Capturing Physical Phenomena in Particle Dynamics Simulations of Granular Fault Gouge

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Abstract

Recent simulations using the particle dynamics method (PDM) have successfully captured many features of natural shear zones as illuminated in laboratory studies. However, 2D simulations conducted on idealized assemblages of particles using simple elastic-frictional contact laws, yield friction values much lower than natural materials, and lack time- and velocity-dependent changes in strength that influence dynamic fault slip. I describe preliminary results of new PDM simulations, in which particle rotations are restricted and time-dependent contact healing is introduced. The resulting behavior is qualitatively similar to that described by empirically-based rate-state friction laws, and provides new physical insight into the discrete mechanics of natural faults.

Introduction

Particle dynamics method (PDM) simulations represent a unique tool for studying the mechanics of gouge-bearing shear zones, providing views into active and evolving faults in ways never imagined in the field or in the lab. To date, PDM simulations have successfully captured many aspects of fault zone mechanics and deformation as documented in laboratory experiments. These include strain localization and delocalization, stick-slip sliding, and characteristic fracture arrays (e.g., Mora and Place, 1998[14]; Morgan, 1999[15]; Morgan and Boettcher, 1999[16]; Aharonov and Sparks, 1999[2]). However, several fundamental experimental results thought to be important in the earthquake generation process, have not been well represented by PDM models. In particular, friction coefficients determined for numerical systems are commonly ~0.25 - 0.30, much lower than ~0.6 predicted by Byerlee's law, a result attributed to the particle rolling in 2D assemblages. In addition, due to the simplified contact laws employed, PDM simulations do not show 2nd order changes in friction with strain, thought to influence stability of sliding and seismogenesis (e.g., Dieterich, 1979[7], Marone et al., 1990[13]; Marone, 1998a[11], 1998b[12]; Beeler et al., 1996[4]). These differences between experimental and numerical friction need to be reconciled before we can apply PDM simulations to the study of more complicated, natural fault systems.

Here, I present preliminary results of recent studies focused on improving and updating PDM simulations using the discrete element method (DEM; Cundall and Strack, 1979[5]) to better reproduce laboratory observations of shear strength and variations in friction with
strain. By restricting particle mobility as a proxy for grain roughness, interlocking, and out-of-plane contacts, and by implementing time-dependent healing at interparticle contacts, it is possible to qualitatively reproduce the scale and phenomenology of rate and state constitutive laws for friction. These DEM results bring us one step closer to building a consistent, physics-based description of fault friction phenomena that can be extrapolated to natural faults and an understanding of their seismogenic behavior.

**DEM Simulations**

**Particle Rolling**

The low shear strengths in PDM simulations of granular shear, result from high levels of particle rolling in idealized 2D assemblages (Mora and Place, 1998[14]; Morgan and Boettcher, 1999[16]), as recently confirmed by laboratory experiments using smooth, rounded glass beads and rods (Mair et al., 2002[10]; Frye and Marone, 2002[8]). Particle rolling cannot be as common in natural 3D systems, due the presence of irregularly shaped, interlocking particles over a wide range of sizes (e.g., Mair et al., 2002[10]). Therefore, to better match the dynamics of natural fault zone particles, we seek a proxy to reduce or prevent coordinated particle rolling in the numerical systems. This can be accomplished by damping the angular rotations of particles. A suite of 2D numerical simulations shows the effect of rotational damping for a wide range of interparticle friction, $\mu_p$ values. Fault friction, $\mu_f$ is seen to increase with the increased of damping, but still yields unreasonably low values at high $\mu_p$ (Figure 1). Clearly, if particles can roll, this remains a preferred deformation mechanism. Full damping of particle rotations (no rolling), however, leads to a nearly linear increase in $\mu_f$ with $\mu_p$, such that interparticle friction can be parameterized to gain realistic values for $\mu_f$. In the experiments presented below, we selected $\mu_p$ of 0.3 to yield $\mu_f$ of 0.6, consistent with Byerlee’s law.

![Figure 1. Average value of sliding friction, $\mu_f$ is plotted as a function of interparticle friction, $\mu_p$, for 2D simulations with damped angular rotations. Rolling varies from 100% (no damping) to 0% (no rolling).](image-url)
Contact Friction

Most existing PDM models of faults use simple elastic-frictional contact laws (e.g., Mora and Place, 1998[14]; Morgan, 1999[15]; Aharanov and Sparks, 1999[2]). Lacking memory, such laws cannot reproduce 2nd order time- and velocity-dependent changes in friction documented in laboratory experiments. In the laboratory, contact healing has been shown to depend on the logarithm of contact duration (e.g., Dieterich, 1972[6]; Beeler et al., 1994[3]; Marone, 1998a[11]. One of the important features to include in simulations, therefore, is contact memory, allowing friction and cohesion to vary during static contact.

Friction at interparticle contacts can be implemented in several ways: (1) One simple approach is to use two different friction coefficients - static friction drops instantaneously to a lower dynamic friction upon onset of slip; when slip stops, friction is reset to its static value. This approach causes rapid strength loss during dynamic slip, and instantaneous strength recovery. The choice of friction coefficients, however, is somewhat arbitrary, and the instantaneous transition precludes strength evolution during shear. (2) At the other extreme, rate- and state-friction laws can be imposed directly at particle contacts. Abe et al. (2001[1]) show this produces rate- and state-friction like behavior at the assemblage scale, but modeled friction parameters differ at the contact and assemblage. This approach is very CPU intensive (Abe, personal communication, 2002), and not ideal for large systems representative of geologic fault zones. (3) An intermediate solution is to introduce contact healing alone, i.e., by tracking contact duration and calculating friction as:

\[
\mu = \mu_0, \quad t=0
\]

\[
\mu = \mu_0 + b \ln(t), \quad t>0
\]

Preliminary work using the latter approach yields very rich results, reproducing much of the rate- and state-friction phenomenology, including steady-state velocity strengthening, log(time) healing of the system during static holds, direct change in friction with velocity steps, and strength evolution with slip as a function of static contact duration.

Figure 2. Particle configurations; sidebars show degree of localization.. (a) Initial configuration. (b) Distributed bulk strain field at 150% shear strain for control test. (c) Distributed strain field at 150%, with persistent slip planes, sheared at 0.001 \mu m/s with contact healing. (d) Localized strain field at 150% shear strain, sheared at 0.01 \mu m/s with contact healing.
Time-Dependent Contact Healing

The simulations described here all begin with the identical starting configuration, a consolidated assemblage of particles bounded by walls spaced 9 mm apart (Figure 2a). The upper wall is displaced at a constant velocity ranging from 0.1 to 0.001 µm/s. For comparison, simulations were conducted with and without time-dependent contact healing. Without healing, deformation tends to be distributed (Figure 2b). With contact healing, strain starts to localize (Figure 2c and d), apparently as stronger contacts increasingly resist slip, focusing deformation into actively deforming zones.

The mechanical behavior of the shear zone depends on sliding velocity. Low wall velocities produce characteristic stick-slip behavior, with repeated sequences of elastic loading, pre-failure plastic yield, and finally failure, accompanied by a sudden strength drop (Figure 3a and b). Each event is accompanied by gradual dilation followed by sudden contraction. Peak $\mu_f$ is ~0.6-0.62 in the control system and ~0.7 with contact strengthening. Higher velocities result in contrasting behavior, reminiscent of the oscillating mode described by Nasuno et al. (1997[17]). Strength and volume strain still fluctuate throughout the experiment, but stick-slip cycles are poorly developed and dilation-contraction sequences are subdued (Figure 3c and d).

![Figure 3. Friction, $\mu_f$ (solid) and volume strain (dotted) data for four numerical experiments.](image)

- (a) Wall velocity of 0.001 µm/s results in repeated stick-slip events with consistent peak strengths. (b) Enlarged view of boxed region in (a) shows form of stick-slip cycles. Elastic modulus is nearly constant for a test, but appears to be higher with contact healing. (c) Wall velocity of 0.1 µm/s produces similar fluctuations in friction and volume strain, however, in detail, (d) stick-slip cycles are absent and friction and volume-strain exhibit nearly symmetric oscillations.

Plots of mean sliding friction and dilation for all experiments show significant variability, but indicate a direct velocity dependence (Figure 4a and b). This velocity strengthening behavior is consistent with laboratory studies of granular gouge during initial shearing, and implies stable sliding (e.g., Marone et al., 1990[13]; Beeler et al.,
Figure 4. Mean values of steady-state experimental quantities for all experiments. (a) Friction and (b) volume strain show logarithmic increases with sliding velocity, indicative of velocity strengthening behavior. (c) Percentage of sliding contacts is also observed to increase with velocity, but the functional form of the relationship is not clear.

The mechanism responsible for this behavior is suggested by the increase in percentage of sliding contacts at higher velocities (Figure 4c), suggesting under these conditions, more unfavorably oriented contacts are activated.

To examine shear zone restrengthening, static hold tests were carried out for different durations, using identical starting configurations. Both frictional relaxation during holds and peak strength upon reloading increased logarithmically with hold time (Figure 5a and d; Figure 6). Changes in sliding contacts mirrored the frictional response (Figure 5b and e). Shear zone dilation was suppressed during and after holds (Figure 5c and f). The results of static hold tests are qualitatively similar to laboratory experiments (e.g., Marone, 1998a[11]; Karner and Marone, 1998[9]). Immediately following static holds, friction and volume strain paths are very similar, however, these trends diverge and become effectively uncorrelated within ~5% strain, despite the identical initial conditions (Figure 5).
Figure 6. Plot of friction, $\mu_f$ against log(hold time) for static loading tests carried out at 138% strain for wall velocity of 0.1 $\mu$m/s (e.g., Figure 5).

Another manifestation of rate- and state-friction is the variation in friction during velocity stepping experiments (e.g., Marone et al., 1990[13]; Mair et al., 2002[10]). In our simulations, fluctuations in strength produced by irregular stick-slip events tend to mask transient changes in strength when comparing experiments, but the use of identical starting configurations reveals both direct and evolving changes in friction during velocity steps (Figure 7a and c). The percentage of sliding contacts mirrors changes in friction (Figure 7b and d), strongly arguing that velocity changes produce an immediate readjustment of contact loads, forcing a reconfiguration of the system through contact sliding and assemblage dilation. The characteristic slip length for these examples is about 6-8% shear strain, but it is not yet known what governs this scaling.

Figure 7. Friction, $\mu_f$ and volume strain data for instantaneous 100 times changes in sliding velocity, between 0.1 $\mu$m/s (black) and 0.001 $\mu$m/s (gray). Constant velocity tests shown for comparison. (a) Friction and (b) percentage of sliding contacts show direct increase in response to velocity jump, then decay to higher mean value over 6% strain. (c) Friction and (b) percentage sliding contacts declines in response to velocity drop, then gradually climb to lower mean value over 7-8% shear strain.
Conclusions

In summary, recent PDM studies show that simple modifications to particle contact laws and restrictions on particle mobility, can approach laboratory estimates for sliding friction, and successfully reproduce many time- and state-dependent 2nd order changes in friction, lending insight into the micromechanisms responsible for these phenomena. Even though interparticle contact strength depends only on the time of static contact in these models, the bulk assemblage response reveals velocity- and slip-dependent behavior associated with changes in deformation mechanism, particle configuration and packing, and contact orientation. These results demonstrate the complexity of, and range of factors that control, granular deformation under dynamic conditions. Clearly, further work is necessary to more fully characterize the physics of this system.

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References


