Parameter determination of the non-local granular fluidity model for wood chips by comparison to well-defined experimental flow systems

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fcic FEEDSTOCK-CONVERSION INTERFACE CONSORTIUM

The unique role of biomass

While the growing need for sustainable electric power can be met by other renewable sources. . .

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While the growing need for sustainable electric power can be met by other renewable sources. . .

biomass is our primary renewable source of carbon-based fuels and chemicals.

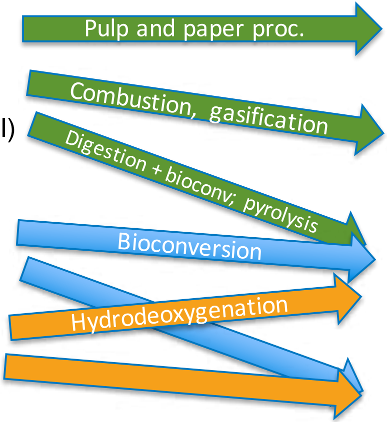
Terrestrial biomass utilization

Biomass Feedstock

Lignocellulosic
- Woody (trees)
- Herbaceous (grass)
- Waste (agri, municipal)

Sugar/Starch
- Corn
- Sugar cane

Plant oils



Utilization

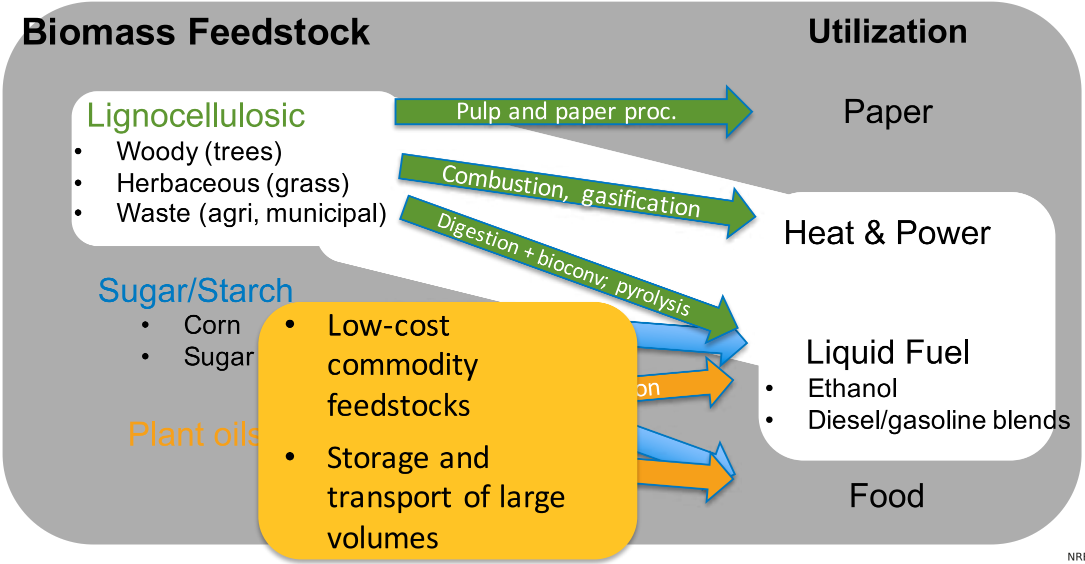
Paper

Heat & Power

Liquid Fuel
- Ethanol
- Diesel/gasoline blends

Food

Terrestrial biomass utilization



Terrestrial biomass feedstocks

- Non-spherical particles
  - “Chips” (plates, rods)
  - Fibers (flexible)
- Heterogeneous (size, shape, and composition)
- Low density
- Compressible
- Moisture content: 10-50%

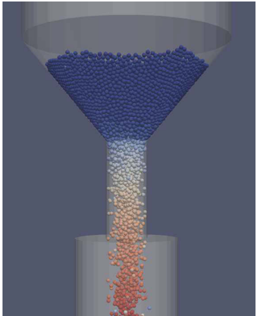
Short term goal: model feed-handling operations of simple biomass (wood chips with narrow size range)

Image from Jenike & Johanson

Mathematical models of dense granular materials

Discrete element method (DEM)

- Interactions between individual particles computed and all particles tracked
- State-of-the-art for flows of granular materials
- Limited by computational cost to a few million particles



Continuum models

- Mohr-Coulomb
- Drucker-Prager-Cap
  - Originally used in solid-mechanics frameworks (probing structural failure)
  - Recent work to implement for dynamic flow (FEM simulations)
- Inertial (“μ-I”) rheology
  - Shear and pressure-dependent friction coefficient
  - Implemented in a fluid mechanics framework
- Non-local granular fluidity
  - Extension of inertial rheology
  - Aims to capture “nonlocal” phenomena
- Nonlocal Hypoplasticity, NorSand, Others?

Inertial ("μ-I") rheology

Implemented as a generalized Newtonian fluid [1,2]

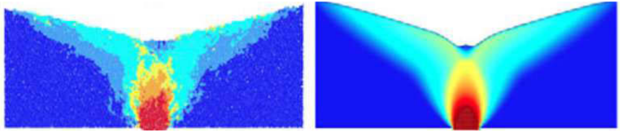
- Navier-Stokes equations
- Inertial rheology viscosity: depends on strain rate and pressure
- Shown to reproduce bulk-flow phenomena, e.g., Beverloo scaling in flow from a silo
- Ill-posed for some parameter values (due to pressure term in viscosity)?[3]

$$\nabla \cdot \mathbf{u} = 0$$

$$\rho_B \left(\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} \right) = \rho_B \mathbf{g} - \nabla p + \nabla \cdot (2\eta \mathbf{D})$$

$$\eta = \frac{\mu(I) p}{\dot{\gamma}}$$

$$\mu(I) = \mu_s + \frac{\Delta\mu}{1 + I_0/I}, \quad I = \frac{d\dot{\gamma}}{\sqrt{p/\rho_p}}$$



DEM (left) and Inertial rheology (right)[2]

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[1] Jop, P., *et al.* (2006). Nature, **441**:727–730

[2] Staron, L., *et al.* (2014). The European Physical Journal E, **37**:5

[3] Barker, T., *et al.* (2015). Journal of Fluid Mechanics, **779**:794–818

Nonlocal granular fluidity (NLGF)

Extension of inertial rheology[4],[5]

- "Fluidity", $g(x)$, with an evolution equation: propagation of flow that depends on particle length scale
- Previously evaluated in steady-state flows and simple geometries (no dynamic simulations)
  - Shown to reproduce nonlocal phenomena, e.g., stop height of flow on an incline
- Pressure-viscosity-shear instability?

$$\nabla \cdot \mathbf{u} = 0$$

$$\rho_B \left(\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} \right) = \rho_B \mathrm{g} - \nabla p + \nabla \cdot (2\eta \mathbf{D})$$

$$\eta = \frac{p}{g}, \quad \mu = \frac{\dot{\gamma}}{g}$$

$$t_0 \frac{\mathrm{d}g}{\mathrm{d}t} = A^2 d^2 \nabla^2 g - \Delta\mu \left(\frac{\mu_s - \mu}{\mu_2 - \mu} \right) g - \frac{\Delta\mu}{I_0} \sqrt{\frac{\rho_p d^2}{p}} \mu g^2$$

[4] Henann, D.L., & Kamrin, K. (2013). PNAS, **110**:6730–6735
[5] Kamrin, K., & Henann, D.L. (2014). Soft Matter, **11**:179–185

NLGF model parameters

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parameter
repeated or derived parameter
field variable

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- Material properties (e.g., pine chips)

$$\rho_B, \quad \rho_p, \quad d$$

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- Material properties (e.g., pine chips)

$$\rho_B, \quad \rho_p, \quad d$$

- 3 parameters shared with *inertial-rheology* model:

$$\mu_s, \quad \mu_2, \quad I_0, \quad (\Delta\mu = \mu_2 + \mu_s)$$

Can be determined directly from inclined-plane flow experiments.

NLGF model parameters

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- 2 new parameters:

$$A, \quad t_0$$

Can be determined by matching model results to flow experiments.

NLGF model parameters

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- 2 new parameters:

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  Can be determined by matching model results to flow experiments.

- Limits needed on values for fluidity, friction coefficient, and pressure to prevent divide by zero:

$$g_{\min} = 10^{-6}, \quad \mu_{\max} = 0.98\mu_2, \quad p_{\min} = 10\,\mathrm{Pa}$$

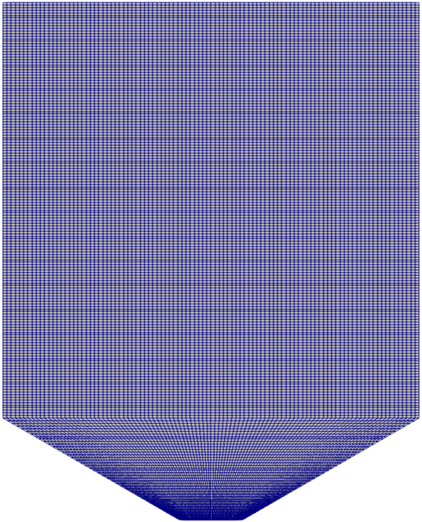
CFD implementation

- Open-source CFD software OpenFOAM
- Incompressible Volume-of-fluid (VOF) method
- Implemented custom rheology model for NLGF
  - Viscosity model with pressure
  - Evolution equation for fluidity
- Simple meshes were developed directly (blockMesh)
  - At least 10k cells (for 2D geometries)
- Boundary conditions for fluidity? Both fixed and zero gradient suggested in literature. Small fixed value is logical for zero slip:

$$g(x = \partial\Omega, t) = g_{\text{min}}$$

- Initial condition:

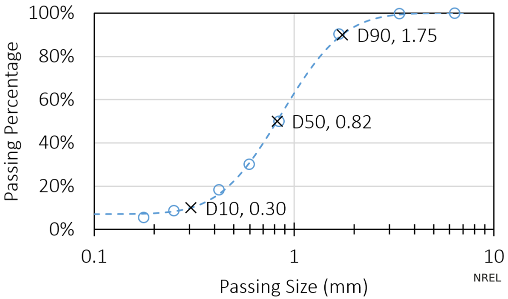
$$g(x, t = 0) = 10$$



Materials

Hammer-milled **loblolly pine** to pass through 1/4 in screen:

$\rho_p = 500\,\text{kg/m}^3$
$\rho_B = 236\,\text{kg/m}^3$
$d_{50} = 0.8\,\text{mm}$



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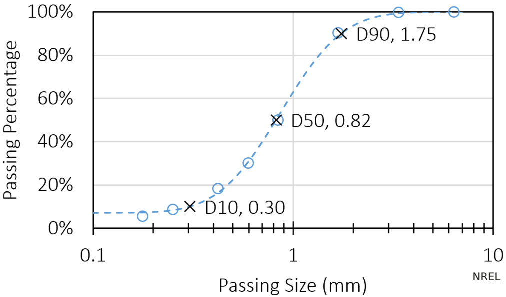
Some simulations used properties of **glass beads** to compare to literature results:

$\rho_p = 2500\,\mathrm{kg/m^3}$
$\rho_B = 1500\,\mathrm{kg/m^3}$
$d = 1\,\mathrm{mm}$

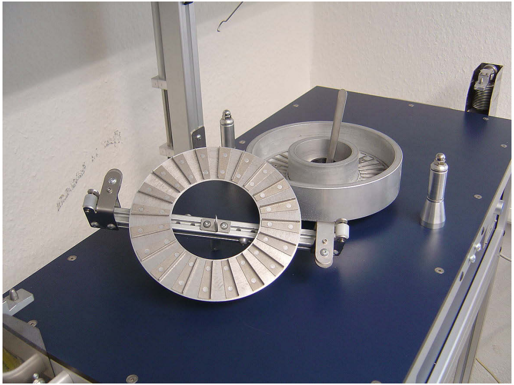


Experimental methods: Inclined plane

- Storage-box filled with material
- Laser-scanner used to measure material position and velocity on ramp
- Gate opened to sufficient height to initiate flow, $75 - 200\,\mathrm{mm}$
- Flow observed and front velocity measured
- Gate closed when $\sim \frac{1}{2}$ of material has exited
- Stop-height profile measured

Experimental methods: Ring-shear tester

- Schulz Ring-Shear Tester (RST-01)
- Mohr-circle analysis of shear stresses vs. compressive stresses
- Standard measurement of cohesion and internal friction



https://www.gfz-potsdam.de/en/section/lithosphere-dynamics/infrastructure/heltec-helmholtz-laboratory-for-tectonic-modelling/lab-infrastructure/

Inclined-plane, experimental results

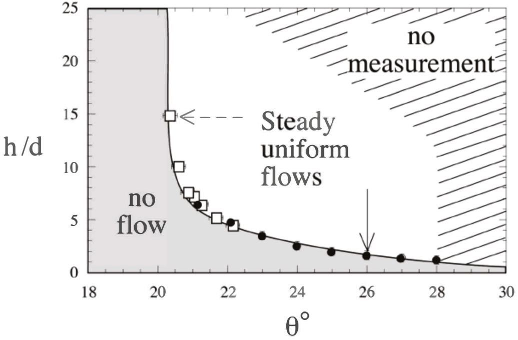
animations/29’5deg_14in_open.mp4

Inclined-plane, experimental results

animations/29'5deg_14in_open.mp4

Inclined-plane, experimental results (cont'd)

Glass beads

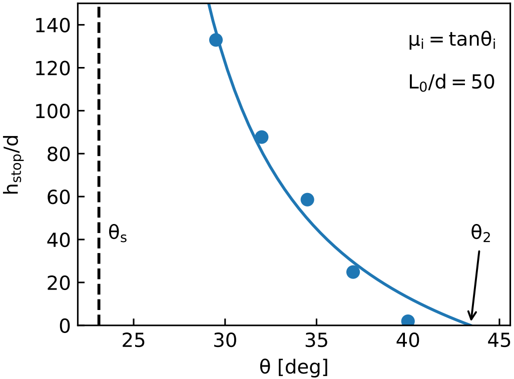


Pouliquen (1999) *Phys. Fluids* 11:542

$$\frac{h_{stop}(\theta)}{d} = \frac{L_0}{d}\left(\frac{\mu_2 - \mu_s}{\tan(\theta) - \mu_s} - 1\right)$$

$L_0/d \sim 2$ for glass beads

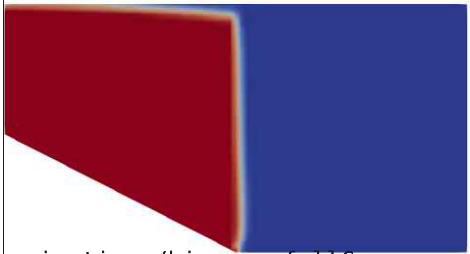
Milled pine



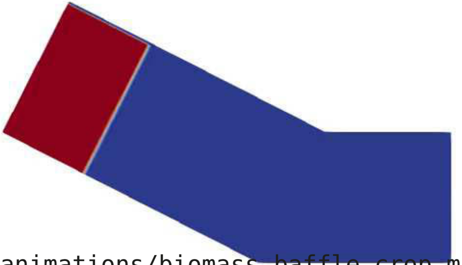
$$I_0 = \frac{5}{2}\frac{d\beta}{L_0\sqrt{\phi\cos(\theta)}}$$

$\beta \propto \langle v \rangle / h \sim 0.1,$ glass beads

Inclined-plane simulations



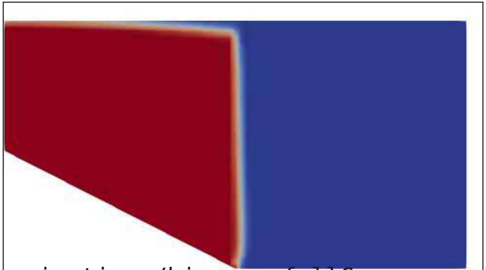
animations/biomass_fullCov_crop_short.mp4



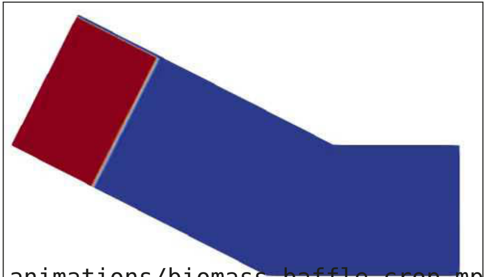
animations/biomass_baffle_crop.mp4

- Biomass parameters for ρ_B, ρ_p, d, μ_s, μ_2, and I_0
- Presumed values for A and t_0
- $\theta = 27°$

Inclined-plane simulations



animations/biomass_fullCov_crop_short.m



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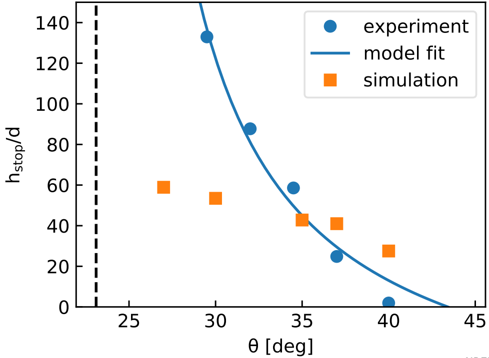
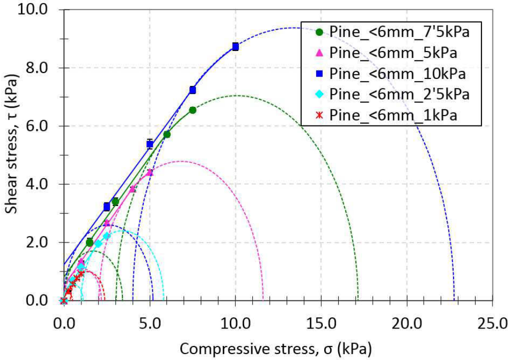


Ring-shear tester

Experimental results, biomass



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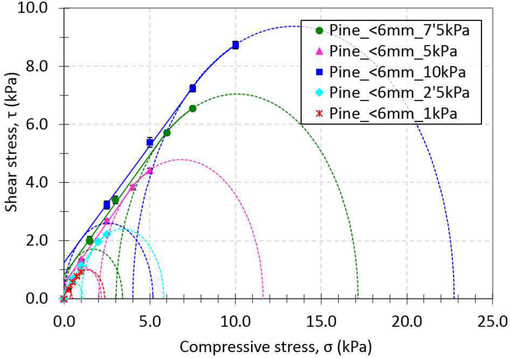
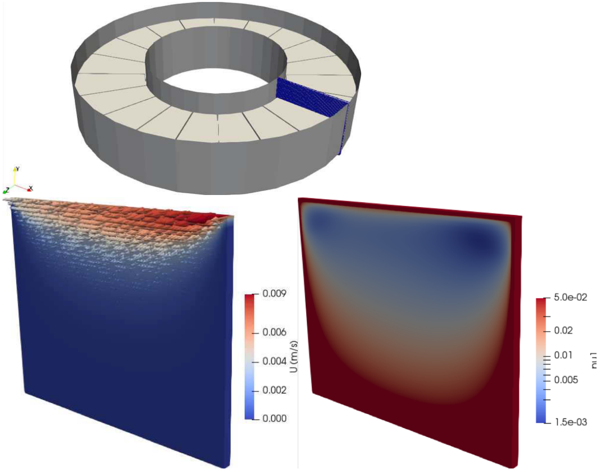
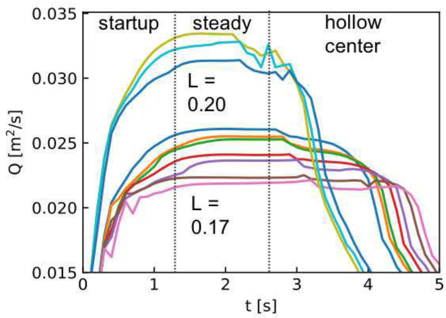


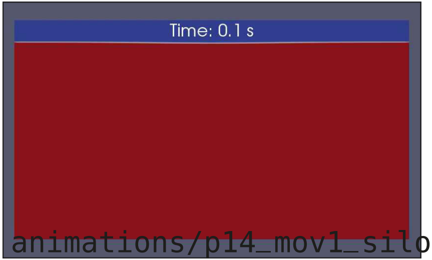
Simulations, qualitative results



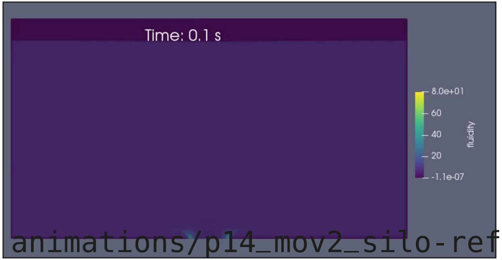
Flows from a silo

- Simple 2D rectangular silo with a centered bottom outlet
- Flow is steady between startup and formation of hollow center
- Static piles remain in the corners of the silo
- Flow profiles obtained for different outlet widths (L) and particle diameters (d)





animations/p14_mov1_silo-refi



animations/p14_mov2_silo-refined

Fluidity

Flows from a silo, Beverloo scaling

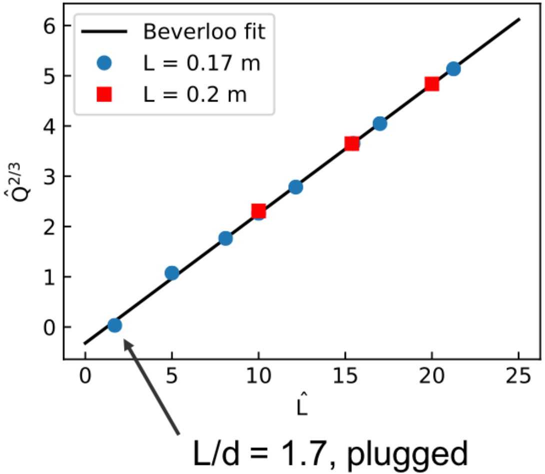
- The steady flow rate correlates with *L*/*d*
- 2D equations:

$$Q = Cg^{1/2}(L - kd)^{3/2}$$

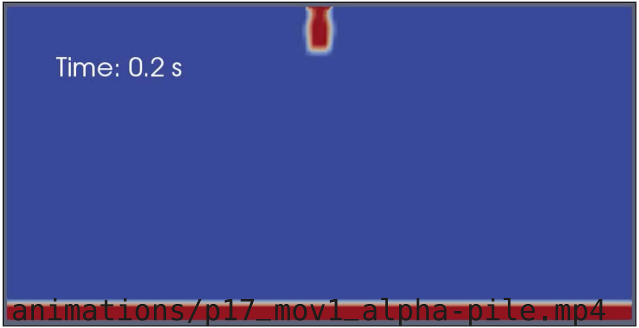
$$\hat{Q}^{2/3} = C^{2/3}(\hat{L} - k)$$

$$\hat{Q} = g^{-1/2}d^{-3/2}Q, \qquad \hat{L} = L/d$$

- Our simulation results confirm Beverloo scaling when changing either *L* or *d*

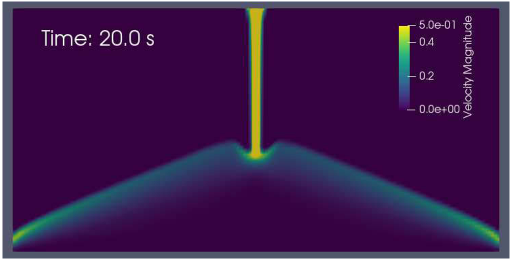


Flow onto a pile

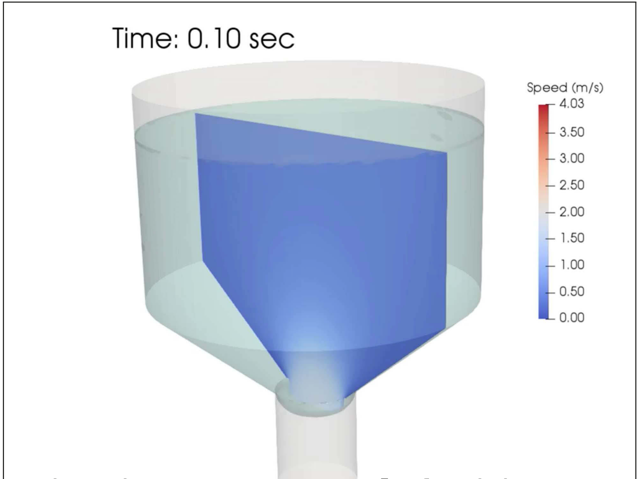


1 m

- Another classic test of granular behavior
- Qualitatively correct results with pile angle between static and dynamic friction angles (21° and 33°)

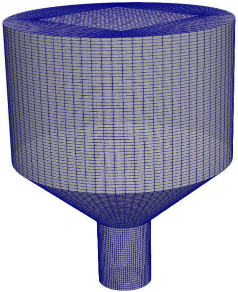


Flow from a hopper (3D)



animations/p19_mov1_nlgf_3d_hopper.mp4

- 3D conical hopper flow successfully performed using HPC
- 1.5 m tall, $\theta = 40°$
- 220,000 cell mesh
- Simulation took 3 h on 32 cpus



Summary and future work

- *Dynamic* NLGF model successfully implemented in a general CFD software package
- Preliminary parameter determination for milled softwood
  - Stop height on inclined ramps
  - Ring shear testing
- Other classic flow phenomena reproduced qualitatively
  - Beverloo scaling in flows from silos
  - Pile formation
  - Hopper discharge
- Industrial-scale 3D simulation of hopper discharge

Future work

- Euler-Euler solver
  - Improved pressure evaluation and numerical stability
  - Variable density
  - Air passage
- Bulk solid compression?

Thank you

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