of shear stress c.f DST

Force on the impactor reach its peak before the rebound



Dyn. jammed region touch the bottom and starts accumulating

Dyn. jammed region reached its peak on the bottom and soften → impactor starts to sink



Rebound depends on the depth of the container

The origin of $F_{\max}$ is the **floating** jammed region

The origin of rebound is the transmission of force from the impactor to the bottom plate and vice versa

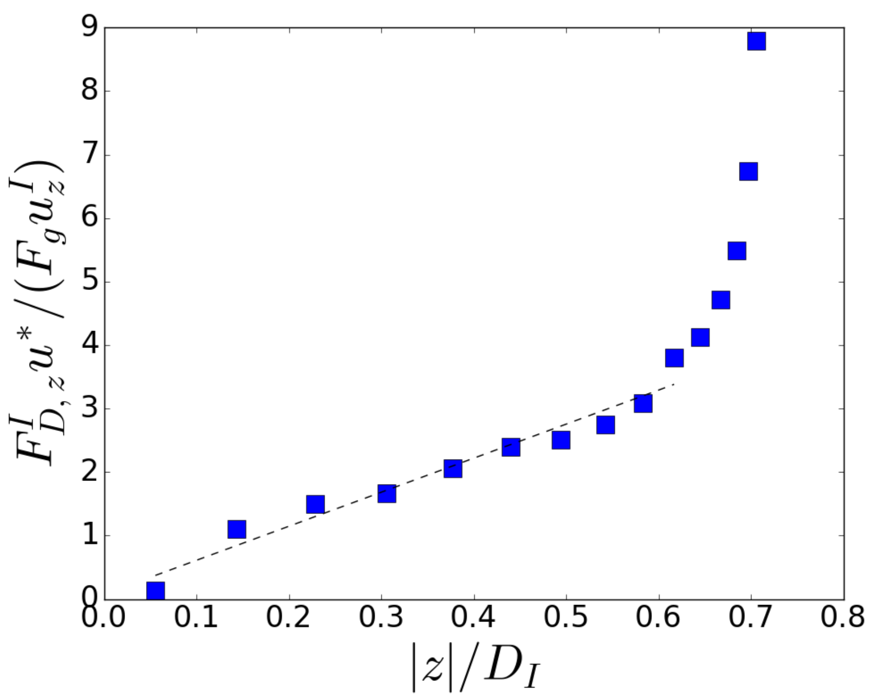
Phenomenology Floating + force chains model

$$m_I \frac{d^2 z_I}{dt^2} = -m_I \tilde{g} + 3\pi\eta_{\text{eff}}\dot{z}_I |z| + n(t) k_n z_I$$

Viscous Elastic

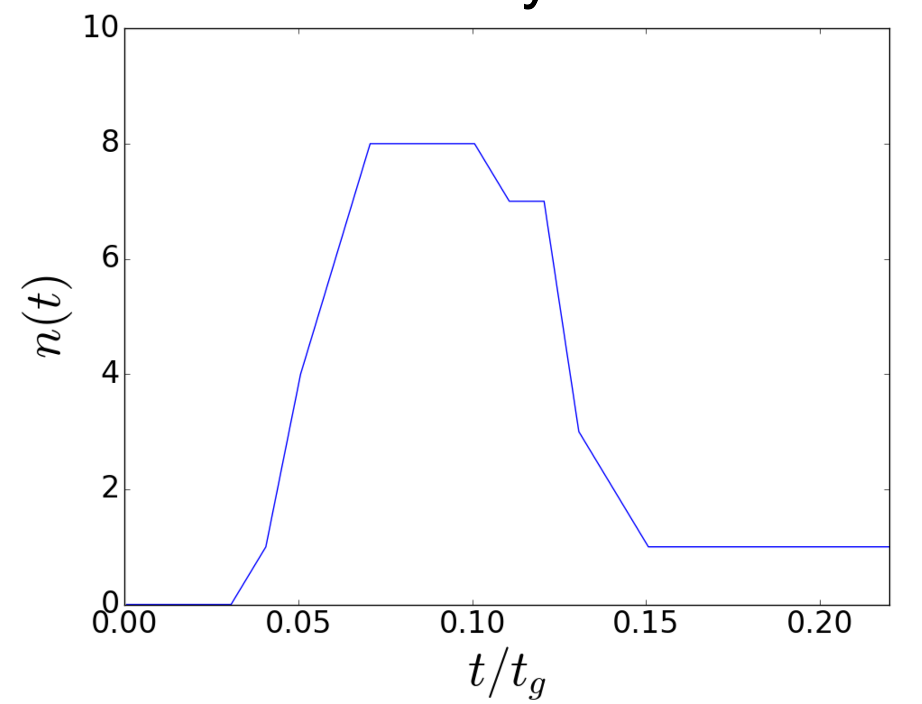
From floating jammed region

Drag on the impactor is proportional to its depth before completely immersed



From force chains

$n(t)$ → Number of percolating force chains from the impactor to the bottom boundary

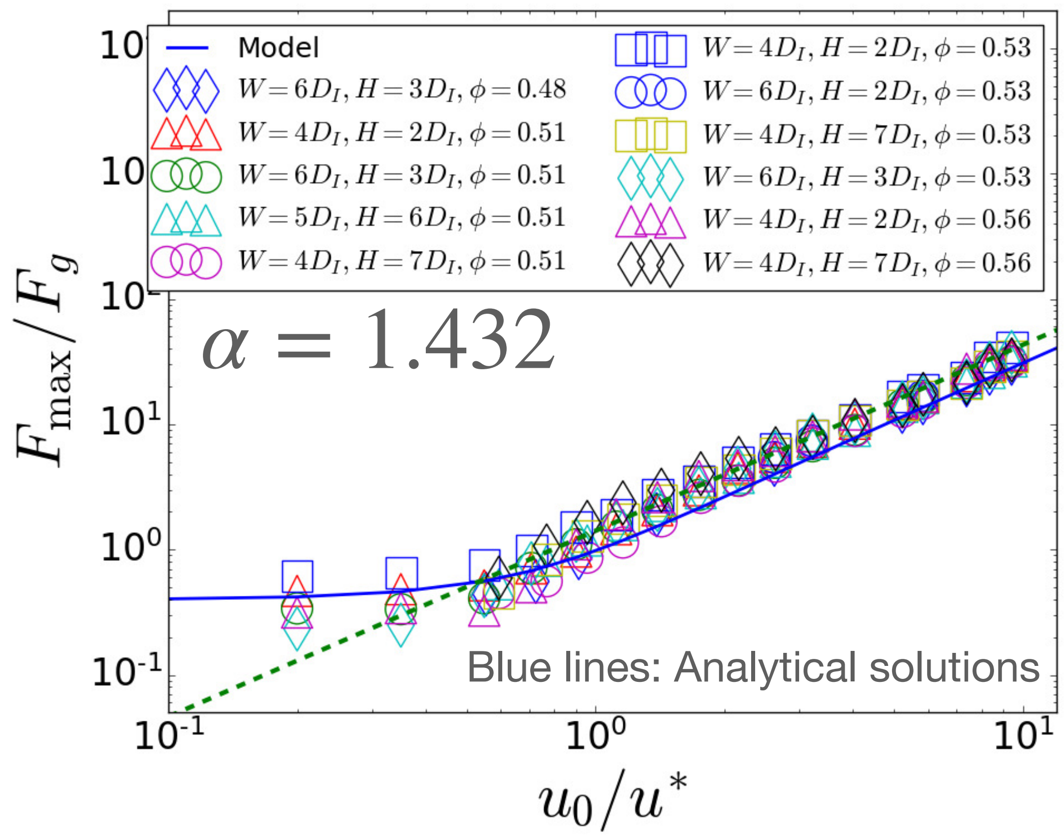


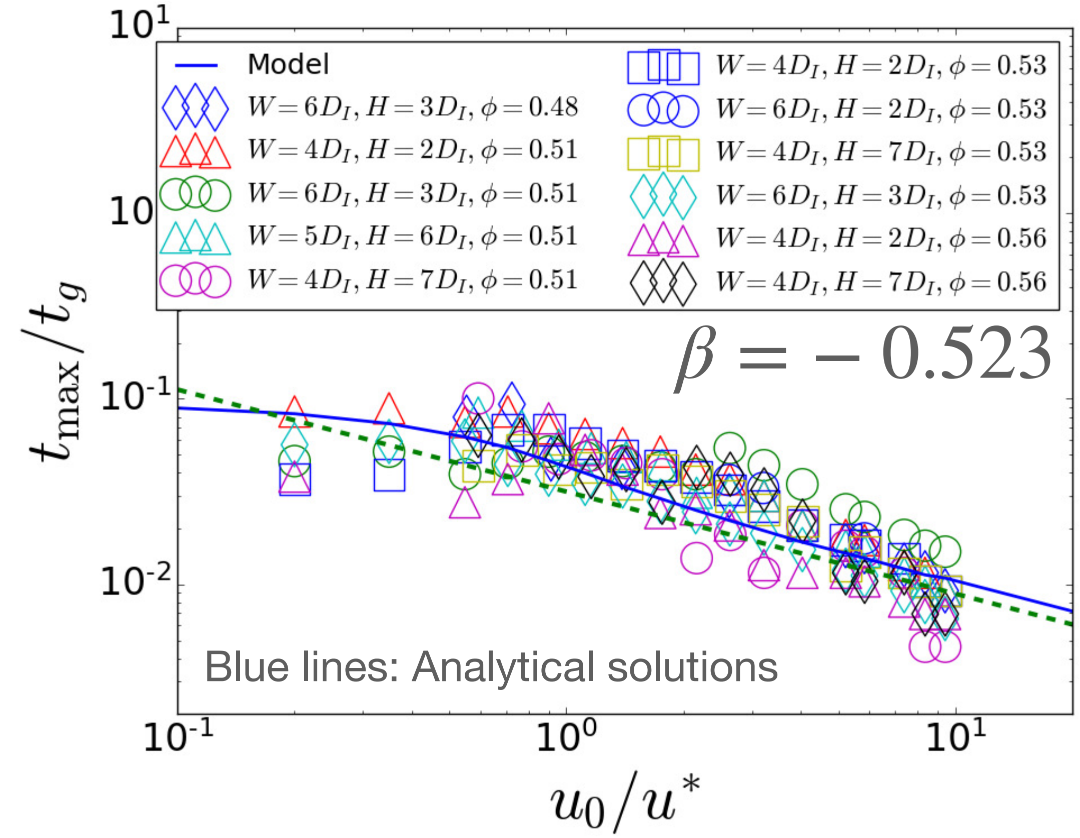
From analytical solution of floating model in $u_0 \gg 1/\eta_{\text{eff}}$ one can obtain

$$F_{\max} \propto u_0^{\frac{3}{2}} \text{ and } t_{\max} \propto u_0^{-\frac{1}{2}}$$

Model vs simulations

Power-law relationships between $F_{\max}$, $t_{\max}$, and u_0

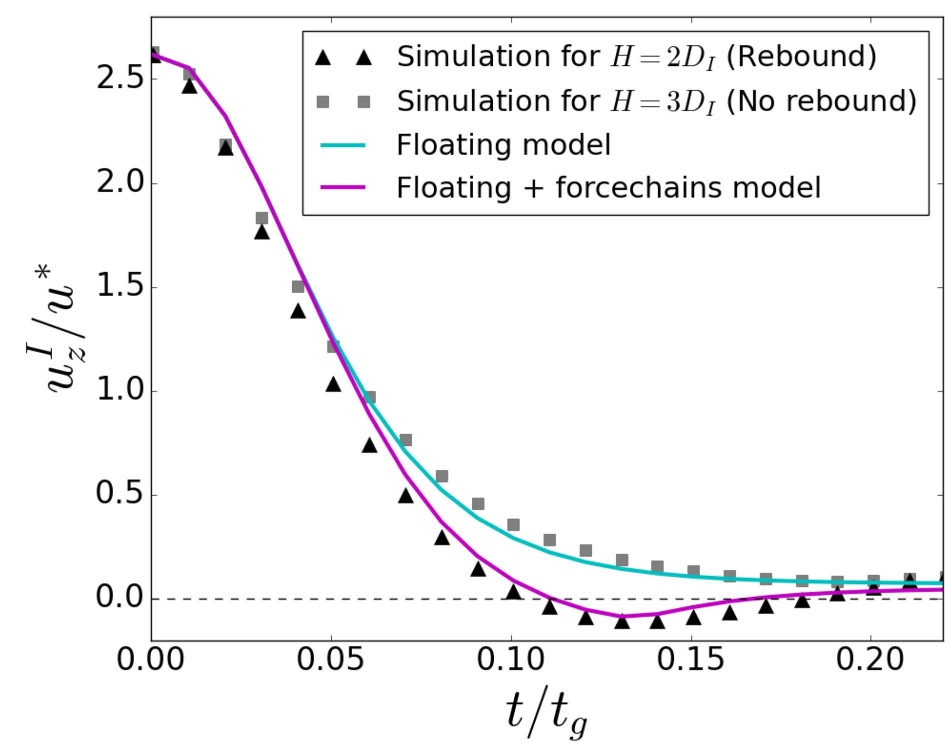




- **Crossover** from low u_0 to high u_0 regime
- High u_0 regime: $F_{\max} \propto u_0^{\alpha}$ and $t_{\max} \propto u_0^{\beta}$
  - Also observed in experiments

    Brassard, et. al, JFM **923**, A38 (2021)
  - Independent of system size

- Elastic term from percolating force chains is necessary to recover rebound



Conclusions

The strength of the impact-induced hardening depends on volume fraction, impact velocity, and the frictional contact between particles

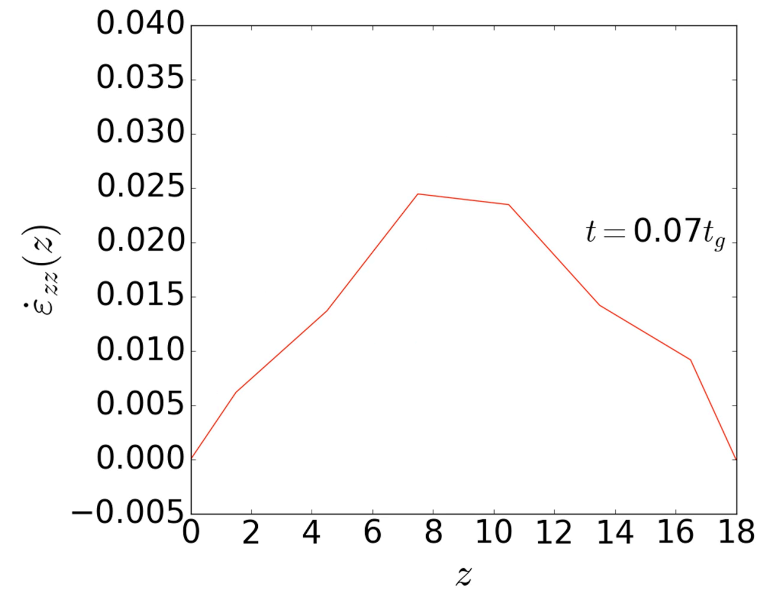
High normal stress (not shear stress)is observed in the dynamically jammed region

Our phenomenology shows that the power-law relationship between $F_{\max}$, $t_{\max}$, and u_0 arises solely from the viscous process

Elastic rebound is originated from elastic force due to the percolating force chains

Future prospects

Dynamics and effective elasticity of the jammed region



Simulations of actual running model e. g Raibert hopper on dense suspensions