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Friction in inertial granular flows: microscopic and macroscopic origins

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ABSTRACT

Granular media are prevalent in dynamic frictional processes throughout nature and technology, from earthquakes to grain transport. Empirical relations describing macroscopic friction as a function of the inertial number have proven successful in predicting experimentally observed velocity and stress profiles when combined with continuum models. However, these relations and the continuum models that employ them do not elucidate the grain-scale origin of friction or its widely observed rate dependence. They also fail to capture the important transient behavior of granular flows relevant to processes like sliding on granular fault gouge. This lack of a micro-to-macro understanding leaves a unified modeling approach for granular media, from quasi-static to rapid flows, elusive. In this study, we present recent theoretical and numerical studies of friction in granular shear flows. We first show that steady-state friction can be explicitly written as a function of coordination number, volume fraction, inertial number, and average per contact dissipation rates. This relation illustrates that steady-state friction emerges from a competition between the dilative tendency of granular flows and grain-scale viscoplastic effects. The dilative tendency results in a decrease in volume fraction and average number of contacts per grain with shear rate. The viscoplastic effects cause per contact dissipation rates to increase with shear rate. We use 3D numerical simulations to investigate how inherent scaling of these properties leads to rate-strengthening in the inertial (or dense) flow regime. This scaling also elucidates the ”“slowing down”“ of rate-strengthening at higher shear rates. Per-contact sliding and collisional dissipation rates are compared for their contribution to total friction and to rate-strengthening. We briefly discuss how consideration of other dissipative processes (e.g., grain breakage) may alter frictional properties in the context of this relationship. We also compare our relation with others developed in the literature. We will also describe ongoing study on the transient behavior of granular flows. We study the analog of the friction relation described earlier for transient behavior and use 3D numerical simulations to study the role of dilatancy and other nonsteady-state processes on the strengthening and weakening behavior that occurs when loading rates change. Transient behavior is particularly important during sliding on granular fault gouge and the findings presented here may lend insight into the grain-scale processes that control frictional behavior during these events.