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Nature of stress accommodation in sheared granular material: Insights from 3D numerical modeling

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Abstract

Active faults often contain distinct accumulations of granular wear material. During shear, this granular material accommodates stress and strain in a heterogeneous manner that may influence fault stability. We present new work to visualize the nature of contact force distributions during 3D granular shear. Our 3D discrete numerical models consist of granular layers subjected to normal loading and direct shear, where gouge particles are simulated by individual spheres interacting at points of contact according to simple laws. During shear, we observe the transient microscopic processes and resulting macroscopic mechanical behavior that emerge from interactions of thousands of particles. We track particle translations and contact forces to determine the nature of internal stress accommodation with accumulated slip for different initial configurations. We view model outputs using novel 3D visualization techniques. Our results highlight the prevalence of transient directed contact force networks that preferentially transmit enhanced stresses across our granular layers. We demonstrate that particle size distribution (psd) controls the nature of the force networks. Models having a narrow (i.e. relatively uniform) psd exhibit discrete pipe-like force clusters with a dominant and focussed orientation oblique to but in the plane of shear. Wider psd models (e.g. power law size distributions $D=2.6$) also show a directed contact force network oblique to shear but enjoy a wider range of orientations and show more out-of-plane linkages perpendicular to shear. Macroscopic friction level, is insensitive to these distinct force network morphologies, however, force network evolution appears to be linked to fluctuations in macroscopic friction. Our results are consistent with predictions, based on recent laboratory observations, that force network morphologies are sensitive to grain characteristics such as particle size distribution of a sheared granular layer. Our numerical approach offers the potential to investigate correlations between contact force geometry, evolution and resulting macroscopic friction, thus allowing us to explore ideas that heterogeneous force distributions in gouge material may exert an important control on fault stability and hence the seismic potential of active faults.

Keywords: numerical modeling; force chains; fault gouge; earthquake mechanics

1. Introduction

Faults in nature often have significant accumulations of granular fault gouge. The presence and evolution state of this gouge affects frictional strength and stability. Both these properties in turn determine the

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mechanical nature of slip along a given fault. To understand the processes that may be operating in faults with gouge it is useful to investigate sheared granular material. At present there are 2 main approaches: laboratory friction experiments; and numerical modeling.

Laboratory friction experiments are generally conducted either at high stresses (MPa) (e.g. Karner and Marone, 2001) relevant to geophysical conditions or at relatively low stresses (Pa) (e.g. Losert et al., 2000). Despite the difference in conditions, the relatively low stress experiments may help elucidate particular micro processes that are relevant to higher stress experiments and hence natural fault systems. With some notable exceptions much of the numerical modeling work in this field has been conducted in 2D (Mora and Place, 1998; Aharonov and Sparks, 1999; Morgan and Boettcher, 1999). Recent work (Hazzard and Mair, 2003; Abe and Mair, 2005) has revealed the importance of out-of-plane motions and grain fracture in sheared granular systems and demonstrated that 3D numerical modeling is essential to investigate processes that may be operating in faults.

There is growing evidence (Cates et al., 1998; Howell et al., 1999) that force distributions in sheared granular materials are highly heterogeneous i.e. particles do not all carry the same load. Direct observations of force chains in 2D photo elastic shearing experiments conducted at low stresses (e.g. Oda et al., 1982; Howell et al., 1999) indicate that enhanced load is preferentially carried on a limited number of particles that set up a network of force chains. Between these chains are shielded regions where particles carry reduced load. 2D numerical modeling (Cundall et al., 1982; Morgan and Boettcher, 1999; Aharonov and Sparks, 1999) confirms the prevalence of these features.

The presence of force chains have been invoked to help explain the comminution of granular fault gouge (Sammis et al., 1987) and they offer a convenient way to interpret results from recent 3D laboratory shearing experiments at geophysically relevant conditions

Table 1
Numerical simulations

Simulation	psd	Diameter (std)	d/H	μ (mean)	μ (std)	dil rate (std)	F_{max}
tn021g	Gaussian	254 (22)	0.068			0.0115	
tn027g	Gaussian	254 (22)	0.068	0.3538	0.00946	0.0106	3.13
tn028g*	Gaussian	254 (22)	0.068				
tn029g **	Gaussian	254 (22)	0.068	0.3573	0.35728		3.21
tn030g	Gaussian	254 (22)	0.068	0.3591	0.00967		2.85
tn031g	Gaussian	254 (22)	0.068	0.3539	0.01184		3.31
tn051g+	Gaussian	254 (22)	0.068				
tn035g2	Gaussian	254 (44)	0.068	0.3585	0.01286		3.68
tn036g2	Gaussian	254 (44)	0.068	0.3611	0.0127		3.19
tn044g	Gaussian	254 (22)	0.068	0.3553	0.01138		3.41
tn048g	Gaussian	254 (22)	0.068	0.3603	0.01219		2.68
tn049g	Gaussian	254 (22)	0.068	0.354	0.0117		2.5
tn040g	Gaussian	400 (44)	0.108	0.3612	0.01759	0.0198	5.74
tn041g	Gaussian	400 (44)	0.108	0.3536	0.02355		5.87
tn037g	Gaussian	500 (44)	0.135	0.3517	0.0219		8.72
tn038g	Gaussian	500 (88)	0.135	0.3639	0.02833		15.2
tn045g	Gaussian	500 (44)	0.135	0.337	0.02445	0.0283	9.0
tn050g	Gaussian	500 (44)	0.135	0.3608	0.02413		6.71
tn052g	Gaussian	500 (44)	0.135	0.3488	0.03344	0.0287	8.14
tn046g	Gaussian	600 (60)	0.162	0.3618	0.0308		16.5
tn047g	Gaussian	600 (60)	0.162	0.3377	0.03074	0.0302	17.8
tn014f	Powerlaw $D=2.6$			0.348914	0.0090		3.86
tn032f	Powerlaw $D=2.6$			0.347329	0.0102		4.86
tn033f	Powerlaw $D=1.6$			0.371007	0.0157		4.77
tn053f	Powerlaw $D=1.6$			0.364849	0.0227		
tn034f	Powerlaw $D=0.8$			0.35881	0.0165		7.74
tn054f	Powerlaw $D=0.8$			0.35361	0.0214		

Modeled particles have microproperties as follows: shear modulus 22 GPa; Poisson's ratio 0.25; and an inter-particle friction of 0.5. Normal stress is 5 MPa. Particle size distribution is Gaussian or Power Law. Mean and standard deviation (std) of particle diameter are given in μm. Initial layer thickness is 3.7 mm. d/h is scaled grain size where d=mean diameter and H is initial layer thickness. Dil rate is standard deviation (std) in dilatancy rate. Boundary is rough and 1 particle wide (except in the case where it is 2 particles wide=*; 4 particles wide=**, or consists of a smooth boundary=+).