Effects of gouge fragment shape on fault friction: New 3D modelling results

Steffen Abe1 and Karen Mair2

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The friction of granular fault gouge plays an important role in governing the mechanical behavior and hence earthquake potential of faults. Using numerical modelling, significant progress has recently been made towards understanding the micro-mechanics that drive fault gouge evolution. Despite these insights, many previous numerical models have predicted unrealistically low macroscopic frictional strength. Here we describe modified 3D discrete element simulations of fault gouge evolution. Our particle-based simulations, modelled on laboratory experiments, include breakable bonds between individual particles (or particle clusters) allowing fracture of aggregate grains. With accumulated strain, grains break up, evolving in size and shape to produce a textural signature reminiscent of natural faults. Cluster-simulations, producing pseudo-angular daughter fragments yield realistic frictional strength (0.6). Non-cluster simulations, producing angular and spherical daughter fragments, have much lower friction levels. We therefore demonstrate that gouge fragment shape and resulting interactions dominate the frictional strength of faults. Citation: Abe, S., and K. Mair (2009), Effects of gouge fragment shape on fault friction: New 3D modelling results, Geophys. Res. Lett., 36, LXXXXX, doi:10.1029/2009GL040684.

1. Introduction

The granular wear material (fault gouge) that accumulates between the walls of a fault as it slides, plays an important role in controlling macroscopic sliding friction and the frictional stability of the fault. Fragmentation processes operating in this gouge material during shear, alter grain size distributions [e.g., Sammis et al., 1987; Blenkinsop, 1991; Rawling and Goodwin, 2003; Storti et al., 2003; Billi, 2005], change grain shape [e.g., Storti et al., 2007; Heilbrunner and Keulen, 2006], and hence influence local grain scale interactions. This will undoubtedly change force chain characteristics across the layers [Hazzard and Mair, 2003] and influence the localization state [Beeler et al., 1996; Mair and Marone, 1999] that are both key factors affecting macroscopic sliding behavior.

Laboratory experiments have provided important constraints and understanding of the frictional behavior of sheared granular materials [Mair et al., 2002; Anthony and Marone, 2005], however one limitation is that dynamic grain scale processes must generally be inferred from macroscopic response or determined from ‘snapshot’ microscopically evidence collected at the end of the experiments. Numerical modelling provides a potentially powerful tool with which to investigate grain scale events and interactions that are tricky to view directly in the laboratory. Recent modelling has made significant progress towards better understanding micromechanical processes [e.g., Cundall and Strack, 1979; Aharonov and Sparks, 1999; Morgan, 1998]. Despite these valuable insights however, an overriding issue is that many previous models have predicted unrealistically low values of macroscopic frictional strength.

[1] Here we present new modified 3D simulations of gouge evolution during shear that successfully produce realistic values of macroscopic friction (ca. 0.6). The main new features compared to previous work are the inclusions of rough boundary plates and unbreakable particle clusters. We demonstrate that gouge fragment shape (and resulting geometric interaction) is a crucial factor controlling macroscopic frictional strength. We suggest that the implementation of more complicated grain shapes will dramatically improve the applicability fault gouge models.

2. Method

To model this inherently discrete problem, we use a 3D discrete element (DEM) approach [Cundall and Strack, 1979; Mora and Place, 1994; Place and Mora, 1999]. Previous work [Hazzard and Mair, 2003] has demonstrated that 3D simulations are essential to capture the range of grain scale processes, e.g., out of plane motions, operating in evolving faults. In our simulations, fault gouge grains are modelled as aggregates [Abe and Mair, 2005] composed of many (ca. 8000) individual spherical particles bonded together with breakable elastic bonds (Figure 1). The particles are either grouped together into particle clusters (models C1, C2) or not (models SP1, SP2). When the bond failure threshold is exceeded, aggregate grains can fracture, permitting gouge evolution in a somewhat natural way. The use of aggregate grains composed of particle clusters, where bond strength is much higher inside particle clusters than between the clusters, (see enlarged pastel grain in Figure 1) ensures that broken daughter fragments are predominantly pseudo-angular rather than spherical as is common when the aggregate grains consist of bonded single particles. This modification allows us to directly investigate the effects of grain fragment shape on macroscopic friction. In order to enable the simulation of sufficiently large models, the parallel DEM simulation package ESyS-Particle [Abe et al., 2003] (https://launchpad.net/esys-particle/) has been used.

The initially spherical aggregate grains are constrained between rigid upper and lower boundary blocks (or fault walls) Figure 1. Spherical grains were chosen to...
mimic laboratory experiments on spherical glass beads \[\text{[Mair et al., 2002; Anthony and Marone, 2005]}\] and hence allow proper model validation. The rough surface of the driving plates, triangular saw-toothed grooves cut perpendicular to shear, has also been chosen to closely mimic the shape of the driving plates used in laboratory experiments \[\text{[Mair et al., 2002; Anthony and Marone, 2005]}\]. The size of the grooves relative to the grain diameter is chosen to match the laboratory setup. In addition, we simulate smooth, flat boundaries as has also been done in the laboratory \[\text{[Anthony and Marone, 2005]}\]. The model has repeating boundaries right and left, and frictionless walls front and back. Under constant normal stress, shear is applied to the upper and lower boundaries. Shearing rate is increased linearly to the chosen velocity (over the initial 0.05 shear strain) then held constant for the duration of the simulation. Macroscopic friction is calculated from shear force divided by normal force acting on the upper and lower boundary blocks.

3. Results

Typical particle cluster model simulations (Figure 2) show an increase in macroscopic friction level with accumulated shear strain until a steady-state friction level of \(\approx 0.6\) is reached. This steady-state friction level is the value subsequently plotted in Figure 3 (from this and other simulations). The observed ramp-up is due to the initially spherical aggregate grains breaking down to become pseudo-angular fragments. Fragmentation of the aggregate grains is initially intense becoming less intense with accumulated shear strain (Figure 2). Data from laboratory experiments \[\text{[Mair et al., 2002]}\] where spherical glass beads are sheared and broken up, shows qualitatively comparable behavior with friction ramping up from \(\approx 0.4\) to \(\approx 0.6\). We note however, that the steady state friction level is reached after

Figure 1. (left) Initial setup of a typical fault model and (right) final state of the model after engineering shear strain of ca. 4 at a normal stress of 30MPa. Aggregate grains are composed of either individual particles or particle clusters (see enlarged grain where the pastel colors indicate the clusters) bonded together. The fractured remains of the initially spherical grains are illustrated on right. The inset shows the (i) spherical and (ii) pseudo angular shape of the smallest fragments in single particle (SP) and cluster (C) models respectively.

Figure 2. Macroscopic friction versus shear strain for two cluster models (Model C1, C2) where initially spherical aggregate grains break down to become pseudo-angular fragments with accumulated strain. Comparable laboratory data for initially spherical glass beads being broken into angular fragments during shear is superimposed \[\text{[Mair et al., 2002]}\]. Data for bond breakage rate (second y-axis) highlights the initially high fragmentation rate that decays with shear strain. Note the different shear strain axes for model and lab data.

Figure 3. Summary of mean steady state friction data for different grain shape (spheres/angular) and boundary wall roughness (smooth/rough) configurations. Numerical model results (this study) and laboratory experiments \[\text{[Mair et al., 2002; Frye and Marone, 2002; Anthony and Marone, 2005]}\] are compared.
larger engineering shear strain (\textasciitilde8 in experiments compared to \textasciitilde1 in the models). This distinction is most likely due to the difference in number of grains across the model and laboratory gouge layers. The larger fluctuations in the measured friction in the simulations (Figure 2) are also most likely due to the smaller number of grains in the simulations compared to the laboratory experiments. Significantly larger simulations, using numbers of initial grains comparable to those used in the laboratory experiments, would be needed to confirm this.

The mean steady-state friction data obtained for different model configurations (i.e., different grain shape and boundary wall roughness) at a range of normal stresses are summarized in Figure 3. Also shown are laboratory experimental data for comparable geometries \[\text{[Mair et al., 2002; Anthony and Marone, 2005; Frye and Marone, 2002]}\].

Macroscopic friction is systematically affected by gouge fragment shape and boundary wall roughness. Spherical grains with smooth boundary walls produce the lowest friction levels in our study (\textasciitilde0.3), spherical grains with rough boundary walls have slightly higher friction (\textasciitilde0.45), and angular grains with rough boundary walls result in friction levels of \textasciitilde0.6 (see Figure 3).

4. Discussion

Results from the numerical models are extremely consistent with the trends of the experimental data. Models with pseudo-angular grains and rough boundary walls (\(\mu = 0.59–0.67\)) match the experimental data (\(\mu = 0.57–0.63\)) very closely. As do the models having spherical grains and rough boundary walls (\(\mu = 0.42–0.49\)) with comparable laboratory experiments conducted using spherical glass bead gouge (\(\mu = 0.44–0.47\) \[\text{[Mair et al., 2002; Frye and Marone, 2002; Anthony and Marone, 2005]}\]. The fit between numerical and experimental data for models with smooth boundary walls is not quite so good but this can be explained by the fact that the boundaries in the numerical models are not perfectly smooth but are rough at the particle scale whereas the boundary blocks used in the laboratory experiments are mirror finished hardened steel. Notably, for a given geometry, steady state friction shows no trend with normal stress.

The systematic increase of frictional strength with increasing abundance of angular grains (Figures 2 and 3) and increased wall roughness (Figure 3) in our simulations matches the results obtained from comparable laboratory studies very well. The likely cause is that angular grains are essentially stuck or jammed and although they clearly rotate, they require a larger shear force to be able to do so whereas spheres roll much more efficiently.

A series of simulations that are identical except that they use different values of the micro-friction parameters at the particle level, ranging from 0.4 to 1.5, (Figure 4) illustrate the insensitivity of the macroscopic friction measured at the boundaries of our model, to the micro-friction parameters prescribed to individual particles. Similar observations of the saturation of the macroscopic friction for increasing particle-level friction have previously been made in 2D simulations of granular fault gouge \[\text{[Mora and Place, 1998]}\], however in 2D the macroscopic friction level was limited to ca. 0.4. This demonstrates that gouge grain geometry is a much more important factor than particle scale friction in setting the macroscopic friction level.

The comparison between friction data obtained from models with different resolution (i.e., 190 000 and 480 000 particles) (Figure 4) also shows that the mean steady state friction level is not significantly influenced by the model resolution, at least for the model sizes used to date (this resolution insensitivity may not hold for very small models).

Importantly, our new results from particle cluster models are largely consistent in terms of grain scale processes and developing microstructures with our recent findings on non-clustered models \[\text{[Abe and Mair, 2005; Mair and Abe, 2008]}\]. We still observe survivor grains, i.e., those retaining 75% of their original equivalent diameter to relatively large shear strains. Regions of strain localization still appear to correspond to regions having smaller grain size. However, we see that with rough boundaries, the regions of localized strain are not always concentrated at the boundary as is commonly the case for smooth boundary runs, but are located within the layer. Additionally, for particle cluster models with rough boundaries, the regions of strain localization appear to be less persistent, suggesting local strain hardening.

5. Conclusions

We show that gouge fragment angularity is crucial in controlling macroscopic friction. By doing so, we demonstrate the limitations of using ideal spherical indistuctible particles in simulations of fault gouge behavior. The very good agreement between the results from our new cluster simulations and the available laboratory data indicates that gouge fragment angularity has been an important “missing ingredient” that has, in effect, prevented previous DEM simulations of fault gouge from reaching realistic values of frictional strength. Due to advances in available computational resources, the implementation of more complicated geometries into large scale simulations of faults is now possible.
feasible. We conclude therefore that this is an important and necessary step in order to better understanding the mechanics of earthquake faults.

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References


S. Abe, Geologie-Endogene Dynamik, RWTH Aachen University, Lochnerstrasse 4-20, D-52056 Aachen, Germany. (s.abe@ged.rwth-aachen.de)

K. Mair, Physics of Geological Processes, University of Oslo, PO Box 1048 Blindern, N-0316 Oslo, Norway. (karen.mair@fys.uio.no)