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Frictional behavior of granular gravel–ice mixtures in vertically rotating drum experiments and implications for rock–ice avalanches

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ABSTRACT

Rapid mass movements involving large proportions of ice and snow can travel significantly further downslope than pure rock avalanches and may transform into debris-flows as the ice melts and as water from the stream network or water-saturated debris is incorporated. Currently, ice is thought to have three distinctive effects: 1) reduction of the friction within the moving mass itself, 2) increase of pore pressure as the ice melts and consequent reduction of the shear resistance of the flowing material, and 3) reduction of boundary friction where the failing mass travels on a glacier. However, measurement-based evidence to support these hypotheses is largely missing. In this study, laboratory experiments on the first two mechanisms were carried out in two partially-filled large rotating drums, one in Vienna (Austria) and a second in Berkeley (USA). Varying proportions of cold gravel and gravel-sized ice were mixed and added to the rotating drum running at constant rotational velocity until all ice had melted. Flow behavior was recorded with flow depth, normal force, shear force, pore-water pressure, and temperature sensors. The bulk friction coefficient was found to decrease linearly with increasing ice content by ~20% in the early phase of the experiments, before significant portions of the ice transformed into water. For ice contents larger than 40% by volume, the transformation from a dry granular flow to debris-flow-like movement or hyperconcentrated flow was observed when pore-water pressures rose and approached the normal forces along the flow profile. Pore-water pressure from melting ice developed within several minutes after the start of the experiments and, as it increased, progressively reduced the friction coefficient. The results emphasize that the presence of ice in granular moving material can significantly reduce the friction coefficient of both dry and partially-saturated debris. Due to size effects and the absence of other factors reducing friction (e.g. surfaces with low friction and rock comminution), the absolute measured friction coefficients from the laboratory experiments were larger than those found from natural events. However, the relative changes in friction coefficients depending on the ice and water content may also be considered in real-scale hazard assessments of rapid mass movements in high mountain environments.

1. Introduction

Cryospheric systems are sensitive to climate change and generally respond quickly (Haeberli et al., 1997; Noetzli and Gruber, 2009; Salzmann et al., 2007). The decay of glaciers and degradation of permafrost can cause slope instabilities and large rapid mass movements in steep high mountain areas (Davies et al., 2001; Dramis et al., 1995; Geertsema et al., 2006; Gruber and Haeberli, 2007; Haeberli et al., 1997; Haeberli et al., 2003; Harris et al., 2001; Harris et al., 2003). The number of large slope failures in glaciated high mountain areas has increased in the last two decades as compared to the 20th century and may further increase in future (Fischer, 2009; Geertsema et al., 2006; Huggel et al., 2010; Van Der Woerd et al., 2004). While there is a broad variety of possible effects causing high mobility of large rapid mass movements (see discussion in Erismann and Abele, 2001; Korup et al., in press), slope failures from glacial environments are often subject to an additionally enhanced mobility for several reasons (e.g. Evans and Clague, 1988): 1) due to their origin, the moving mass usually contains or entrains a considerable proportion of snow and ice which reduces friction within the moving mass, 2) the transported snow and ice continuously supply meltwater due to frictional heating and convective mixing with non-frozen ground material and air, reducing the shear resistance of the flowing material as it reaches lower regions, and 3) propagation over a glacier which serves as a low friction surface can strongly increase the avalanche velocity and hence its momentum, resulting in an extended runout distance.

The rock avalanches on Sherman glacier on March 27, 1964 (Shreve, 1966), from Mt. Munday around June, 1997 (Evans and Clague, 1998), from Aoraki/Mt. Cook in 1991 (McSaveney, 2002), and the earthquake-triggered large multiple landslides and rock avalanches at Black Rapids on

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November 3, 2002 (Jibson et al., 2006) are a few examples for large and/or long-runout events on glacial surfaces. The enormous rock and ice masses which detached from Huascarán in Peru on January 10, 1962 and May 31, 1970 have caused a total death toll of 7000 people ((Evans et al., 2009a), with older estimations reaching as high as 22,000 casualties (Plafker and Ericksen, 1978)), and have dramatically shown the catastrophic potential of combined rock–ice avalanches if they reach populated regions. On September 22, 2002, the extreme mobility of gravel-ice mixtures was again tragically demonstrated by the Kolka glacier failure in the Russian Caucasus (Evans et al., 2009b; Kotlyakov et al., 2004). Both events were characterized by extremely high velocities, high ice contents, and flow transformations (multi-phase movement) along the flow path, to debris-flows that traveled a great distance downstream (Petrakov et al., 2008). The unexpected and sudden initiation of large rock–ice avalanches makes any direct physical measurements in the field impossible. Therefore, the current knowledge of rock–ice avalanches is largely based on post-event documentation, using remote sensing data and some field investigations of the source zone, travel path, and deposition area. While a broad range of case studies exist, there is no physical quantification of the effects of ice on frictional characteristics available.

In this study we focus on the frictional characteristics of different gravel–ice mixtures and on the development of an inter-granular fluid (water) phase by using two large rotating drums. The first aspect considers the influence of the proportion of granular ice on the bulk friction coefficient (tangent of friction angle) while the second aspect concentrates on the time-evolution of the friction angle when the ice is melting, mimicking the evolution of a rock–ice avalanche during its runout. Rotating drums have been used for debris-flow rheology studies (Huizinga, 1996; Kaitna and Rickenmann, 2007b), measurements of bedrock erosion by debris-flows (Hsu et al., 2007; 2008), abrasion of fluvially transported grains (Kodama, 1994; Mikoš and Jaeggi, 1995), observations of grain-size segregation (Henein et al., 1985; Hsu, 2010), and for investigations on flow characteristics of dry granular material (Chou and Lee, 2009), but not for granular flow experiments containing gravel and ice. An advantage of drum experiments is that experimental devices allow measurements for pre-defined time spans at a given rotational velocity and enable long periods of observation so that flow transformations related to the melting of ice can be observed. The experimental setup in rotating drums is suited to study the flow process in a quasi-stationary regime, but neither initiation nor deposition.

2. Experimental design

2.1. Drum characteristics and velocity scaling

Because full dynamic similarity for geometrically similar flows at different sizes is probably impossible to achieve (Iverson et al., 2010), the best way to reduce this problem is to use the largest possible scale (Hsu, 2010). The laboratory experiments were performed in two similar vertically rotating drums with diameters of 246 cm in Vienna and 399 cm in Berkeley (Fig. 1 and Table 1). Each drum had its own advantages: The rotational drum in Berkeley was the largest facility available, while the smaller drum in Vienna has additional and redundant instruments. In addition, because of its smaller size and consequently reduced effort needed to set up and document flows, more experiments can be conducted in the smaller drum. The ratio of diameters of the smaller drum to the larger drum is 0.62. This value served for linear geometrical scaling of most parameters between the two drums. The width of both drums is given and cannot be changed, however the proportionality factor of 0.56 is very close to 0.62.

To prevent sliding on the otherwise smooth drum bed, in the larger drum 25 mm high risers were placed every 20 cm along the bed, while on the bottom of the smaller drum a 10 × 10 mm PVC grid with a height of approximately 2 mm was fixed. Hence, the proportion of the height of the different roughness elements between the two drums is only 0.08 compared to 0.62 for geometry in general. Because individual grains are caught between the risers of the larger drum as well as in the PVC grid at the bottom of the smaller drum, the effective sliding surface during the experiments largely consisted of grains from the mixture. This roughening of the boundary ensured that a basal resistance similar to that of a flow over a natural rough boundary was established.

The volumes of the mixtures were scaled by identical percentage fills to be comparable between the two different drums as proposed by Henein et al. (1983b). Our goal was to use a volume of material that created flows significantly thicker than the maximum grain diameter, but minimized the infilling of the drum to reduce bed curvature effects. In the larger drum we used a volume of 0.4 m^3 that corresponds to a percentage fill of 4.00% with a radius of 1.994 m and a drum width of 0.8 m. Applying the same percentage fill to the radius and width of the smaller drum led to the volume of 0.0856 m^3 that was used there.

We were using the same liquids in the laboratory as in nature (air and water), so that full dynamical scaling which includes Froude- and Reynolds-similarity was impossible (see discussion by Paola et al., 2009). For geometrical length scales λ_L in the order of ~100 between real events and experiments, Reynolds scaling would consequently have required velocities many times larger than in natural flows (having average velocities often around 50 m/s), which was impossible in the laboratory. Furthermore, Reynolds scaling is more appropriate for questions related to the relative importance of inertial and viscous forces, and field evidence, e.g. the presence of turbulence, suggests that inertial forces dominate. Froude scaling, which we use in this study, has been applied with some success to other mass movements (e.g. for some aspects of debris-flows, Rickenmann, 1999; Kaitna, 2006; Paola et al., 2009), where the relative importance of gravitational and inertial forces is expected to be relevant. Accordingly, the target rotational velocities u_{drum} (equal to average flow velocity relative to the channel bed) in the two drums were

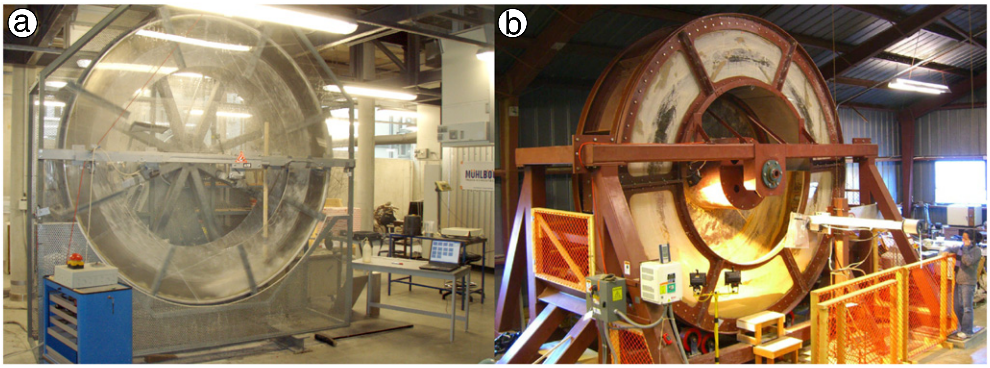

Fig. 1. Smaller rotating drum in Vienna (a) and larger rotating drum in Berkeley (b).