Influence of particle size and shear velocity on the frictional properties and slip instabilities of sheared granular materials

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Abstract

Granular friction plays a significant role in controlling diverse styles of movement for landslides. Field observations also demonstrate that landslides may exhibit slow, stable creep, periodicity stick-slip or accelerative sliding, which are similar to the diverse styles of motion inferred for faults and subduction zones. Laboratory friction experiments provide insight into the mechanisms of different spatiotemporal patterns of failure for theses catastrophic events. However, the effects of particle characteristics and mechanical conditions on the strength and stability are not well understood. In the present research, we report on laboratory experiments designed to investigate the frictional behaviors with particular emphasis on the influence of particle size and shear velocity on the strength and stability in sheared granular materials. The experiments employed the dynamic ring shear apparatus and were run at room temperature and humidity. We mainly find that: (1) the particle size and shear velocity have profound influence on the strength and instability of sheared granular materials; (2) within a regime of low shear velocities and large particles, the ultralow shear resistance will appears to be associated with localized shearing; (3) the granular assemblies composed of small particles will show stable sliding with varying the shear velocity. Here we suggest that: (1) frictional behaviors depend on the number of force chains (particle size effects) and contact time of inter-particles (shear velocity effects); (2) the failure of arch jamming leads to the dramatic destabilization in locally sheared particles; (3) the formation of longer force chains will result in more compliant granular deformation. Our results highlight the fundamental role of particle size and shear velocity on the frictional properties and instability of granular materials, and provide important constraints to understand the diversity and complex movement for landslides.

Keywords: granular materials; particle size; shear velocity; frictional properties; slip instability; locally shearing

1. Introduction

Frictional properties provide the fundamental underpinnings of many geophysical processes, ranging from landslides to earthquakes, which are often adequately described as frictional instabilities along preexisting basal shear zones or fault zones (Harp and Jibson, 1996; Parise and Wasowski, 1999; Chambon et al., 2006; Chigira and Yagi, 2006; Friedmann et al., 2006; Kaproth and Marone, 2013; Schulz and Wang, 2014). These locally deformed zones are composed of comminution, disaggregation, and alignment granular materials that play a significant role in controlling and determining the diverse styles of movement, such as continuous slow-stable creep, periodic stick-slip or accelerative sliding (Fleming and Johnson, 1989; Petley et al., 2005; Wang et al., 2010). Generally, despite the great diversity and complexity, the frictional strength of these gouge zones will gradually increase and dynamically drop to a low value, inferred as stick-slip instability, which has been recognized as an analogy phenomenon of an earthquake, and also indicates many similarities of the reactivated large landslides (Brace and Byerlee, 1966; Scholz, 2002; Clague and Stead, 2012). Source parameters for such kind of instabilities, such as the magnitude of stress drops and recurrence intervals of catastrophic failures, are systematically varied and vital for predicting their occurrences and characters, and also for assessing resulting hazards (Scholz, 2002; Clague and Stead, 2012). It is worth mentioning that the existing studies did effectively offer abundant evidence of frictional instability and proved particularly fruitful. Neverthless, it remains elusive how intrinsic characteristics of grains directly affect the instability of locally sheared granular materials under different mechanic conditions.

Similar to previous studies, we sought to evaluate the frictional behaviors and slip instability for locally sheared granular materials with particular emphasis the intrinsic properties of particle size and shear velocity. We presented specific laboratory experiments aiming at simulating a thick granular layer by using dry cohesionless glass beads with uniform particle size to rule out the influence of particle shape. We stepped the shear velocity sequence from low to high, and described our results by involving the framework of granular micromechanical.

2. Experimental method

We performed a series of tests by employing a servo-hydraulic controlled ring shear apparatus (Figure 1). The geometry has two independent servo controlled load feedback firmware to maintain constant normal stress and shear stress (or shear velocity), respectively. The rotating (lower) part of the chamber is forced by a servo controlled ram at different constant displacement rate, while the stationary (upper) opposes shearing through two arms with integrated force sensors. Such fixed shear plane results in the formation of a horizontal shear zone near where the upper and lower cylinder parts meet. Sample thickness changes are continuously monitored by using a displacement transducer. A set of rubber gaskets between the upper and lower cylinder pairs is designed to prevent leakage of sample and pore fluid. Extension work has been done to investigate the shear behaviors for landslide materials using this assembly (Sassa et al., 2004; Wang and Sassa, 2009; Wang et al., 2010; Schulz and Wang, 2014) and additional details concerning this intelligent device are reported by Sassa et al. (2003).

The discrete landslide materials or weared granular materials in shear zone might be displaced under wide range of rates, meanwhile the material properties also could dictate the frictional strength and instability, via the grain size or particle shape. To further investigate such kind of effect of particle characteristics and mechanical conditions on friction properties in locally sheared granular materials, we used spherical glass beads as an ideal analogy materials for exploring the role of particle size and ruling out the large uncertainly associated with the particle shape effects (Yang and Wei, 2012). In the present study, four uniform grain sizes (ranging from ~0.1-5 mm) were used. All dry spherical samples were sheared under room temperature and humidity (about ~20°C and ~50~70%, respectively) in order to exclude the possible influence of hydrothermal and physicochemical processes of grain-scale frictional contact (Scuderi et al., 2014). Annular specimens were constructed at 3 cm wide (within an inner diameter of 12 cm and outer diameter of 18 cm) and about 5 cm high. The laboratory experiments were conducted at velocity range of 0.005~1mm/s, and normal stress of 200 kPa, and data were recorded at sampling rate between 100 and 1000 Hz. Other experimental conditions are presented in Table1.

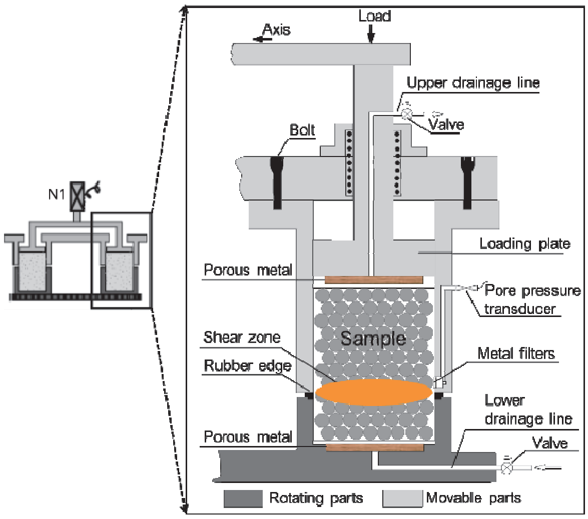

Figure 1. Schematic diagram of the ring shear apparatus. Left figure shows cross section of the entire specimen configuration. Normal stress is applied vertically, and shear velocity is driven by rotating the lower part. The horizontal shear band will formed where the upper and lower cylinder parts meet.

Table 1. Experiment conditions

Particle size (mm)	Sample height (cm)	Bulk volume (cm^3)	Sliding type
4.7 – 5.3	4.82	681.41	Stick-slip
1.0 – 1.41	4.79	677.17	Stick-slip
0.5 – 0.71	4.78	675.76	Stick-slip
0.106 – 0.149	4.80	678.59	Stable sliding

Note: All experiments were performed under a constant normal stress (200 kPa) and shear velocity sequences were gradually stepped from 0.005 mm/s to 1.0 mm/s at room temperature (~20°C) and humidity (~50 – 70%).

3. Results

3.1 Characteristics of frictional instability events

Fig. 2 presents a selected section of data from an experiment to reveal the dynamic instabilities for samples with different particle sizes under the same shear velocity (V_L = 0.01 mm/s). In response to a variation of particle size, three general observations can be made. First, the sample layers composed of larger particle sizes revolves unstable stick-slip behavior (Fig. 2a-c), whereas the smallest particle size exhibits an almost stable-sliding character (Fig. 2d). Second, the failures for granular materials (i.e., stick-slip instabilities) vary from relative regular to irregular (Fig. 2), and such instabilities are largest for samples within the largest particles. Third, the frequency of such instability events increase with decreasing of particle size, and the longer stick-slip recurrence interval occur at larger particle size. It is noteworthy that such kind of stick-slip characteristics has also been reported in previous work (Mair et al., 2002; Anthony and Marone, 2005), and our results suggest that particle size has a fundamental effect on the frictional instability within localized shear zones.

Upon an increase in shear velocity, we find that fluctuations in shear stress still can be observed among samples with larger particle size throughout (Fig 2a-c and Fig. 3). Fig. 3 provides a selected detail of the dynamic instabilities against shear velocity for the same particle size (1.0~1.41mm). The duration periods of repetitive stick-slip instabilities are sensitive to the shear velocity, which exhibits an increase in stick-slip event frequency. For the velocity step sequence from 0.005 mm/s to 0.01 mm/s, the peak strength has a slight decrease, but the variation of minimum shear strength experiences minor changes.

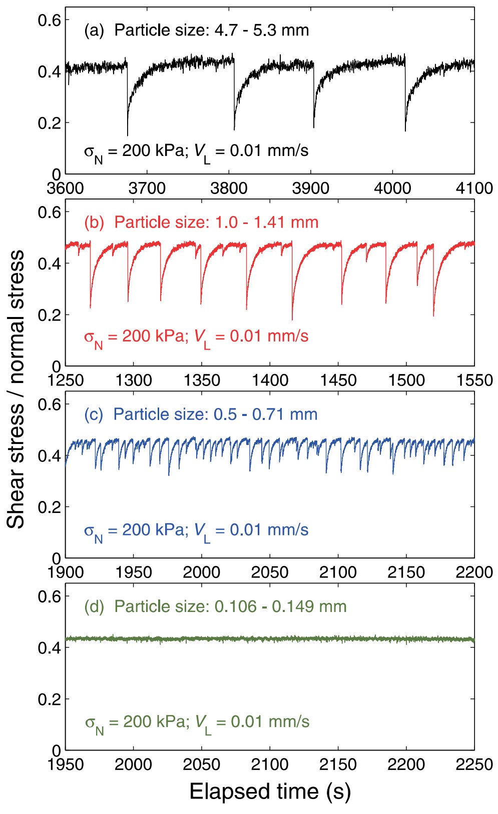

Fig. 2 Friction data taken from sections of experimental data where the shear velocity is 0.01 mm/s for different particle sizes, (a) 4.7 – 5.3 mm; (b) 1.0 – 1.41 mm; (c) 0.5 – 0.71 mm; (d) 0.106 – 0.149 mm. Stress drops decrease and event frequencies increase with decreasing of particle sizes until stable sliding occurring.

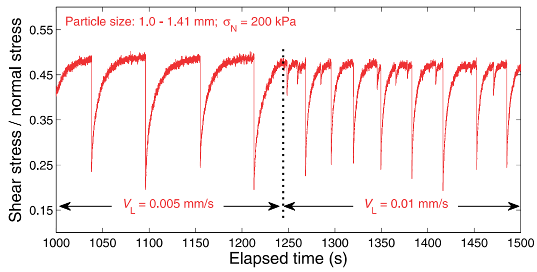

Fig. 3 Friction data taken from section of experimental data for 1.0 – 1.41 mm particles. The shear velocities are 0.005 and 0.01 mm/s, respectively. Data show repeated stick-slip events with variations in amplitude and frequency.

3.2 Effect of particle size and shear velocity on stress drop

For a series of multiple stick-slip events, the magnitude of stress drop shows a strong correction with particle size and shear velocity (Figure 4). Considering the frictional properties for smallest particle sizes (0.106 – 0.149mm) almost show stable sliding behaviors (Fig. 2d), we only analyzed all large instability events for the other three particle sizes in each shear velocity. All stick-slip events were picked up by hand considering a threshold value ($\Delta\mu > 0.02$) to insure that no noise was picked up as events, reporting the mean value and statistical variability, with error bars calculated by using a standard error of the mean method (Fig. 4).

For our range of shear velocities, the changes of maximum friction (μ_{max}) for largest particle size (4.7 – 5.3mm) are ~0.05, accompanying a slight decrease below ~0.1 mm/s and not obvious change above that velocity. However, the μ_{max} of the other relative smaller particle sizes (i.e., 1.0 – 1.41mm and 0.5 – 0.71mm) gradually decrease with the logarithm of shear velocity, and the range of variations is ~0.1 (Fig. 4a). Note that our data show that μ_{max} is not only velocity-dependent, which is consistent with previous work (Nasuno et al., 1998; Albert et al., 2001; Mair et al., 2002; Anthony and Marone, 2005), but also particle-size-dependent. When the shear velocities are below at ~0.1 mm/s, the largest particle size (4.7 – 5.3mm) exhibit lower μ_{max} than the other two relative smaller particle sizes. Interestingly, upon the shear velocity of ~0.1mm/s, the largest particle size (4.7 – 5.3mm) has a higher μ_{max} due to not strongly sensitive to shear velocity.

Furthermore, we compare the changes of minimum friction (μ_{min}) during dynamic friction drops for our range of shear velocity. As shown in Fig. 4b, following the shear velocity sequence, the value of μ_{min} is general higher in sample composed of smaller particles at each given velocity, which suggests the larger particles may induce more dynamic instabilities (i.e., lower minimum friction strength). For these data the mean value of μ_{min} ranges from ~0.32 to ~0.38 for the smallest particles and from ~0.17 to ~0.25 for the largest particles. For each particle size, the variations of μ_{min} show velocity-dependent. As shear velocity stepping from low to fast, smallest particles (i.e., 0.5 – 0.71 mm) exhibit a slightly decrease. However, this relation is not observed for larger particles (i.e., 1.0 – 1.41 mm and 4.7 – 5.3 mm). The value of μ_{min} for intermediate size (i.e., 1.0 – 1.41 mm) shows a decreasing trend while for largest particle (i.e., 4.7 – 5.3 mm) varies roughly with velocity below ~0.1 mm/s. But both the two sizes show an increase in μ_{min} with velocity above ~0.1 mm/s.

We compare the variations of friction drop ($\Delta\mu$) as a function of particle size and shear velocity to emphasize the stick-slip properties for granular materials (Fig. 4c). It is note that the $\Delta\mu$ is always higher for larger particles in contrast with the trend of μ_{min} at a given shear velocity. For each particle size, the value of $\Delta\mu$ is larger at lower shear velocities, according to the tendency in relation to $\Delta\mu$ and shear velocity. Moreover, it is striking that the velocity dependence of $\Delta\mu$ changes slope at ~0.1 mm/s. For the intermediate size (i.e., 1.0 – 1.41 mm), the $\Delta\mu$ decreases more sharply than the other two particle sizes for velocities > ~0.1 mm/s.

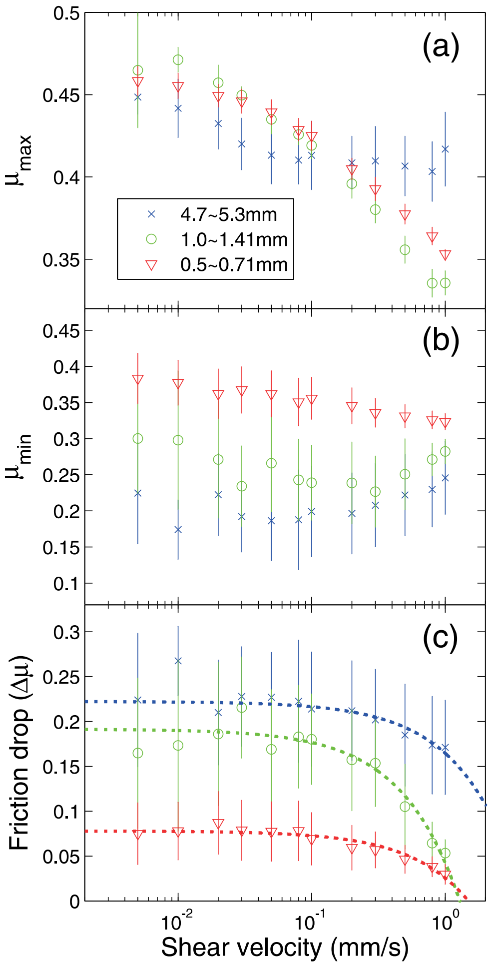

Fig. 4 Stick-slip friction parameters as a function of particle size and shear velocity. (a) maximum friction, (b) minimum friction and (c) friction drop ($\Delta\mu = \mu_{max} - \mu_{min}$) as a function of shear velocity for each particle size, respectively. Data points represent mean values with error bars calculated by using a standard error of the mean method for all events at each shear velocity. Note that experiments in which composed of larger particles tend to have higher friction drops than smaller particles for our range of shear velocities. Friction drops decrease systematically with increasing shear velocity, and the friction drops markedly decrease when velocity increases above ~0.1 mm/s for each particle.

4. Discussion

The dynamical drops in stress have been recognized as an important correction to the catastrophic failures, such as the rupture of gouge-filled faults, the initial and movement for landslides. It has also been documented that the observed periodic stick-slip behaviors in laboratory will be an effective way to investigate the origins and mechanisms for these events. Many assumptions have been approached in the last decades (Brace and Byerlee, 1966; Scholz, 2002; Clague and Stead, 2012).

The rupture of asperity has been proposed to understand the frictional instabilities between solid surfaces (Scholz, 2002). The magnitude of asperity normally ranges about ~μm, it is also reasonable to infer that the asperity rupture can induce the fluctuations in stress. However, our observed data show that the stress drop of locally sheared granular materials are more catastrophic, and we believe that this is not response for the stress drops of the present study.

The sheared and loaded granular medium form layer-spanning chains of stressed particles, and granular force chains are separated by regions of spectator grains that support little to no load. Such stressed particles cause jamming to provide resistance to deforming, and some highly stressed particles along the network of force chains may support most external loads. When the stored elastic energy exceeds grain yield strength of highly stressed particles, the formed force chains can lose by crushing (grain fracture) (Davies and McSaveney, 2002; Crosta et al., 2007; McSaveney and Davies, 2007). The failure of force chains can partially or fully release the elastic strain, which result in the probability of sudden, dynamic reduction of frictional resistance. It is note that before the failure of force chains, the particles can suffer the external loads being solid condition (stick behavior); but after the failure of force chains, the can bear no stresses briefly behaving as a liquid condition (slip behavior), transmitting pressure to their surroundings. As examined by laboratory tests (Mair et al., 2002), the breakage and comminution of analogy glass beads always occur under the higher regime of confining stress (generally higher than ~20 MPa for granular materials). Moreover, all samples in our study were examined after shearing and we cannot find any fragments. Therefore, we infer that the transition from jamming to rolling of force chains may be induced by the relative motion among granular materials, such as inter-granular slip and grains rotation. For a given shear velocity, the friction drops are higher for larger particles, and the value deceases with the decrease of particle size, until stable sliding observed in a relative small size. We suggest that the influence of shear velocity on frictional instability is related to the nature of contact time, while the effect of particle size is associated with the development of contact area and the number of force chains acting across the granular layer. Note that the ring-shear configuration we used in the present study has a fixed shear plane, the failure intensity of force chains should be concentrated near this shear plane due to locally sheared. It is should be pointed out that we do not observe the evolution of force chains and quantify the relationship between grain motions and force chains failure, but legitimately infer how they deform on the basis of the macroscopic frictional response. Further verification of these speculations using experimental data should be of interest.

5. Conclusions

We have shown that particle size and shear velocity have important influence on frictional properties within locally sheared granular materials. The test material of glass beads with uniform particle size distribution allows a well-controlled study. We proposed the framework of granular micromechanical with particular emphasis on the evolution of force chains at grain scale and macroscopic response. The major results and findings of present study are summarized as follows.

(1) Stick-slip instabilities were observed for locally sheared granular materials, and the failure of force chains acting at grain interactions plays the primary role in controlling the dynamic failures without the contribution of particle fragmentation.

(2) Magnitude and frequency of dynamical shear resistance drops are closely relevant to particle size and velocity-stepping sequence. For unstable stick-slip regimes and a given shear velocity, large particles show large stress drop and low event frequency. Within decreasing of particle size, the frictional instabilities have a transition from unstable stick-slip to stable sliding as well as increasing of shear velocity, accompanied by the decrease of magnitude and increase of frequency.

(3) Last, our experimental results suggest that higher-resolution studies of particle properties and mechanical conditions may aid in the search for better understanding the movement characteristics and promoting hazard mitigation for hazards, if similar mechanisms likely operate in nature.

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