Constitutive law of granular matter: numerical and physical experiments

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The rheological properties of granular matter are important in analyzing various phenomena in geosciences such as landslide, debris flow, crater formation, etc. Importantly, it is also essential to friction on faults, as faults contain granular layers that are ground up by the fault motion of the past. It is thus important to clarify constitutive laws of granular matter together with their physical mechanisms.

In general, rheological properties of granular matter may be classified according to their density and shear rate. At low density and high shear rate regime, the frictional properties predicted by a kinetic theory agree with simulations on inclined plane flow. At higher density and lower shear rates, the frictional properties are generally described by the empirical law, which is referred to as the rate and state dependent friction. However, apart from these two end members, a constitutive law in the intermediate regime is still not very clear. It is particularly important to physics of earthquakes, as it determines the heat production rate on a fault rubbing at seismic slip rates. Such frictional heat is responsible for various mechanochemical effects that eventually lubricate a fault.

Here we investigate the constitutive law of granular matter focusing on the intermediate slip velocity regime. We employ the standard numerical model that is referred to as the discrete element method. We focus on the steady states to report the velocity dependence of friction coefficient in a wide range of shear rate. It is found that the friction coefficient μ exhibits the Herschel-Bulkley behavior: $\mu = \mu_0 + aI^{\phi}$, where I is the nondimensional shear rate and μ_0, ϕ, and a denote positive constants. Namely, the friction coefficient is velocity strengthening. We then discuss the physical mechanism that yields this Hershel-Bulkley behavior. By decomposing the energy dissipation rate into two distinctive parts, we show that the velocity strengthening nature is due to the inelastic repulsion between each grain. In the same manner, we can show that the friction coefficient in the lower shear rate regime, μ_0, is determined by the elementary friction coefficient between each grain.

We then analyze the spatial structure of sheared granular layers. Shear deformation tends to localize near the sliding boundary. We show this shear-banding is due to the coupling between shear rate and the density, which is essential feature of granular matter.

Finally, these simulations are compared with experiments. Indeed, the simulation fails to explain the experimental results for the quasistatic deformation, where logarithmic weakening is observed. This is rather trivial as the discrete element method involves purely mechanical forces. At higher shear rate, remarkable velocity strengthening is observed in experiments. This can be explained within the framework described above.