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A local rheology relation that unifies dry, wet, dense, and dilute granular flows

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Geophysical granular flows in general are surrounded by fluid (wet) and exhibit coexisting dense (fluidlike) and dilute (gaslike) flow layers. However, existing rheology models describe only a small subset of these regimes and we are currently very far from reconciling them within a general model. For example, granular kinetic theory describes dilute, dry flows and even its mere extension to the dense, dry regime is currently a matter of controversial debate, especially for realistic frictional particles (e.g., [1,2]). Another example: the viscoinertial rheology describes dense suspensions of particles in density-matched liquids [3] and even its mere extension to slightly lighter liquids, such as for viscous and turbulent bedload sediment transport, is not straightforward (e.g., [4,5]). Here we carry out discrete element method-based simulations of granular flows for a variety of geometries and driving mechanisms, which cover the entire phase space of dry, wet, dense, and dilute conditions: (i) two-dimensional sediment transport driven by a large variety of Newtonian fluids (including oil, water, and air), (ii) rapid gravity-driven flows in ambient static air of varying viscosity, (iii) two-dimensional uniformly sheared viscous suspensions in density-matched fluid of varying viscosity, (iv) two-dimensional dry uniform shear flows, (v) three-dimensional rotating drum flows lubricated by a density-matched fluid, and (vi) a three-dimensional dry rotating drum flow. For all simulated conditions, except for sediment transport and gravity-driven flows close to the flow threshold, we find that the Mohr-Coulomb friction coefficient μ scales with the square root of the local Péclet number $\mathrm{Pe} = \dot{\gamma}d/\sqrt{T}$, provided that the particle diameter exceeds the particle mean free path. The scaling coefficient depends only on tangential contact parameters but not on normal ones, which points to a competition between macroscopic shearing and thermal diffusion as being the physical origin of this scaling. With decreasing Pe and granular temperature gradient $M = d\nabla T/T$, the scaling breaks down as the system becomes increasingly isotropic, allowing the mechanical stabilization of the flow. This leads to a yield condition with a variable yield stress ratio characterized by M, which can be much smaller than its value for homogeneous flows.

[1] Chialvo Sundaresan (2013), doi: 10.1063/1.4812804 ; [2] Berzi Vescovi (2015), doi: 10.1063/1.4905461 ; [3] Trulsson et al. (2012), doi: 10.1103/PhysRevLett.109.118305 ; [4] Houssais et al. (2016), doi: 10.1103/PhysRevE.94.062609 ; [5] Maurin et al. (2016), doi: 10.1017/jfm.2016.520