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Simple rheology unifying dense and dilute granular flows

Thomas Pähtz (1), Orencio Durán (2), Dawie de Klerk (3), and Indresan Govender (4)

(1) Institute of Port, Coastal and Offshore Engineering, Ocean College, Zhejiang University, Hangzhou, China, (2) Department of Ocean Engineering, Texas A&M University, Texas, USA, (3) Centre for Minerals Research, University of Cape Town, Cape Town, South Africa, (4) School of Engineering, University of KwaZulu-Natal, Glenwood, South Africa

Granular material flows in general consist of coexisting dense (liquid-like) and dilute (gas-like) flow layers. However, existing models only describe the rheology of either the dense regime (e.g., the viscoplastic $\mu(I)$ rheology of dry granular flows) or the dilute regime (Granular Kinetic Theory), which currently cannot be reconciled with each other. The problem is that dense rheology models do not take into account particle velocity fluctuations, which play a crucial role in the dilute regime, whereas Granular Kinetic Theory fails for dense flows as particles experience enduring contacts rather than the instantaneous binary collisions assumed by Kinetic Theory, resulting in much less collisional energy dissipation than predicted. Dense rheology models are also known to fail capturing dense, multidirectional granular flows due to a missing alignment between the stress and strain rate tensors. Here we propose a simple modification of the inertial number I in the $\mu(I)$ rheology that makes explicit the role of particle velocity fluctuations. Combined with the constitutive relations for the stress tensor from a Burnett order Kinetic Theory, this modification results in a simple rheology unifying dense and dilute granular flows. This rheology is consistent with experiments and simulations of uniform shear and slow gravity flows and explains complex flow patterns associated with the coexistence of dense and dilute flow layers, as observed in experiments and simulations of rapid gravity flows and sediment transport mediated by viscous and turbulent liquids and gases. It is also consistent with simulations of multidirectional rotating drum flows and thus overcomes a central issue of previous dense rheology models.