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The effect of particle dimensionality on granular friction in laboratory shear zones

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[1] To match the boundary conditions of numerical models and to examine the effect of particle dimensionality on granular friction, we conducted laboratory experiments on rods sheared in 1-D and 2-D configurations, glass beads (3-D), and angular quartz sand (rough 3-D). The average coefficient of friction during stable sliding for 1-D, 2-D, smooth 3-D, and rough 3-D particles is 0.15, 0.3, 0.45, and 0.6, respectively. Frictional strength of 2-D layers exceeds 1-D friction by an amount associated with dilatancy and the additional contact plane in 2-D. We show that 3-D granular friction exceeds 2-D friction by the amount of interparticle friction on the out-of-plane particle contacts that do not exist in 2-D. Data from our 2-D experiments are remarkably similar to numerical results based on 2-D particle dynamic simulations. Our data indicate that application of numerical models of granular friction to tectonic faults will require computations involving rough, 3-D particles. *INDEX TERMS:* 5104 Physical Properties of Rocks: Fracture and flow; 7209 Seismology: Earthquake dynamics and mechanics; 8010 Structural Geology: Fractures and faults. **Citation:** Frye, K. M., and C. Marone, The effect of particle dimensionality on granular friction in laboratory shear zones, *Geophys. Res. Lett.*, *29*(19), 1916, doi:10.1029/2002GL015709, 2002.

1. Introduction

[2] Numerical models provide unique insight into the micro-mechanics of granular shear deformation and offer great potential for bridging the gap between laboratory conditions and scales and those of tectonic faults. However, existing numerical and laboratory studies of granular friction show significant discrepancies [e.g., *Mora and Place*, 1999]. Numerical works show lower frictional strength, larger variations in friction with strain, and lower heat production than existing laboratory experiments. These differences need to be understood before numerical and laboratory results can be combined and applied to a wider range of conditions.

[3] Few studies have been conducted to investigate the effects of initial and boundary conditions on granular friction. Most numerical studies have used smooth 2-D particles [e.g., *Mora and Place*, 1998, 1999; *Morgan*, 1999; *Morgan and Boettcher*, 1999; *Aharonov and Sparks*, 1999], whereas laboratory experiments have focused on natural materials composed of rough, sub-angular particles such as found in natural fault gouge. Laboratory studies show that particle shape, roughness, and fracture have important effects on granular friction [e.g., *Sammis et al.*, 1987; *Losert et al.*, 2000; *Mair et al.* 2002]. At present, these factors have not been studied in numerical models due to computational limitations.

[4] In this paper we report on laboratory experiments designed to match the conditions of numerical models. We investigate the effect of particle dimensionality and shape using direct shear experiments. We find that friction varies systematically with particle dimension and that the discrepancy between numerical and laboratory studies may be explained by differences in initial and boundary conditions.

2. Experimental Methods

[5] All experiments reported in this study were performed in a double-direct shear apparatus in which two layers are sheared simultaneously between three rough, steel forcing blocks (Figure 1). Normal stress was maintained constant by servo-control. The main set of experiments was carried out at low normal stresses σ_n (1 MPa for rods, 5 MPa for beads and sand) so that particle fracture was minimal (Table 1). Additional experiments were performed in the fracture regime at σ_n of 25–40 MPa. Shear load was applied to the center block by imposing a constant displacement rate of 10 μm/s. Stresses and displacements were all recorded at 10 kHz and averaged to 10 samples/s. Measurement resolution was ±0.01 MPa and ±0.1 μm.

[6] Test samples consisted of fused-quartz glass rods, dried strands of standard semolina pasta (Ronzoni #12 Angel Hair), soda-lime glass beads, and angular quartz (Table 1). Both types of rods and the glass beads are smooth at the particle scale. The quartz was sub-angular Ottawa sand, which is >99% SiO_2 as supplied by the US Silica Co. We used Natural Grain product F-110, which has median particle size of 110 μm. Soda-lime glass beads had median particle size of 110 μm and two size ranges were studied (Table 1). The quartz and pasta rods were 1 mm in diameter. Nominal friction contact dimension was 10 cm × 10 cm in all experiments (Figure 1).

[7] Layers of particles were constructed in a leveling jig to ensure reproducible layer thickness. Sand and glass bead layers were constructed to be 3 mm thick, and layers of rods were 7 mm thick. The rods were arranged in two configurations (Figure 1). Rods with the long axis perpendicular to shear were used to simulate 2-D granular shear. In this

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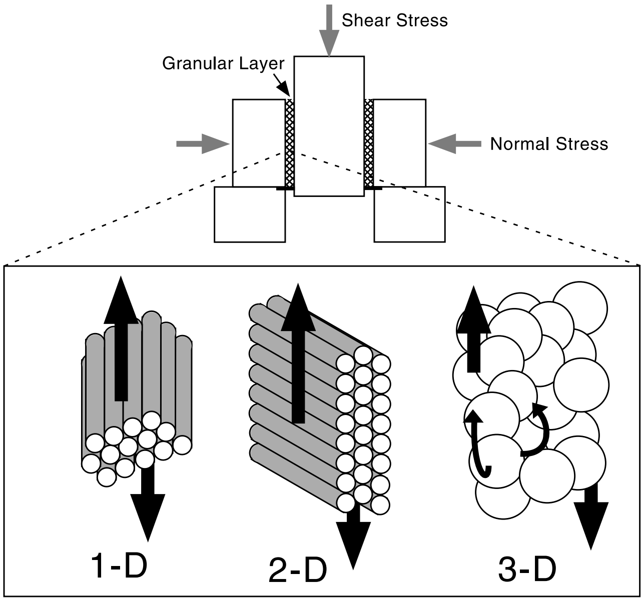

Figure 1. Laboratory configuration to study the role of particle dimensionality in granular friction. Biaxial shear apparatus (top) provides controlled deformation under applied normal stress. Rods and spheres are oriented to produce 1-D, 2-D, or 3-D conditions in double direct shear. In the 1-D case, shear is accommodated by grain boundary slip parallel to the shear direction. For a 2-D granular layer, shear occurs by rolling or sliding and dilation or compaction. In the 3-D case particles have components of motion in all 3 directions.

configuration, shear involves two degrees of freedom: motion in the shear direction and motion perpendicular to the shear plane causing layer dilation or compaction. Rods were also sheared parallel to their axes to create a 1-D granular case (Figure 1). 1-D shear involves only one degree of freedom: grain boundary sliding in the direction of shear. Motion perpendicular to shear is not excluded, but dilation or compaction is not required for shear. The 1-D rods were cut longer than the side blocks to ensure that the nominal area of frictional contact remained constant during shear.

3. Experimental Results

[8] We found that the frictional strength of 3-D particles ranged from 0.45 for smooth beads to 0.6 for angular sand (Table 1), in agreement with previous work [*Mair et al.*, 2002]. In the 2-D shear configuration, both pasta and quartz rods exhibited stable sliding and large fluctuations in friction with shear (Figure 2a). For each configuration of particles, we report the mean sliding friction μ_{ss} over the displacement interval 6–10 mm and, for the 2-D layers, the standard deviation of friction fluctuations in that interval (Table 1). Sliding friction for 2-D layers of quartz rods fluctuated in the range 0.14 to 0.37 after initial loading (Figure 2a). The amplitude of friction variations for 2-D pasta rods was smaller, with friction ranging from 0.25 to 0.31. In both cases, the dominant wavelength of friction fluctuations was roughly 2 mm, or twice the rod diameter. In contrast, angular quartz sand exhibited a constant coefficient of sliding friction of 0.63.

[9] We compared the natural variations in 2-D friction to time-dependent changes associated with healing and static recovery [e.g., *Marone*, 1998]. Figure 2a shows two slide-hold-slide tests in which holds of 100 s duration were imposed. Time-dependent frictional healing is measured by the increase in peak frictional strength after shear resumes relative to initial sliding friction. We find that healing is small compared to the natural variations of friction for non-breaking rods in the 2-D configuration.

[10] Measurements of layer thickness show that 2-D friction variations correlate strongly with dilatancy rate *dh/dx* (Figure 2b). A positive dilatancy rate corresponds to an increase in layer thickness and negative *dh/dx* indicates compaction. We determined dilatancy rate using a least squares best fit in a moving window of 350 data points (shear strain of 0.048). Window sizes from 0.014 to 0.068, shear strain, yield correlation coefficients between friction and dilatancy rate of 0.72–0.76 during steady-state shearing (Figure 2b). Quartz rods exhibit larger amplitude friction fluctuations and larger variations in dilatancy rate than pasta rods (Table 1). The maximum dilatancy rate averages 0.08 for quartz rods and 0.03 for pasta rods.

[11] Since our 2-D particles do not fracture, layers must dilate or compact against the applied normal stress to accommodate shearing. The macroscopic frictional strength τ of a granular material depends linearly on the sum of work to overcome interparticle friction μ_p (this includes sliding and rolling at constant volume on all planes of contact) and work of volume strain [e.g., *Mead*, 1925; *Bishop*, 1954; *Marone et al.*, 1990; *Geminard et al*, 1999],

$$\tau = \sigma\left(\mu_p + d\theta/d\gamma\right). \quad (1)$$

where is θ volume strain, γ is shear strain, and σ is effective normal stress. Taking $d\theta = dV/V$ and $d\gamma = dx/h$, where V is layer volume given by thickness h and area A, and assuming that volume change in the plane of the layer is negligible, Equation 1 reduces to:

$$\tau = \sigma\left(\mu_p + dh/dx\right) \quad (2)$$

Since the measured frictional strength in our experiments is τ/σ, Equation (2) predicts that friction and dilatancy rate

Table 1.

Exp.	Type	Material	Particle size(μm)	σ_n, (Mpa)	μ_{ss} avg. (±1 std. dev.)
m290	3-D	Qtz. sand	50–150	5	0.63
m302	3-D	Qtz. sand	50–150	5	0.63
m490	3-D	Qtz. sand	50–150	40	0.58
m429	3-D	Glass beads	105–149	25	0.44
m349	3-D	Glass beads	105–149	5	0.47
m444	3-D	Glass beads	1–800	5	0.45
m445	3-D	Glass beads	1–800	5	0.45
m446	3-D	Glass beads	1–800	5	0.46
m518	2-D	Qtz. rods	1000	1	0.27 (±0.11)
m473	2-D	Pasta rods	1000	1	0.28 (±0.03)
m524	1-D	Qtz. rods	1000	1	0.16
m525	1-D	Qtz. rods	1000	1	0.19
m474	1-D	Pasta rods	1000	1	0.14

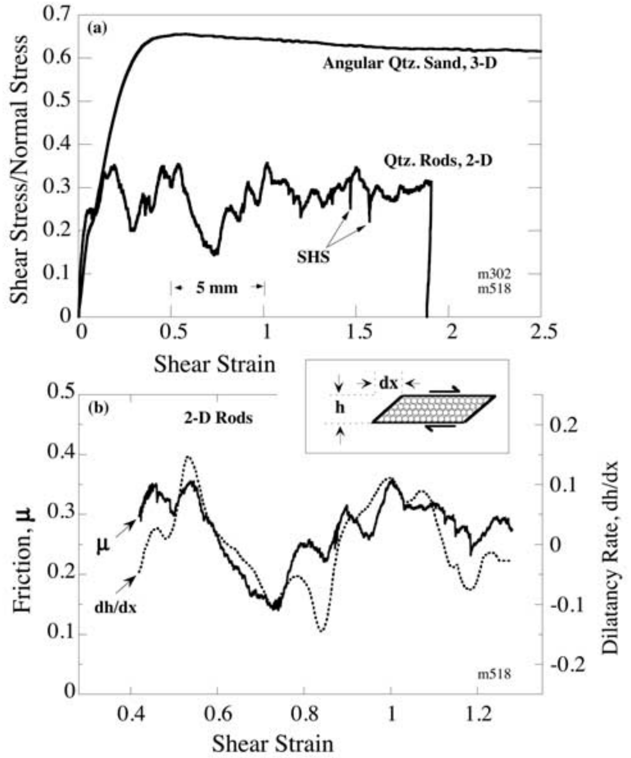

Figure 2. (a) Laboratory data for granular layers composed of quartz glass rods (2-D) and quartz sand (3-D). Arrows labeled SHS denote time dependent healing tests (100 s hold periods were imposed followed by continued shear) and show that natural fluctuations in 2-D friction are large compared to rate/state friction effects. (b) 2-D friction data are compared with measurements of the dilatancy rate. Inset shows schematic 2-D granular layer. Positive values of dh/dx indicate layer dilation. Note the high degree of correlation between frictional strength and dilatancy rate, consistent with the importance of volumetric work in the total energy budget for 2-D granular shear.

will correlate strongly, as we observe for 2-D friction (Figure 2b). We find that variations in friction and dilatancy rate have the same amplitude, which suggests that the observed variations in shear strength $\tau(\gamma)$ are attributable to variations in $dh/dx(\gamma)$.

[12] Shear of 2-D particles can be accommodated by grain boundary slip or rolling operating in concert with dilation or compaction. We isolated the mechanism of grain boundary sliding by conducting 1-D granular shear experiments on smooth rods. Friction is significantly lower in 1-D than in 2-D (Figure 3). Measurements of layer thickness show that 1-D shear occurs at constant volume.

[13] The frictional strength of 1-D particles is 0.14–0.19 and is significantly less variable during shear than 2-D particles (Figure 3). The frictional strength of smooth glass beads is intermediate between the 2-D case and the angular particles of quartz sand. The large friction fluctuations in 2-D are not present in the 1-D or 3-D cases. Our data show that sliding friction increases systematically with increasing granular particle dimension and roughness (Figure 3).

[14] We compare the friction data from our 2-D experiments with the numerical results obtained by *Morgan* [1999], who used the particle dynamics method and 2-D particles (Figure 4). The similarity between the laboratory and numerical results is remarkable. For both data sets friction fluctuates about 0.3 and correlates strongly with dilatancy rate.

4. Discussion and Implications

[15] We observe a linear relationship between particle dimension and the frictional strength of sheared granular layers (Figure 3b). This suggests a simple scaling between average frictional strength and granular degree of freedom.

[16] Our 1-D experiments provide an estimate of interparticle friction of 0.15–0.19, which is consistent with sliding friction for smooth, unlubricated surfaces at low normal stress [*Rabinowicz*, 1995]. We take the low end of this range, $\mu_p = 0.15$, for combined sliding and rolling to account for a reduction in friction due to rolling and because a slight degree of strain hardening occurs in our experiments due to small amounts of grain fracture during shear. Using this value for μ_p and accounting for interparticle friction on both sets of contact surfaces in 2-D (e.g., surfaces parallel to the shear plane and surfaces perpendicular to the shear direction upon which rolling or sliding must occur to accommodate

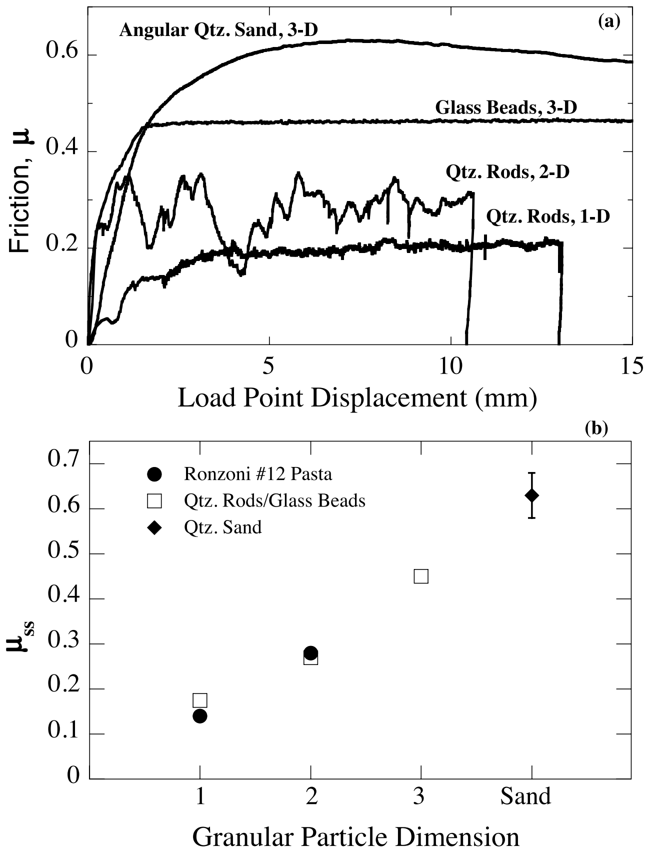

Figure 3. (a) Friction data for four types of granular layers showing that sliding friction increases systematically from 2-D and 1-D particles. (b) The average value of stable sliding friction is plotted against particle dimension. Friction increases systematically with increasing granular particle dimension. Error bar on represents a maximum value for measurement error and reproducibility of all data.

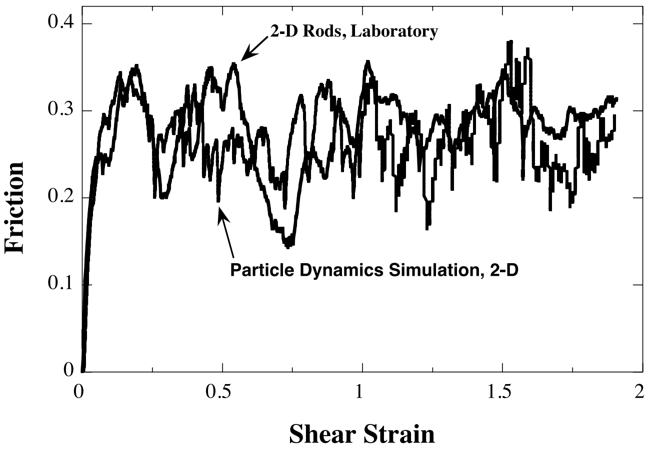

Figure 4. Comparison of laboratory data for shear of rods in the 2-D configuration and numerical results for 2-D granular friction. Friction strength and its variation with shear are nearly identical. Simulation results from *Morgan* [1999].

shear in an extended 2-D assembly) yields an expected average friction value of 0.3, which is quite close to the experimentally measured value of 0.27–0.28.

[17] The observed fluctuations in friction for 2-D layers can be explained quantitatively using Equation (2) and the measured dilatancy rate. The maximum dilatancy rate averages 0.08 for quartz rods (Figure 2) and 0.03 for pasta rods. Therefore, the expected peak friction of 2-D particles is 0.38 for quartz and 0.33 for pasta, which has a contribution of 0.3 from interparticle friction in each case. These values are in good agreement with our experimental measurements, which show maximum friction of 0.37 for quartz rods and 0.31 for pasta rods.

[18] The above reasoning may be extended to 3-D by accounting for interparticle friction on each of the three possible contact planes, including the lateral contacts parallel to the shear direction. Using the μ_p value of 0.15 yields an expected friction value of 0.45, which is in good agreement with our experimental measurements of 0.45–0.47 (Table 1). We posit that for smooth particles, granular friction of 3-D particles exceeds friction of 2-D particles by the amount of interparticle friction on the out-of-plane contacts that do not exist in 2-D.

[19] Data from our 2-D experiments are remarkably similar to numerical results based on 2-D particle dynamic simulations. In both cases, friction fluctuates with a dominant wavelength equal to twice the particle diameter and these fluctuations are much greater than rate/state friction effects (Figure 2a). Our data show that discrepancies between laboratory and numerical studies are likely due to differences in initial conditions (rough versus smooth particles) and particle dimensionality.

[20] It has been proposed that grain rolling reduces macroscopic frictional strength in numerical models and that this effect may be important in explaining anomalously weak tectonic fault zones [e.g., *Mora and Place*, 1998, 1999]. These numerical studies used 2-D, smooth particles that did not fracture or fractured into smaller smooth particles. Our data suggest that the reduced friction found in these studies is due to the use of smooth 2-D particles. Since natural faults are composed of angular, 3-D particles that undergo fracture, we find no evidence for a weakening mechanism associated with the presence of fault gouge.

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