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The Role of Granular Mechanics and Porous Flow for Ice Sheet Behavior in a Changing Climate

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ESCO 2020: Climate MS, 2020-06-08

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Rignot et al. 2011 Science

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Clark et al. 2018 Earth Surf. Process. Landforms

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Grounding-zone wedges



Anandakrishnan et al. 2007 Science

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Bart et al. 2017 Scientific Reports

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Bart et al. 2017 Scientific Reports

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Bart et al. 2017 Scientific Reports

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Dowdeswell et al. 2020 Science

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Ice-stream stabilization



Alley et al. 2007 Science

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No model for till transport ↓ No physically-based modeling

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Granular modeling

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Particle-scale modeling: Discrete-element method



Damsgaard et al. 2013 J. Geophys. Res.



Damsgaard et al. 2016 Geophys. Res. Lett.

Normal stress σ_0 on wall with fixed p_t^{top} Fixed $v_{p,top}^x$ Static, impermeable wall Damsgaard et al. 2015 The Crvosphere



Granular rheology ○ ○●

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Conclusions

Particle-scale modeling: Discrete-element method

sphere

git://adamsgaard.dk/sphere C++, Nvidia C, cmake, Python, Paraview massively parallel, GPGPU detailed physics and fluid-grain coupling 20,191 LOC

3 months on nvidia tesla k40



Damsgaard et al. 2015 The Cryosphere

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Continuum modeling of granular mechanics

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Phase transitions in granular materials



Houssais et al. 2015 Nat. Comm.

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Mohr Coulomb





Iverson 2010 J. Glaciol.



Charles-Augustin de Coulomb, b. 1736

Christian Otto Mohr, b. 1835

Karl von Terzaghi, b. 1883

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Local rheology for dense granular flows: $\mu(I)$, $\Phi(I)$

$$I = \frac{\dot{\gamma}d}{\sqrt{N/\rho}}$$

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Jop et al. 2005 J. Fluid Mech.:

$$au = \mu(I)N$$

$$\mu(I) = \mu_{\rm s} + \frac{\mu_2 - \mu_{\rm s}}{I_0/I + 1}$$

Pouliquen et al. 2006 J. Stat. Mech .:

$$\Phi(I) = \Phi_{\max} - (\Phi_{\max} - \Phi_{\min})I$$



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Non-local granular fluidity rheology

 $\dot{\gamma}=g(\mu,N)\mu$

$$g_{\mathsf{local}}(\mu, N) = egin{cases} \sqrt{d^2 N /
ho_{\mathsf{s}}}(\mu - \mu_{\mathsf{s}}) / (b\mu) & ext{if } \mu > \mu_{\mathsf{s}} \\ 0 & ext{if } \mu \leq \mu_{\mathsf{s}} \end{cases}$$

$$abla^2 g = rac{1}{\xi^2(\mu)}(g-g_{\mathsf{local}})$$

$$\xi(\mu) = \frac{Ad}{\sqrt{|\mu - \mu_{\mathsf{s}}|}}$$

Henann and Kamrin 2013 PNAS

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CNGF-PF: Cohesive NGF w. pore fluid



$$\sigma_{\rm n}' = \sigma_{\rm n} - p_{\rm f}$$

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Model setup



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Strain distribution



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Granular modeling: Discrete-element method vs. continuum model

sphere

git://adamsgaard.dk/sphere C++, Nvidia C, cmake, Python, Paraview massively parallel, GPGPU detailed physics and fluid-grain coupling 20,191 LOC

3 months on nvidia tesla k40

1d-fd-simple-shear

git://adamsgaard.dk/1d_fd_simple_shear C99, makefiles, gnuplot single threaded simple physics, simple fluid-grain coupling 2,348 LOC 70 ms on 2012 laptop

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Deep or shallow deformation?

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Deep or shallow deformation?



Maximum deformation depth: z'

$$0 = \sqrt{2}\sin\left(\frac{7\pi}{4} - \frac{z'}{d_{\rm s}}\right) + \frac{(\rho_{\rm s} - \rho_{\rm f})Gd_{\rm s}}{A_{\rm f}}\exp\left(\frac{z'}{d_{\rm s}}\right)$$

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Next steps: Ice-water-sediment coupling



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Conclusions

- First-principles granular rheologies promising for coupled simulations
- Rheology consistent with critical-state sediment mechanics and laboratory experiments
- Computationally lightweight compared to particle-based methods
- Towards testable field predictions of subglacial deformation and glacier dynamics

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Resources

Slides:

https://adamsgaard.dk/npub/esco2020-damsgaard.pdf

Source code:

https://src.adamsgaard.dk/1d_fd_simple_shear

Preprint: "Evolving basal slip under glaciers and ice streams" https://arxiv.org/abs/2002.02436