MEASUREMENTS OF WEAK SNOWPACK LAYER FRICTION

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ABSTRACT: An essential stage in the release of an avalanche is the propagation of a fracture through a weak snowpack layer. As the fracture propagates, the slab looses its support and comes into contact with the bed surface. In the area of contact, the sliding motion of the slab is constrained by frictional forces. This particular friction process has received little experimental attention until today. Studies on sliding friction have mainly been performed on snow samples composed of small rounded grains in direct contact. In the present study we determine the friction coefficient of weak layers by analysing video records of snow samples sliding down-slope after a weak layer had fractured. The slab and the bed surface are then in indirect contact as the interface consists of the collapsed weak layer. The experiments were carried out in the mountains of British Columbia, Canada, and in the mountains around Davos, Switzerland , between 2002 and 2009. Assuming Coulomb-type friction the initial acceleration of the snow sample is used to determine the friction coefficients. The measurements show an initial friction coefficient on the order of 0.6 and the tendency to decrease thereafter. This is accompanied by the gradual erosion of the interface between the slab and the bed surface.

KEYWORDS: Particle image velocimetry, friction, weak layers, avalanche formation

1. INTRODUCTION

In order for a snow slab avalanche to release, a fracture has to propagate through a weak snowpack layer. Recent research has shown that this process involves the crushing of the weak layer (van Herwijnen et al., 2008). As the weak layer fractures, the slab looses its support and subsides. The slab then comes into contact with the bed surface and sliding of the slab is constrained by frictional forces.

In this work we present results from field experiments in which the coefficient of friction of freshly collapsed weak layers is measured. The experiments were carried out in the mountains of British Columbia, Canada, during the winters of 2002-2003 and 2003-2004 and in the mountains around Davos, Switzerland, during the winter of 2008-2009.

2. METHODS

2.1 Field methods

Video recordings of propagating fractures and the subsequent down-slope movement of the overlying slab were analyzed to determine the coefficient of friction of weak snowpack layers in 34 experiments (10 rutschblock tests, 21 propagation saw tests and on 3 skier-tested slopes). In all these tests, one side of the snow sample was completely exposed by shovelling. Black markers were placed in the vertical snow wall above the weak layer to analyze the movement of the slab (Figure 1). The experiments were either recorded with a high-speed camera or with a standard digital camera.

2.2 Image analysis and coefficient of friction

Particle tracking velocimetry software (Crocker and Grier, 1996) was used to analyse the images using a coordinate system as defined in Figure 1: the *x*-axis pointing in down-slope direction parallel to the snow surface, the *y*-axis pointing towards the ground normal to the snow surface (Figure 1). The particle tracking software enables to determine the displacement ($u_x(t),u_y(t)$) of the markers at any given time. The velocity ($v_x(t),v_y(t)$) of the markers can then be derived by numerical derivation of the displacement.

In order to determine the coefficient of friction, we assumed coulomb-type friction, whereby the frictional resistance to the down-slope motion due to the gravitational pull F_g on the slab is proportional to the normal force F_n exerted by the weight of the slab on the bed surface (Figure 1). The constant of proportion μ is called the coefficient of friction. The acceleration a of the slab is then given by:

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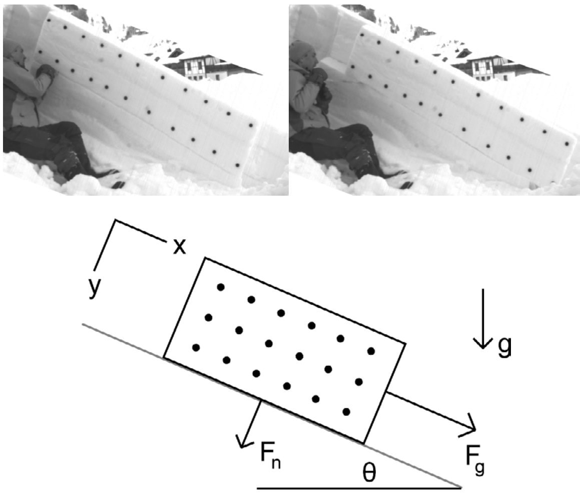

Figure 1: First and last image from a video sequence used to determine the coefficient of friction of a weak snowpack layer in a propagation saw test. Below is a schematic drawing of the forces acting on the slab and the coordinate system used in the image analysis.

$$a = \frac{1}{M}(F_g - \mu F_n) = g(\sin\theta - \mu\cos\theta) \qquad (1)$$

where M is the mass per unit area of the slab, g is the gravitational acceleration and θ is the slope angle. Thus, by measuring the acceleration of the slab after fracture propagation, one can determine the coefficient of friction of the weak layer.

The acceleration of the snow slab was determined by using the equation of motion of the slope parallel velocity:

$$v_x(t) = v_0 + at \qquad (2)$$

where v_0 is the (non-zero) slope parallel velocity of the slab after fracture propagation. According to equation (2), the slope parallel velocity should increase linearly with time. The slope of the curve between v_x and t determines the acceleration. For all experiments an average coefficient of friction was determined for the entire length of the recording after fracture propagation. The increased temporal resolution in some high-speed camera sequences with good quality images allowed for a more detailed observation of the variation of the coefficient of friction.

3. RESULTS

In Figure 2 (a) a typical example of the average slope parallel and slope normal velocity of the markers is shown. When the weak layer fractured it collapsed, as seen by the sharp increase in the slope normal velocity. Thereafter, the slope parallel velocity increased linearly with time, as expected by equation (2), and the weak layer debris as well as the crack faces gradually eroded since v_y did not decrease to zero after fracture. The coefficient of friction calculated for this experiment was 0.57. In Figure 2 (b) the variation of the coefficient of friction after fracture propagation is shown for this experiment. There was a small decrease in the coefficient of friction as the slab moved down-slope, coinciding with the gradual erosion of the crack faces.

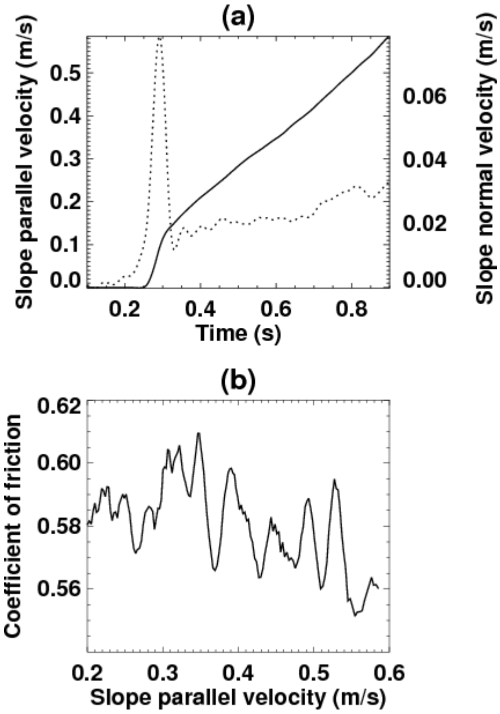

Figure 2: Example of typical measurements in a friction experiment. (a) Average slope parallel (solid line) and slope normal (dashed line) velocity. Note the different scales on the y-axis. (b) Variation of the coefficient of friction with increasing slope parallel velocity of the slab.

An overview of the distribution of the measured coefficients of friction is given in Figure 3. The measured values of μ ranged from 0.52 to 0.68 with a mean value of 0.57. This corresponds to friction angles ranging from 28 to 34 degrees.

4. DISCUSSION AND CONCLUSIONS

Measurements in 34 field experiments show that the coefficient of friction of weak snowpack layers ranged from 0.52 to 0.68 with a mean of 0.57. The measurements also show that

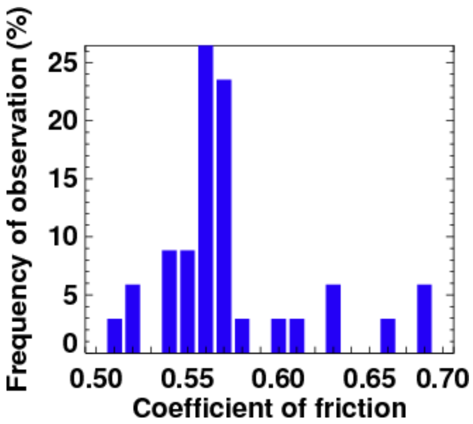

Figure 3: Distribution of the measured coefficients of friction.

the frictional forces decreased slightly as the slab moved down-slope. It is very probable that this is due to the erosion of the weak layer debris and the crack faces, which undoubtedly leads to a smoothing of the sliding interface.

Why are these friction measurements of importance? Theoretically, friction plays a major role in the evolution of fracture in a layered snowpack, and hence slab avalanche release. In the classical shear model (e.g. McClung, 1981) propagation of fractures is not possible on slopes that are inclined below the friction angle. This is due to the fact that the driving force, i.e. the slope parallel component of the gravitational pull on the slab, is not large enough to overcome frictional forces. The measurements presented here show that the friction angle is around 30 degrees. However, most people that travel on snow and in avalanche terrain are well aware that fractures can propagate on slopes well below 30 degrees or even on horizontal terrain, as evidenced by observations of whumpfs and remotely triggered avalanches. This is in sharp contrast to the prediction of the shear model.

Recently, a new model for slab avalanche release has been introduced which incorporates the collapse of the weak layer (Heierli et al., 2008), something which so far has been observed in all documented fractures through weak snowpack layers (e.g. van Herwijnen et al., 2008). In this model, the driving force comes from the release of gravitational potential energy due to the collapse of the weak layer. Frictional forces only come into play once the crack faces come into contact after the weak layer has fractured. Immediately below the friction angle, fracture propagation results in a whumpf, while immediately above the friction angle an avalanche would release. This is in line with field observations and experimental results.

One implication of our findings is that the minimum angle for avalanche release does not depend on shear strength, as predicted by the shear model, but results from crack-face friction which comes into play only as the fracture through the weak layer is already propagating. A practical implication of our findings is that skiers or snowboarders should be aware of abrupt changes in risk with small variations in slope angle. Furthermore, valuable snowpack stability information with regards to fracture initiation and fracture propagation can be obtained on gentle slopes and even on horizontal terrain. Practitioners have known and applied this idea for a very long time.

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