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Fragmentation, Acoustic Effects, and Flash Heating in Sheared Granular Materials: Implications of Geophysical Processes and Physical Constraints for Dynamic Friction

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Incomplete understanding of friction, deformation, and failure is a primary limiting factor in forecasting seismic hazards. We report recent progress on a physics-based framework for constitutive laws. Our methods are rooted in the underlying statistical thermodynamics of amorphous materials, and bridge the gap between microscopic dynamics, laboratory experiments, and dynamic rupture. We expand Shear-Transformation-Zone theory, describing frictional response of sheared gouge layers over a wide range of velocities and normal stresses, to account for geophysically relevant processes such as breakage and thermal heating, as well as grain shapes. We combine theoretical advances with quantitative fits to experimental data obtained within the fault and rock mechanics community. Fragmentation is described by a constitutive equation for grain size reduction involving the applied work rate and pressure, constrained by energy balance. We show that grain breakage is a potential weakening mechanism at high strain rates. It promotes strain localization and may explain long-term persistence of shear bands in natural faults. Shape effects are modeled by an orientational bias that describes grain interlocking and geometric frustration. We interpret inter-particle friction as an additional source of acoustic noise. We obtain quantitative agreement between experimental measurements and theoretical predictions for both internally generated acoustic noise and externally applied vibrations. Frictionally generated thermal heating is incorporated using a contact strength model that accounts for local increases in temperature at grain contacts during sliding. The magnitude of this effect depends on grain size and porosity of the granular layer. Our model predicts logarithmic rate dependence of steady state shear stress in the quasi-static regime. In the dense flow regime frictional strength decreases rapidly with increasing slip rate due to thermal softening at granular interfaces. The transient response following a step in strain rate includes a direct effect and subsequent evolution effect, both depending on the magnitude and direction of the velocity step. The resulting friction models are appropriate for dynamic rupture simulations that extrapolate results to geophysically relevant regimes that are beyond reach of laboratory experiments. Our work offers experimentalists and field workers insights for interpreting data, identifying features to target in future work, and estimating seismic hazards.