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Effect of particle size and shear speed on frictional instability in sheared granular materials during large shear displacement

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ABSTRACT

The frictional behavior of granular materials plays important roles in the movement of geo-materials in landslides and earthquake faults, and of industrial materials; many studies have been put forward to better understand the frictional behavior of granular materials under differing conditions. In this paper we report on laboratory experiments designed to explore the fundamental role of particle size and shear speed in the frictional instabilities for locally sheared granular materials subjected to large shear displacement. We used spherical glass beads with differing particle sizes (~0.1 to 5.0 mm), and sheared them at differing speeds (gradually stepped from 0.005 to 50.0 mm/s in some cases) under a given normal stress of 200 kPa by employing a ring shear apparatus. Results showed that frictional instability occurred in some tests on glass beads with larger particle sizes, and such kind of frictional instability also appeared repeatedly with the progress of shearing. The frictional instabilities (stress drops) were constrained not only by the shear speed but also by the particle size. The magnitude and recurrence time of stress drop decreased with increasing shear speed for a given particle size, however, they increased with increase of particle size at the same shear speed. We evaluated the relationship between stress drop and recurrence time, and found that particle size had greater influence on frictional instability. We suggested that the formation and failure of force chains among the glass beads during larger shear displacement are the main reasons for this kind of frictional instability.

1. Introduction

Frictional properties of granular materials provide many fundamental insights into geophysical processes such as landsliding and earthquake faulting, and these events are often adequately recognized as the failure across preexisting zones, such as landslide shear bands or fault gouges. (Terzaghi, 1950; Lambe and Whitman, 1969; Scholz, 2002). In general, these locally deformed zones are mainly composed of granular materials with a pore-fluid, where granular friction plays a significant role in dictating the diverse styles of deformation when the zones experience a shear stress (Tika et al., 1996; Wang et al., 2010; Schulz and Wang, 2014). Thus better understanding the physical processes of granular friction is not only vital for quantitative interpretation of their occurrences and characters, but also for assessing the resultant hazards (Terzaghi, 1950; Campbell, 1990; Marone, 1998; Scholz, 2002).

The granular materials gain frictional forces through the interaction of grains to resist movement, but the response of granular materials to applied external forces can be very different at different scales. As shown in Fig. 1, several characteristic types of frictional behavior have been identified in shearing granular materials (Albert et al., 2001; Anthony and Marone, 2005). The granular materials can fail in ways that show fluctuating instability (including periodic stick-slip motions, random or stepped fluctuations) or steady stable sliding. The dynamic properties and transition parameters of these phenomena are also important for better understanding the related geophysical events. Particularly, the stick-slip motion has been suggested as analogous to the phenomenon of earthquakes (Brace and Byerlee, 1966; Scholz, 2002), and also indicates some similarities to the reactivation of large landslides (Schaeffer and Iverson, 2008; Wang et al., 2010). Many recent laboratory experiments and numerical simulations have been devoting to investigating such kind of frictional instabilities (Campbell, 1990; Marone, 1998; Mair et al., 2002; Anthony and Marone, 2005; Schaeffer and Iverson, 2008; Scuderi et al., 2014). It has been found that the granular frictional properties are strongly dependent on the mechanical conditions (i.e., normal and shear stresses, shear speed, loading history and etc.). For example, when the applied stress exceeds the yield strength of locally stressed parts, the frictional instability is susceptible to asperity ruptures or grain fractures that may be associated with the fault rupture processes or the mobility of large landslides (Sammis and Steacy, 1994; Crosta et al., 2007; McSaveney and Davies, 2007; Davies and McSaveney, 2009; Davies et al., 2012). The shear speed dependence of

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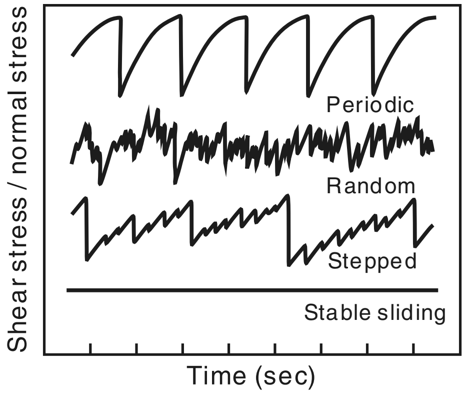

Fig. 1. Graphical representation of frictional behavior for sheared granular materials. Several characteristic types (i.e., periodic, random, stepped or stable sliding) are reproduced from Albert et al. (2001) and Anthony and Marone (2005).

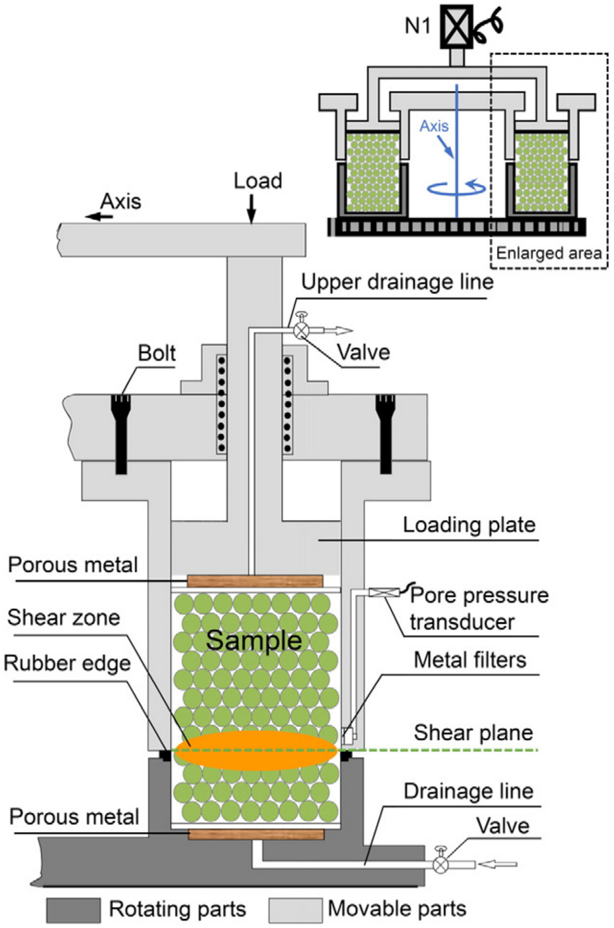

Fig. 2. Schematic diagram of part of the ring shear apparatus. Top figure shows cross section of the entire specimen configuration.

frictional instability in granular materials has been experimentally demonstrated, with data showing that the frictional forces in granular materials can convert from fluctuating instability to stable sliding with increasing shear speed (Miller et al., 1996; Nasuno et al., 1998; Albert et al., 2001).

It is also reported that granular frictional properties depend on material characteristics (i.e., mineralogy, particle size, particle shape and etc.). For instance, by shearing a thin layer of simulated fault gouge in the laboratory, Mair et al. (2002) found that unstable stick-slip instability was promoted for spherical grains, but stable sliding occurred among angular particles; grains with narrow particle-size distribution exhibited stick-slip instability, whereas grains with wider particle-size distributions exhibited stable sliding. Furthermore, Anthony and Marone (2005) examined the role of grain angularity in determining frictional instability for simulated granular gouges in the laboratory, noting a progressive transition from unstable stick-slip instability to stable sliding. When granular gouge composed of >70% spherical grains was sheared between rough surfaces, a repetitive stick-slip instability was observed. They also reported stick-slip instabilities in four series of spherical particles (i.e., 0.062–0.105, 0.105–0.149, 0.250–0.297 and 0.508–0.590 mm), where thin layers (3 mm thick) were sheared between rough surfaces under a given range of loading speeds (i.e., from 0.1 μm/s to 0.3 mm/s).

The above studies offer abundant evidences of frictional properties between surfaces separated by a thin layer of granular materials composed of relative small particle sizes under limited shear displacement. In some cases, these experimental conditions also provide significant information for understanding the spatiotemporal dynamics of earthquake faulting at high pressures (Chester et al., 1993; Micarelli et al., 2003; Chambon et al., 2006). However, field observations show that tectonic fault gouges and sliding zones of landslides generally consist of grains ranging from submicron to centimeter in size, and are likely deformed or slipped from tens of centimeters to hundreds of meters (Scholz, 2002; Billi, 2005; Chambon et al., 2006). Thus, it is necessary to examine the possible effects of larger shear displacement on frictional instability for sheared granular materials consisting of larger grains.

In this study, we designed several series of laboratory experiments by employing a ring shear apparatus (Fig. 2), which allows us to shear centimeter-thick granular samples with larger particle sizes (~0.1–5.0 mm) at shear speeds varying across multiple orders of magnitude (ranging between 0.005 and 50.0 mm/s) and slip displacement (up to several meters). Since aiming at examining the effect of particle size and shear speed on granular friction, we performed all shear tests under a given normal stress of 200 kPa, where the influence of particle plasticity could be negligible as suggested by Nasuno et al. (1998). We also interpreted the observed results by means of the possible formation and failure of force chains. Finally, we discussed the possible implications of our results to landslide dynamics.

2. Experimental method

We performed a series of tests using a servo-hydraulic controlled ring-shear apparatus (Fig. 2). The apparatus has two independent servo-controlled load-feedback firmwares to maintain constant normal stress and shear stress (or angular shear speed). There are two different parts including rotating parts and movable parts as schematically shown in Fig. 2, and the upper parts are designed to be moveable for the setup of testing but kept stationary during test. For the mode of shear-speed control, rotation of the lower part of the chamber is forced by a servo-controlled ram at different constant angular shear speeds, while the upper stationary part opposes shearing through two arms with integrated force sensors to measure the sample's resistance during shearing. In direct shear box test, it has been pointed out that the shear results could be affected by the aperture between the stationary and moving parts in case of occurrence of outflow of samples from the aperture (Kim et al., 2012). Therefore, in our ring shear apparatus, a set of rubber edges (about 2 mm thick) between the upper and lower cylinder pairs is designed to prevent leakage of sample or pore-fluid, if present, and then effectively excludes the possible effect of aperture on the shear behavior. During shearing, a fixed touching force between the rubber edges and upper stationary part was kept by the gap-controlling system such that the friction force between them was kept as a constant. More details concerning the applications of this apparatus to evaluate landslide initiation and mobility mechanisms can be found in