

A SMARTPHONE APPLICATION TO ESTIMATE THE CRITICAL SLOPE ANGLE FOR AVALANCHE RELEASE

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ABSTRACT: Once a weak layer has fractured, slope steepness largely dictates whether or not an avalanche will release. Exceeding the critical slope angle, i.e. angle at which the slab overcomes friction, is an essential condition for dry-snow slab avalanche release. Practitioners continually take this into consideration when assessing avalanche terrain and safe travel routes in alpine environments. However, thus far, such assessments rely on rules of thumb, such as avoiding terrain steeper than 30°, rather than actual measurements. Further, research into critical slope angles has been limited and confined to dry-snow and mostly persistent weak layers and harder slabs. To address these limitations, we developed a simple smart phone app to measure the kinetic friction between the detached slab and the bed surface. We used Optical Flow method to track motion of sliding slabs. We assumed Coulomb friction to calculate the friction between the slab and bed surface and derive the critical slope angle. Using our app on existing videos allowed us to compare our measurements with prior friction research, and we found the app was able to estimate friction to within +/- 1° of previous work. Our preliminary field data consist of 16 measurements on decomposed fragments (DF) and moist faceted crystal (FC) weak layers from four pits spaced 10 meters apart on a single slope. The critical slope angle was 35 +/- 1° for the DF layer and 39 +/- 0.5° for the moist FC layer. Our data also show a constant critical slope angle within the initial 0.1 – 0.2 m. of the down-slope motion, and a decreasing critical slope angle shortly afterward. Our smartphone tool provides a method to quickly estimate critical slope angles in the field. Our goal is to link critical slope angles to specific snow cover properties, and to assess spatial and temporal variability in critical slope angle.

1. INTRODUCTION

Dry slab avalanches start with crack propagation along a weak snowpack layer. As the crack advances, the slab progressively loses support and comes into contact with the bed surface through the weak layer debris. In the area of contact, slab motion is constrained by frictional forces. Crack face friction therefore determines the slope angle above which slab avalanches can release. While it is clearly an important parameter, thus far it has received only modest experimental attention.

Various experimental studies have been performed to measure the friction between homogeneous snow blocks (e.g. Casassa et al., 1989; Casassa et al., 1991), or estimates have been obtained from avalanche field data (e.g. Lang and Dent, 1982; Schaerer, 1975). While such studies provide friction values relevant for avalanche flow, measurements of crack face friction directly after fracture propagation are required to estimate the critical slope angle for avalanche release. van Herwijnen and Heierli (2009) were the first to measure crack face friction after persistent weak layer fracture using a method based on particle tracking to analyze video sequences of Propagation Saw Tests (PST). They obtained friction values which varied from 0.52 to 0.68 with a median of 0.57 (critical slope angle: 29.7°). Simenhois and others (2012) used the same method to

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measure crack-face friction after non-persistent weak layer fracture with results ranging between 0.57 and 0.80 with a median of 0.75 (critical slope angle: 36.9°). They also found a negative correlation between slab hardness and crack-face friction. While these results suggest that crack face friction depends on snow properties, thus far the number of measurements is relatively limited and many questions remain unanswered.

In this paper, we therefore present a smart phone app to quickly measure crack friction in the field. The app is based on the Optical Flow method to track the motion of sliding slabs in field experiments. We also present some preliminary friction data we collected with this app.

2. METHODS

To measure the coefficient of friction, and thus the critical slope angle for avalanche release, we developed a smart phone app essentially based on the same methodology as van Herwijnen and Heierli (2009). The idea behind the method is to make a video recording of a field experiment and to track features identified on a sliding block of snow in the recorded video frames. The trajectories of the features are then used to derive the acceleration of the block. Rather than using Particle Tracking Velocimetry (PTV) requiring round features with a fixed diameter, we used the Optical Flow method, which can be used to track arbitrary features of any shape and size. After recording a field experiment on video with a smart phone, the app is straightforward to use and consists of three simple steps:

1. Entering slope angle and the distance $d[m]$ between two reference points on the snow pit wall.
2. Scaling the image to convert distances measured in pixels to meters.
3. Feature detection and tracking in the video recording to derive the critical slope angle

2.1. Image scaling

To measure the acceleration of the sliding snow block in $m\ s^{-2}$, a conversion factor is required to scale distances recorded in pixels to meters. To do so, the user adjusts the vertical edges of a rectangle on the smart phone's screen to align with two reference points that are separated by a known distance $d[m]$ (Figure 11). The distance $oD[pixels]$ between these two points on the screen can then be converted to by:

$$\lambda = \frac{d}{oD}.$$

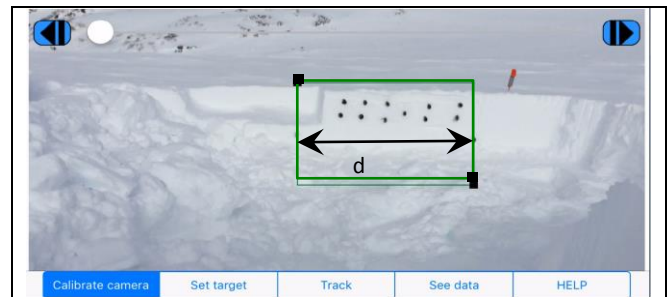


Figure 1: Converting measured distances from pixels to meters is essential to estimate the critical slope angle. The user adjusts the square width and location (green lines) with the outer edges aligned with two points in the snow pit walls separated by a known distance d .

2.2. Optical flow and critical slope angle estimation

To track moving objects, features need to be identified on a video frame. We therefore placed markers in the slab above the weak layer. These markers can be any kind of object, the main requirement is that they are dark and do not disturb the snow cover in any appreciable manner. Good features are corners which typically consist of areas with large gradients in pixel intensity on both x and y axes (i.e. a dark object on a white background) (Shi and Tomasi, 1994). These features are automatically detected in the first video frame. From these automatically detected features, we used 20 with the strongest pixel intensity differential on both the x and y axes. These features are then detected in each successive frame of the video recording (Sparse Optical Flow).

We calculate the displacement of the features by using the Optical Flow Method (Lukas and Kanada, 1981; LK). The LK Method uses spatial and temporal partial derivatives of pixel intensity to calculate displacement between two successive video frames. The basic assumptions are that: 1) the intensity values between video frames does not change, 2) the location of a feature between two successive video frames changes by only a few pixels, and 3) a point behaves in unison with its neighbors. The first two assumptions are expressed in a formal Taylor series providing an approximation of the location and time of pixel intensities. This Taylor series is developed into the velocity equation which is used to derive the displacement of the features. Assumption 2 may not be valid when the video frame rate is too low or the smart phone camera is too close to the sliding snow block and tracking errors may occur. Therefore, we assumed that for point i , the velocity vector v_i was erroneous if: $|v_i| > |median - 1.5 absolutemediandeviation|$. Finally, the third assumption allows us to develop a set of equations to solve the feature location on both image axes.

We used open source (OpenCV) API functions for feature detection and for the LK Optical Flow method, and we set the tracking accuracy to +/- 0.3 mm.

We averaged the slope parallel velocity of all 20 features to obtain the velocity of the slab v_x and acceleration:

$$a = d v_x / dt$$

for each frame. We then average the acceleration over the first 0.1 m of sliding to calculate the coefficient of friction assuming Coulomb-type friction (Figure 2) by:

$$\mu = \tan(\psi) - \frac{a}{g \cos(\psi)}, \psi \neq 90^\circ,$$

where g is the acceleration of gravity and ψ the slope angle. From the coefficient of friction, we can obtain the critical slope angle:

$$\psi_{cr} = \arctan(\mu)$$

2.3. Verification

We tested the app in a controlled setting with five different materials with known critical slope

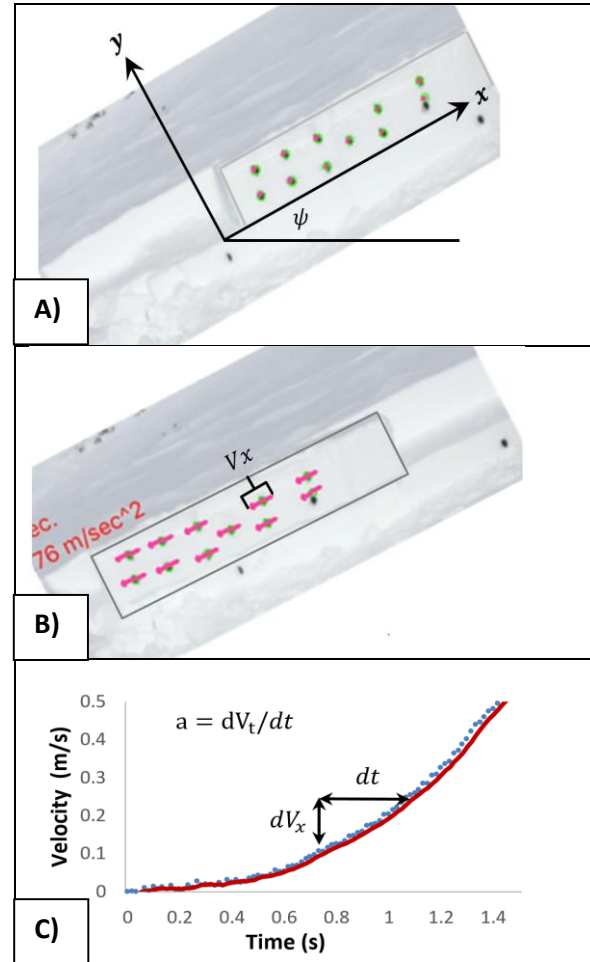


Figure 2: Motion tracking and acceleration calculation. Images A and B are from the app screen shots from the initial and later point of the sliding motion. The pink bars are proportional the sliding speed in the last frame. C is a chart of the changes of velocity with time with an illustration of motion acceleration.

angles sliding over a sloped wooden platform. We determined the critical slope angle of these materials (two types of plastic, paper, wax paper and wood) with the app by recording videos of blocks sliding over wooden platform with different slope angles. We compared our measurements using both higher and lower slope angles than the critical angles. We also used the app on four existing videos that van Herwijnen and Heierli (2009) had previously analyzed and compared the app to their results.

2.4. Field experiments

We used a PST-like test (Gauthier and Jamieson 2008; Greene et al. 2010) to make video recordings of snow slabs sliding downhill after weak layer fracture. We changed the test geometry by cutting the side of the block perpendicular to the slope and by excavating a wider sliding area around and below the isolated block (Figure 3). The latter was done to ensure undisturbed sliding motion after weak layer fracture. We placed pieces of plastic spoons as markers in the snow slab above the weak layer to track the motion of the slab during sliding (Figure 3).

We recorded our tests using a smart phone camera mounted on a tripod at a frame rate of 60 frames per second (fps). We used a smart phone that records in Constant Frame Rate Mode. To measure the slope angle we used Sunnto inclinometer, with an accuracy of +/- 1°.

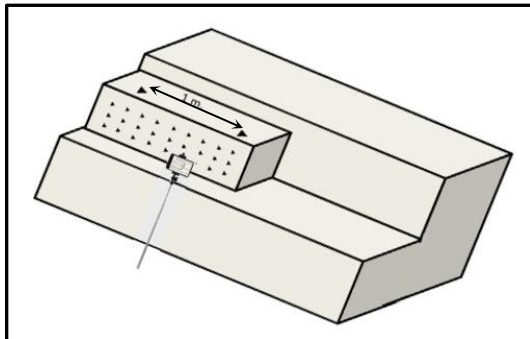


Figure 3: Schematic representation of the experimental setup.

2.4.1. Snowpack

Our 3 March 2016 tests were on a weak layer of 1F hard, 2 cm thick mixed faceted crystals (FC) and rounded grains (RG) (Figure 4), and on 13 March 2016 we tested two weak layers of decomposed fragments (DF) and moist faceted crystals (FC) (Figure 4).

3. RESULTS

3.1. Verification

The app performed well in our verification work. When measuring the friction against known critical sliding angles, the app was able

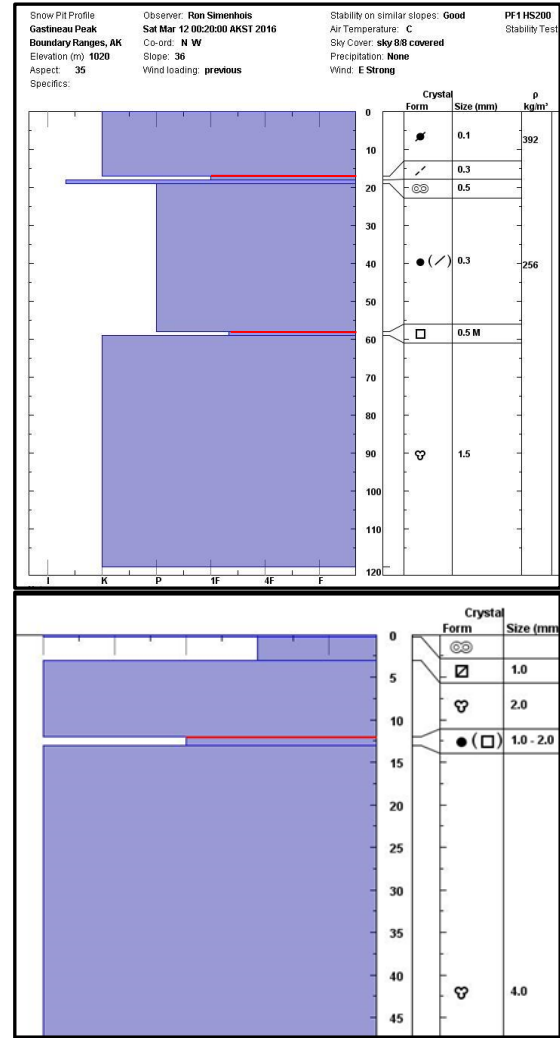


Figure 4: Top: Snow profile observed on 3 March 2016. Bottom: Snow profile observed on 13 March 2016. The tested weak layers of both profiles are marked with the red lines.

to calculate sliding angles within 1° of the known angle (Table 1). Further, we compared the performance of the app to analyses made by van Herwijnen and Heierli (2009). In these comparisons, the app again calculated critical sliding angles to within 1° of previously reported values (Table 1). We find these results encouraging. In essence, our smart phone app automatically measured critical slope angles in real time that had previously required a personal computer and office work for data analysis.

Table 1: Comparing results from the app to both controlled environment tests and to videos analyzed by van Herwijnen and Heierli (2009) shows that the app performs quite well.

Material:	Tested critical slope angle	App
Plastic #1 / Wood	19°	18°-19°
Plastic #2 / Wood	19°	19°-20°
Paper #1 / Wood	21°	20°
Paper #2 / Wood	21°	21°-22°
Wood / Wood	24°	23°
Video:	van Herwijnen and Heierli (2009)	App
A	29°	28°
B	30°	30°
C	30°	31°
D	28°	29°

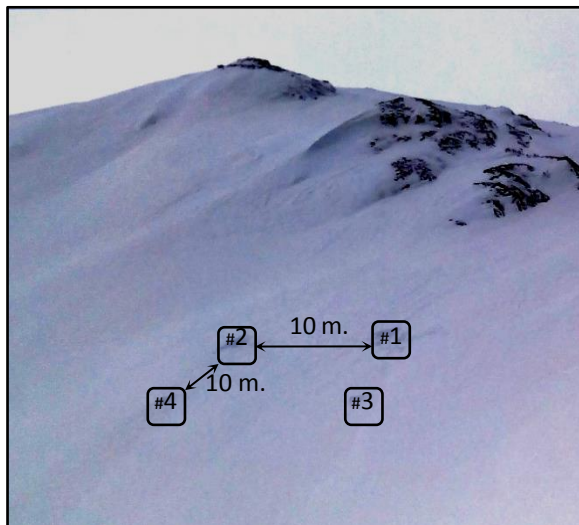


Figure 5: Location of the four snow pits is on the right.

3.2. Field experiments

In March 2016 we performed preliminary measurements at two different sites in Southeast Alaska. On 13 March 2016 we conducted measurements on a Northeast facing slope at 1065 m.a.s.l. in four different snow pits 10 m apart (Figure 5). We tested two weak layers, one consisting of decomposed fragmented particles (DF) and one consisting of moist faceted crystals (FC; Figure 4, top). Slope angles in these pits varied between 34° and 36°. In total, we performed 16 measurements, two

measurements for each weak layer in each snow pit. After weak layer fracture, the snow slabs slid down-slope with an increasing velocity for the DF layer and came to a stop after a short sliding distance for the FC layer. Thus, the slope angle in the snow pits was higher than the critical slope angle for the DF layer and lower for the FC layer. Indeed, the video recordings of the experiments on the smart phone confirmed this, showing that the critical slope angle was significantly higher for the moist FC layer (39 +/- 0.5°) than for the DF layer (35 +/- 1°; U-test: p<0.01; Figure 6).

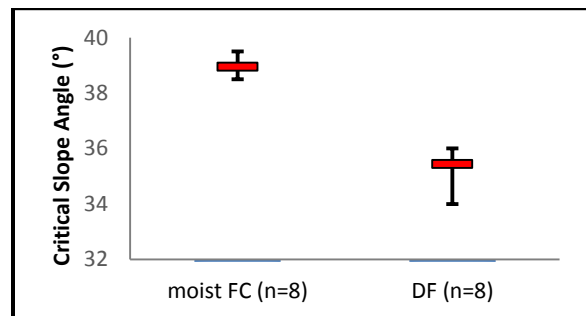


Figure 6: Moist FC vs. DF Critical slope angle comparison chart. The horizontal bars represent the median values. The vertical bars are the minimum and maximum measurements for each weak layer

On 3 March 2016 we conducted three friction measurements to investigate the influence of slab sliding distance on measured friction values. In all three measurements, the critical slope angle did not decrease much during the initial 15 to 20 cm of down-slope motion. However, for larger sliding distances the decrease in friction was more pronounced (i.e. lower critical slope angle). Overall, our measurements show that the critical slope angle decrease by about 4.5° within the first meter of down-slope movement (Figure 7). In other words, in these snow pits, the critical slope angle decreased from 40° in the initial stages of motion to about 35° within one meter (Figure 7). These measurements demonstrate a clear reduction in friction as the slab begins sliding over the bed surface.

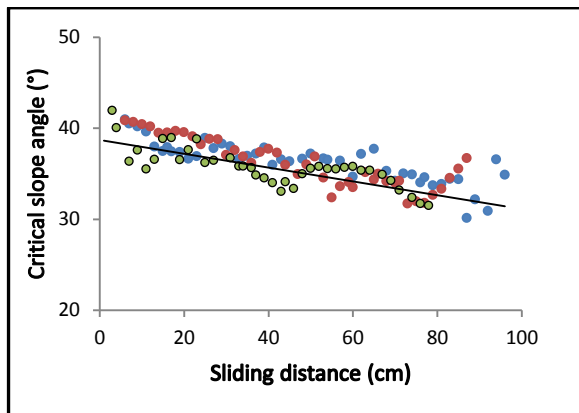


Figure 7: Critical slope angle with sliding distance for experiments performed on a 41° slope (red and blue dots) and on a 40° slope (green dots).

4. DISCUSSION AND CONCLUSIONS

We presented a newly developed smart phone app designed to estimate the critical slope angle for avalanche release in near real-time. Little additional equipment is required for measurements since the app requires only a smart phone, a mounting pole and a few small items to stick in the snow as markers. Our initial verification measurements are very encouraging, with results consistent with both previously published measurements by van

Herwijnen and Heierli (2009) as well as measurements of known critical slope angles of different materials. Our preliminary field data show different friction values (critical slope angles) for different weak layers on the same slope, and small variations in friction values for the same layer within a distance of 10 m. We also found a slight decrease in friction with sliding distance, consistent with results presented by van Herwijnen and Heierli (2009). This is likely due to crack face smoothing as the block of snow slides over the bed surface. This app facilitates rapid measurements of friction in the field. It allows researchers to better assess how friction varies with different weak layers, different slab depths, and over changes in time and space. We hope to use the app for these studies over the next several seasons in different snow climates. We intend to share this app with the avalanche community after testing period. Our hope is that app users will share the data they collect with us. In the past, estimating critical slope angles involved collecting videos in the field, returning to the office, and conducting specialized analyses, an endeavor clearly beyond the scope of most avalanche practitioners. This app allows field workers to utilize the computing power they carry in their pocket to make measurements of critical slope angles in the field, thereby opening up the eventual possibility of using such measurements for decision-making. Clearly we need to do more work before critical decisions can be based on this app. First, the app will need more thorough testing to ensure its effectiveness. Second, we need to collect more data on the role of friction in avalanche release so we better understand how the measured critical slope angles from this app relate to slope angles of actual avalanches (van Herwijnen et al 2016). Our goal is that through this additional work and improved understanding, a practitioner might be able to eventually use measurements from this app as one more piece of relevant data for making good decisions in avalanche terrain.

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