Recent experimental studies show that the value of friction varies over a wide range of sliding velocities (slow sliding exhibits high friction and rate-and-state behavior, and remarkable weakening occurs as velocity approaches seismic velocity). In this study, we extend a microphysically-based friction model for granular gouges (Chen and Spiers, 2016; Niemeyer and Spiers, 2007) to the high-velocity regime, by introducing additional creep mechanism(s) activated by frictional heating. The modeling results capture all of the main features and trends seen in the experiments, including both steady state and transient aspects of the observed behavior, with reasonable quantitative agreement.

1. Chen-Niemeijer-Spiers (CNS) Microphysical Model

Fig. 1 Conceptual model of a) solid-solid frictional interface and b) granular friction, giving physical underpinnings for classic rate-and-state friction laws and a general microphysical friction model, respectively.

2. Extension to high velocity regime: frictional heating actives new creep mechanism(s)

1. At low velocities, it shows velocity strengthening behavior with deformation accommodated by non-dilatant plastic creep.

2. At intermediate velocities, as the velocity increases, the friction behavior will be first controlled by dilatant granular slip that is mediated by compactional contact creep, giving rise to a velocity weakening behavior; as the velocity increases further, the frictional behavior will be controlled by GBS which is inherently rate-strengthening.

3. At high velocities, dynamic friction decreases substantially due to thermal weakening effects (e.g. Thermal pressurization, flash heating, superplasticity).

3. Steady-state behavior

Steady-state friction is within the shear zone following an arbitrary damage (De-Patian et al., 2015) and depends on the surface properties of the PSZ.


Fig. 6. Evolution of friction with displacement and calculated temperature of the shear zone (Left: laboratory results, Right: model prediction).

4b. Smith et al. (2015): “strengthening phase” and slip localization

Fig. 7. Predicted evolution of friction with the logarithm of displacement and the pre-weakening strengthening phase with normal stress (Left: laboratory results, Right: model prediction).

4c. Pozzi et al. (2018): recrystallization and microstructure evolution

Fig. 9. Predicted friction and microstructural parameters with displacement. (a) friction, (b) temperature, (c) porosity and (d) grain size over log(gouge thickness).

5. Discussion and future work

(1) Extended CNS model predicts a steady-state frictional strong profile over a wide velocity range (Fig. 5).

(2) The model reproduces typical laboratory experiments (friction and compaction/dilation, Fig. 6).

(3) Dynamic weakening occurs after a “prolonged strengthening phase” which shortens with increasing normal stress (Fig. 7) and increasing slip rate (not shown).

(4) The model predicts a “Sintering Gradient” zone, extending beyond the PSZ, characterized by low-porosity and nearly-uniform grain size, whose grain size and thickness increase with shear displacement (Fig. 9 and 10).

As grain size increases, dislocation creep will become increasingly important (c.f. creep-accommodated GBS).

Limitation: prescribed slip localization.

Future work: (1) stability analysis; (2) earthquake cycle simulations with the extended model.