Shear and normal stresses measured on the SLF Snow Chute

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Shear and normal stresses measured on the SLF Snow Chute

Marius Schaefer

July 23, 2015

Abstract

Shear stresses on the running surface are believed to crucially determine the flow of snow avalanches. We present measurements of shear and normal stresses on the running surface as well as measurements of flow depth of snow flows down the SLF Snow Chute before and after a reduction of the chute's inclination. In the measurements before the inclination change, maxima of measured normal stresses agreed with the maxima of the normal component of the column weight calculated using pre-release snow density. After the reduction of inclination stresses increased considerably and the magnitude of the increase depended on the density of the flow. Using the measurements of normal stress and flow depth before the inclination change, a depth-averaged flow density was computed. The flow density was lower in the front and the tail of the avalanches and approached the pre-release density in the avalanche body. The ratio of measured shear to normal stresses, the coefficient of friction, was higher in wet snow flows than in dry snow flows. Analysing the dependence of the coefficient of friction on parameters varying between the experiments, we found higher coefficients of friction for higher densities, snow and air temperatures and average avalanche velocities. The total avalanche volume correlated negatively with the coefficient of friction. Measured coefficients of friction were generally lower as expected for flows of constant velocity which might indicate the importance of other frictional processes such as friction at the snow-air interface, which is supported by the evolution of small dilute snow clouds in top of the flows that consisted of dry snow.
1 Introduction

To protect infrastructure located in mountainous regions, models are needed that predict avalanche run-out distances and impact pressures. Currently used models are based on strongly simplified physics (Bartelt et al., 1999; Christen et al., 2002; Sampl and Zwinger, 2004; Christen et al., 2010). These models work well because they are calibrated by back-calculating known events (Salm et al., 1990; Gruber, 1998; Gruber and Bartelt, 2007; Sailer et al., 2008; Naaim et al., 2010). Problems can arise in the prediction of snow avalanches, when the avalanche track to predict differs considerably in topography or snow conditions from the paths used for calibration (Issler et al., 2005). Therefore, an important goal of avalanche science is to develop avalanche models with input parameters (like for example friction parameters) depending on physical (a priori measurable) quantities.

In a pioneering contribution, Casassa et al. (1991) measured the coefficient of friction between prepared snow samples in the laboratory and found an increase of the coefficient of friction with the snow temperature.

Naaim et al. (2013) analysed the dependence of two friction parameters on modelled snow properties, back-calculating 735 snow avalanche events in the Chamonix valley. For the friction parameter that quantifies the contribution of the retarding stresses which depends on the normal stress, increasing trends where found with snow temperature and snow density and a decreasing trend with liquid water content.

Steinkogler et al. (2014) analysed the influence of snow cover properties on the flow dynamics of five avalanches observed at the Swiss Avalanche Test Site located in Vallée de la Sionne. They found that front velocity decreased with increasing averaged temperature of the snow-pack.

An appropriate tool to study the behaviour of flowing snow under controlled conditions are chute experiments. The WSL Institute for Snow and Avalanche Research SLF operates a 30 m long and 2.5 m wide chute at Weissfluhjoch near Davos, Switzerland (SLF Snow Chute hereafter). It has been renovated and equipped with a great variety of sensors (Tiefenbacher and Kern, 2004; Kern et al., 2004). Optical velocity sensors and a high-speed camera were installed in a sharp wedge in the middle of the snow chute, in order to obtain insight into velocity variations and flow behaviour in the lower 10 cm of the snow. Analyzing the images of the high-speed camera Schaefer et al. (2010) identified a very small shear layer of smaller than 2 cm (in flows of up to 80 cm depth) with extremely high shear rates (up to 600/s). Velocity profiles varied throughout the flow and a turbulent flow structure was observed in the lower 10 cm of the flows.

Platzer et al. (2007a,b) measured basal shear and normal forces on the SLF Snow Chute by means of force plates. They concluded that the basal friction could be satisfactorily modelled with velocity-independent friction parameters, and these
friction parameters depended on snow properties. But they also could not exclude a velocity dependence of the basal friction. Here we present new results from the same force plates as employed by Platzer et al. (2007a,b). However, two important modifications were made to the set-up: 1) one force plate was placed before the first bend of the snow chute in order to obtain data from the undisturbed flow and 2) rubber mats were screwed on both force plates in order to obtain the same type running surface on the force plates as on the rest of the snow chute.

We briefly describe the experimental set-up in Section 2 and present our results in Section 3. In Section 4 we discuss our findings in the light of previous studies. In Section 5 we analyze the dependence of the measured friction coefficient both on measurable snow properties like density or temperature and its dependence on avalanche parameters like total volume and average velocity. In Section 5 we summarize our findings and give an outlook about possible interesting experiments on snow flows under controlled conditions.

2 Methods

2.1 The SLF Snow Chute

The SLF Snow Chute (Figure 1) consists of a 10 m long reservoir, a 10 m long acceleration section, followed by a 4 m long measurement section and finally a 6 m long run-out. It is 2.5 m wide. In the experiments the inclination to the horizontal of the two uppermost, movable sections of the chute was set to the maximum possible inclination of $45^\circ$, to ensure the release of the avalanches. The slope of the measurement section was $40^\circ$ and in the run-out zone $13^\circ$. In the acceleration section and the measurement section, rubber mats cover and roughen the smooth running surface of the chute. They have a

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width of 6 cm and are mounted with a spacing of 2.5 cm in flow direction (Figure 1a and b). During the experiments, snow sticks in the voids and the rough boundary condition at the bottom initiates the shearing motion inside the avalanche body. Before the experiments snow surrounding the Weissfluhjoch at 2670 m above sea level was shovelled by hand into the snow chute’s reservoir. Before each experiment, the snow density inside the reservoir was measured using a density cylinder and a calibrated force gauge. Most of the times, the density measurements were repeated up to three times to obtain a measure of the variability of the density inside the reservoir. Air temperature and snow temperature inside the reservoir was measured with a digital thermometer with a nominal precision of 0.5°C (Milwaukee Thermometer TH310). The SLF Snow Chute is described in more detail in Tiefenbacher and Kern (2004).

2.2 Force plates

Two identical force plates were installed at the end of the acceleration section and in the beginning of the measurement section (Figure 1). The force plates contain three strain-gauge sensors (HBM Electronics, Germany, model U9B) that measure the normal stresses and one strain-gauge sensor that measures the shear stresses exerted by snow flow. The three sensors that measure the normal force component are placed in the corners of an equilateral triangle construction of aluminium in which the barycentre of the triangle is at the centre of the force plate. The sensor that was installed to measure the shear force was aligned in the flow direction. To ensure that the force transducers are loaded only in one direction, socketed stanchions were used to prevent a tilting of the force plates. All four sensors have a nominal maximum load of 5 kN (HBM company). The force plate systems were calibrated with known weights. During the experiments the signal of the resistance strain gauge was recorded and the voltage was afterwards converted into normal and shear stresses using the calibration curves of the sensors and the plate surface of 0.462 m². The voltage signals were captured with a sampling frequency of 20 kHz by an AD converter card and stored on a computer. The noise amplitude varied from 20 to 40 Pascal between the experiments. A more detailed description of the force plates is given in Platzer et al. (2007a).

2.3 Laser distance sensors

To measure the depth of the snow flows, laser distance sensors (model BOD 66M Balluf) were mounted on wooden bridges above the centre of the force plates (Figure 1b and c). The laser operates at a wavelength of 660 nm (red light) with a light spot of 10 mm. The acquisition frequency is indicated by the producer to be 250 Hertz. The measurement range was 20 cm to 2 m. The laser distance sensors were calibrated with objects of known height to be able to convert the recorded volt signal to distances after the experiments. The amplitude of noise of the Laser sensors’ signal was 0.01 Volts which approximately
corresponded to 2 cm.

3 Results

3.1 General observations

With the presented set-up, 17 avalanches could successfully be released during the winter 2008/09. Properties of 12 avalanches that exhibited high quality stress data are presented in Table 1. The experiment season ranged from end of January until end of May. The density of the shovelled snow measured before the experiments ranged from 280 kg/m$^3$ to 640 kg/m$^3$. The uncertainty of the density values is the standard deviation between the different measurement repetitions. ±? means that only one density measurement was made. Only two experiments were conducted with relatively fresh and light snow. This is due to the fact that after a heavy snowfall all the infrastructure had to be freed from the snow before conducting an experiment. Furthermore, the naturally precipitated snow inside the reservoir could not be released before moving it with the shovel, because it froze to the container ground and walls. Flow density is the mean value of $\rho_f(t)$ (see Figure 2) that was calculated using the measurements of normal stress and flow depth before the inclination change, assuming the normal stresses to be the determined by the column weight, which is a good approximation for shallow avalanches (Savage and Hutter, 1989):

$$\rho_f(t) = \frac{N(t)}{gH(t)\cos\theta}. \quad (1)$$

<table>
<thead>
<tr>
<th>Exp.No.</th>
<th>Date</th>
<th>Pre-release Snow Density</th>
<th>Flow Density</th>
<th>Snow Temp.</th>
<th>Air Temp.</th>
<th>Mean Vel.</th>
<th>Volume</th>
<th>$\rho_1$</th>
<th>$\rho_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>20-Jan</td>
<td>291±7</td>
<td>180±40</td>
<td>-4.5±0.5</td>
<td>-7±0.5</td>
<td>5.6±0.1</td>
<td>6.7±1.0</td>
<td>0.52±0.12</td>
<td>0.50±0.14</td>
</tr>
<tr>
<td>2</td>
<td>05-Feb</td>
<td>423±10</td>
<td>386±39</td>
<td>-7±0.5</td>
<td>-6±0.5</td>
<td>7.7±0.1</td>
<td>10.2±0.8</td>
<td>0.57±0.06</td>
<td>0.48±0.10</td>
</tr>
<tr>
<td>3</td>
<td>05-Feb</td>
<td>431±4</td>
<td>147±29</td>
<td>-4±0.5</td>
<td>-5±0.5</td>
<td>5.1±0.0</td>
<td>2.3±0.5</td>
<td>0.54±0.13</td>
<td>0.66±0.21</td>
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<tr>
<td>4</td>
<td>05-Feb</td>
<td>415±4</td>
<td>439±96</td>
<td>-4±0.5</td>
<td>-4±0.5</td>
<td>8.1±0.2</td>
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<td>0.62±0.13</td>
<td>0.67±0.37</td>
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<td>5</td>
<td>18-Mar</td>
<td>427±6</td>
<td>225±107</td>
<td>-2±0.5</td>
<td>-5±0.5</td>
<td>6.0±0.1</td>
<td>11.2±1.4</td>
<td>0.50±0.06</td>
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<td>6</td>
<td>25-Mar</td>
<td>281±28</td>
<td>207±61</td>
<td>-10±</td>
<td>-10.6±0.5</td>
<td>7.1±0.3</td>
<td>12.4±0.5</td>
<td>0.40±0.19</td>
<td>0.40±0.16</td>
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<tr>
<td>7</td>
<td>31-Mar</td>
<td>331±56</td>
<td>260±112</td>
<td>0±0.5</td>
<td>1.8±0.5</td>
<td>6.1±0.3</td>
<td>6.3±1.1</td>
<td>0.48±0.18</td>
<td>0.79±0.22</td>
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<tr>
<td>8</td>
<td>31-Mar</td>
<td>265±46</td>
<td>173±48</td>
<td>-1.5±0.5</td>
<td>4.1±0.5</td>
<td>9.1±0.4</td>
<td>9.9±0.1</td>
<td>0.61±0.05</td>
<td>0.80±0.24</td>
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<tr>
<td>9</td>
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<td>353±15</td>
<td>101±29</td>
<td>-1.8±0.5</td>
<td>2.1±0.5</td>
<td>7.5±0.2</td>
<td>7.4±1.1</td>
<td>0.64±0.06</td>
<td>0.76±0.27</td>
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<tr>
<td>10</td>
<td>19-May</td>
<td>608±7</td>
<td>371±112</td>
<td>-0.1±0.5</td>
<td>4.3±0.5</td>
<td>8.3±0.3</td>
<td>6.6±2.2</td>
<td>0.93±0.17</td>
<td>0.66±0.22</td>
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<tr>
<td>11</td>
<td>19-May</td>
<td>556±7</td>
<td>395±91</td>
<td>-0.1±0.5</td>
<td>4.6±0.5</td>
<td>8.0±0.1</td>
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<td>1.03±0.23</td>
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</tr>
<tr>
<td>12</td>
<td>19-May</td>
<td>635±7</td>
<td>465±56</td>
<td>0±0.5</td>
<td>4.8±0.5</td>
<td>8.9±0.3</td>
<td>4.3±1.0</td>
<td>0.92±0.09</td>
<td>0.58±0.14</td>
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Table 1: Dates and parameters of the 12 avalanches studied in this paper. * means that the values were not measured directly, but were inferred from a close by automatic weather station.

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Here $N(t)$ and $H(t)$ denote the measured normal stress and flow depth respectively, $g$ is the gravitational acceleration and $\theta$ is the inclination of the chute at the measurement location. The uncertainty of the flow density is the standard deviation of $\rho_f(t)$, which is the variation of the inferred density during the experiment. Ambient temperatures during the experiments ranged from $-10^\circ C$ to $5^\circ C$. Snow temperature ranged from $-7^\circ C$ to $0^\circ C$. As uncertainty of the temperature measurements we indicate the precision of the thermometer. For measured snow temperatures of $0^\circ C$ the uncertainty interval of one sigma, will be asymmetrical around the measured values, since snow does not exist at positive temperatures. For experiment No. 7 we indicate in parenthesis a value inferred from the recordings of a close by automatic weather station. This experiment was the second of four experiments on the same day and since clearly negative snow temperatures were measured in the experiments before and after this experiment, we think that the recorded snow temperature probably does not correspond to the real snow temperature for this experiment and argue that the recorded value is due to a human or instrumental error.

The mean velocity of the flow was obtained by cross-correlating the signals of the two laser sensors in order to obtain the time shift between the two signals. The distance between both sensors was 86 cm. As the slope transitions from $45^\circ$ to $40^\circ$ was located between these two sensors, the detailed shape of the signals often changed from one sensor to the other. Large correlation windows of one to three seconds, were necessary to obtain stable velocities. Two example for the velocity data obtained by cross-correlating the time series recorded by the Laser Sensors are shown in Figure 2. In both examples, the correlation time window was 2 seconds. The velocity data which correspond to the avalanche bodies, were used to compute the average avalanche velocity. The uncertainty of the velocity measurements indicated in Table 1 is the standard deviation of the velocity signal during the avalanche.

Figure 2: Signals of the Laser Sensors in experiment No. 8 and No. 11 (blue and green lines); velocities obtained from cross-correlating intervals of the Laser Sensors’ signals (red crosses); maximum value of the correlation function (black circles).

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The volume of the flows was estimated by integrating the signal of the flow depth measurements multiplied by the average velocity and the width of the chute. Sometimes the results from the integration of the signals of the first flow depth sensor and the second flow depth sensor differed considerably. In Table 1 we present the average of both values and the error indicates the standard deviation between the two measurements, which can also be interpreted as an indication for the reliability of the flow depth measurements. In reality there are additional sources of uncertainties in the volume measurements as for example the uncertainty of the velocity and biases due to an uneven surface of the avalanche. So, avalanche volumes indicated in Table 1 should be interpreted rather as a crude estimate and small errors in Table 1 should be interpreted as an indicator of consistent measurements of both Laser sensors and not as the real uncertainty of the volume estimate. \( \mu_1 \) and \( \mu_2 \) are the average coefficients of friction measured at upper force plate (force plate 1) and the lower force plate (force plate 2) respectively during the experiments, corresponding to the time average of:

\[
\mu(t) = S(t)/N(t),
\]

where \( S(t) \) denotes the measured shear stress and \( N(t) \) the measured normal stress. As starting point of the average we used the point in time at which the normal stress of the plate reached 200 Pa and as stopping point when it went below 200 Pa. This was done, because of the inherent uncertainties in the measurements of the normal stress: small errors in the measurements of \( N \), at small values of \( N \), cause important uncertainties in \( \mu \) (see Figures 6 and 8).

### 3.2 Time evolution of stresses, flow depth, density and coefficient of friction

In this section we will present in detail the time evolution of several parameters for four selected avalanches that represent the 12 avalanches: one small event with light snow (No. 1), one large event with light snow (No. 6), one large event with intermediate density (No. 2) and one event with dense, wet snow (No. 12).

The first three events where conducted under freezing conditions whilst the last was conducted in spring with positive ambient temperatures. Figure 3 shows snapshots of the four avalanches. Videos are available in the supplementary material.

In Figure 4 we present the shear and normal stresses measured in these four avalanches at the upper force plate (force plate 1), before the change of inclination of the chute. The different absolute time is caused by different manual triggering and has no physical meaning at all. For comparison we also show the flow-normal component of the column weight \( W_0 \) calculated using the pre-release snow density \( \rho_0 \) according to:

\[
W_0(t) = \rho_0 g H(t) \cos \theta.
\]
(a) Experiment No. 1 is flowing down the acceleration section of the snow chute  
(b) Experiment No. 10 is flowing down the acceleration section of the snow chute

(c) Experiment No. 6 is starting from the release gate  
(d) Experiment No. 2 is reaching the measurement section

Figure 3: Snapshots of four experiments
Figure 4: Stresses measured at the upper force plate (force plate 1) together with the flow-normal component of the column weight $W_0$ calculated using equation (2) for four selected avalanches. Note the different scaling of the y-axes.
The stress data is smoothed with a running average using a time window of 0.025 s to reduce noise, whilst the data from the laser sensor are smoothed over a larger time window of 0.1 s to account for the smaller measurement surface of the sensor. We observe that for three of the four experiments maxima of $W_0$ agree with maxima of the normal stress measured on force plate 1. For experiment No. 1 $W_0$ is higher than the measured normal stress throughout the entire avalanche event. We suspect that the density measurement before the experiment, which was not repeated, was not effectuated with a representative sample. This idea is motivated by the fact that there was occurring precipitation of fresh snow during the experiment at that day. Another possible explanation for the disagreement could be a partly blocking of the force plate by freezing fresh snow, which reduced the measured force signal. For the experiments No. 2 and No. 6 a peak in $W_0$ is observed before the maximum of measured normal stress. This peak could be caused by a small not very dense snow cloud which produces high flow depth at the laser sensor but low normal stresses on the force plates, which can also be observed in the video images of the experiments (Figure. 3). In experiment No. 10 $W_0$ is very similar to the measured normal stress in the beginning but is much higher for the reminder of the avalanche. We think that this probably due to a problem of the upper Laser sensor which overestimates the flow depth due to multiple reflections in the wet splashing snow. This idea is confirmed by the fact that the second Laser sensor is measuring a much lower avalanche volume, which causes the high uncertainty of the volume value indicated in Table 1. In Figure 5 we present flow density for the same four experiments which was computed using equation (1). The thick blue line indicates the computed density whilst the thin blue lines indicate the uncertainty interval of the flow density, which was obtained by the Gaussian formula of error propagation using as uncertainties for $N$ and $H$ the amplitude of the noise which corresponded to 30 Pa and 2 cm respectively. In all four experiments the flow density $\rho_f$ is rapidly increasing in head of the avalanche reaching a value similar to the pre-release density $\rho_0$, near to the maximum in flow depth in the experiments No. 2, 6 and 10. In the experiments No. 2 and 6 the flow density is decreasing again towards the tail of the avalanche. In experiments No. 10 the inferred flow density decreases rapidly after the first maximum in flow depth. However since this experiment was conducted with wet snow which does not tend to mix with air very much, we think that this reduction is produced by incorrect data from the flow depth sensor (see above). This the reason why we present this part of the data with a dotted line. In experiment No. 1 the flow density is varying through the experiment, but as in the other experiments local maxima in flow density are mostly near to maxima in flow depth.

In Figure 6 we present, for the same four experiments, the quotient between the measured shear stress and normal stress, calculated according to equation (2). The time series of $\mu$ was smoothed with a moving average using a time window of 0.1 s. The thick blue line indicates $\mu$ whilst the thin blue lines indicate its uncertainty interval, which was again obtained by the Gaussian formula of error propagation using 30 Pa as uncertainty of $S$ and $N$. It is visible that the coefficient of Nov. 2002
Figure 5: Flow densities for the four selected avalanches computed using equation (1). Vertical blue line indicates the value of the pre-release density $\rho_0$. 
Figure 6: Coefficient of friction together with the scaled flow depth $H_s(t) = H(t)/\max(H(t))$ measured at the upper force plate (force plate 1).
friction varies considerably during the experiments. Experiment No. 6 and Experiment No. 10 show a strong increase of the coefficient of friction towards the tail of the avalanches. An increase is also visible in experiment No. 2 but less pronounced.

In experiment No. 1 we see a strong increase in the coefficient of friction at an intermediate part of the avalanche where the measured flow depth has a local minimum. So, generally we can state that the coefficient of friction seems to increase towards the tail of the avalanches or at low flow depths. This seems, however, not to be the case for low flow depths at the front of the avalanches, where we observe low coefficients of friction. Note the increasing uncertainty of $\mu$ at small normal stresses, especially at the tail of experiment No. 6.

In Figure 7 we present the measured shear and normal stresses and $W_0$ for the same four avalanches at the lower force plate, after the bend in the chute. Here we observe contrasting results for experiments No. 1 and No. 6 as compared to experiments No. 2 and No. 10. In experiments No. 1 and No. 6 the normal stresses are again relatively well approximated by flow-normal component of the column weight $W_0$, with exception of a short part at the front of the avalanches where probably a dilute snow cloud is present. For the experiments No. 2 and No. 10 the measured normal stresses are much higher.

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than the one measured at the upper force plate and the normal stresses are much higher than $W_0$. These two experiments are the experiments that exhibit higher densities. And at the experiment No. 10, where the discrepancy between measured normal stress and $W_0$ is highest is also the experiment with highest density. Considering also the other eight experiments we can state, that the bend in the chute seems to increase the measured stresses, but this increase seems to crucially depend on the density of the snow.

In Figure 7 we present the coefficient of friction measured at the lower force plate (2). The thin blue lines correspond to the uncertainty interval of $\mu$, defined as in Figure 6. Generally, at force plate 2, a similar behaviour of the coefficient of friction is observed to the one observed at force plate 1: for lower flow depths and towards the end of the flows the coefficient of friction seems to increase. However, for the experiments No. 2, No. 6 and No. 10 also high coefficients of friction are observed at the front of the avalanches. Since this behaviour was not observed at force plate 1, where the flows were undisturbed, we argue that this high values of the coefficient of friction at the front of the avalanches is perhaps introduced

![Figure 7: Coefficient of friction measured at the lower force plate (2).](image)

Figure 8: Coefficient of friction together with the scaled flow depth $H_s(t) = H(t)/\max(H(t))$ measured at the lower force plate (force plate 2).
4 Discussion

In comparison to the range of coefficients of friction from 0.1 to 0.6 measured by Platzer et al. (2007a), our measured range (0.4 to 1.03) is clearly higher. This could be due to several reasons: first the rubber mats screwed on the force plates have considerably increased their surface roughness, which caused additional shear stresses on the moving snow pack. The higher coefficients of friction measured with our set-up at an inclination of 45 degrees could also indicate a dependence of the coefficient of friction on the velocity, since Platzer et al. (2007a) measured at much lower inclinations.

It is interesting to note that during the experiments the coefficient of friction is nearly always below the tangent of the inclination angle. This means, if the shallowness assumption is valid, and the normal stress is equal to the flow-normal component of the column weight, that the (downstream) volume forces of the snow column above the force plate \((\rho g H \sin(\theta))\) were higher than the measured shear stresses on the running surface:

\[
\mu < \tan \theta \Rightarrow S < N \tan \theta = \rho g H \sin \theta.
\] (4)

If the rest of the surface stresses on the volume element above the force plate were negligible, conservation of momentum would imply that most of the parts of the avalanche were accelerating at the measurement location. This contradicts earlier observations on the same experimental device, which indicated that the snow flows reach stable front velocities at the end of the acceleration section (Kern et al., 2004). If, at constant velocity, the measured shear stress at the running surface is clearly smaller than the driving volume forces, this could indicate that there exist important retarding stresses at other surfaces of the volume element, i.e. the sidewalls of the snow chute or the free surface. The existence of dilute snow clouds in top of the dry snow avalanches is another indication that the interaction with the air at the free surface can develop important stresses.

The greater difference from the measured coefficient of friction to the tangent of the inclination angle observed in dryer, less dense snow avalanches in comparison to wet snow avalanches (see experiments No. 6 and No. 10 in Figure 5 (c) and (d) for example) could indicate that these additional retarding stresses are of higher importance for dry snow avalanches than for wet snow avalanches.

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5 Variation of the coefficient of friction with avalanche parameters

When looking for dependencies of the coefficient of friction on avalanche parameters (like for example the ones presented in Table 1), it is important to note that this analysis excludes the retarding stresses that are independent of the normal stress like for example turbulent velocity dependent friction. The coefficient that relates the retarding stresses to normal stress is often called Coulomb Friction parameter in avalanche dynamics. However, since the Coulomb Friction model is a model that claims a constant relation between normal stress and shear stress for dry friction between rigid bodies, we avoid the word Coulomb Friction parameter. Instead we want to speak of a coefficient of friction, which in the most general point of view may depend on all thinkable parameters of the snow flow.

The avalanche parameters presented in Table 1 can be divided into a priori measurable parameters (air temperature, snow temperature and snow density) and a posteriori parameters which were measured during the experiment: the avalanche’s volume and its mean velocity. First, we want to analyse the dependence of the measured coefficient of friction on the a priori measurable parameters. Here, we concentrate on analyzing the dependence of the “undisturbed” coefficient of friction measured at the upper force plate (force plate 1) on avalanche parameters, since the effect of the bend in the chute on the coefficient of friction is not trivial at all. In Figure 9 we present the mean coefficient of friction measured during the experiments plotted against the a priori measured snow density (a) and snow temperature (b). A clear increase of the coefficient of friction is observed with increasing snow density and increasing snow temperature. The Pearson correlation coefficient $r$ between the snow density and the coefficient of friction was 0.84 and the trend line of the linear fit is shown in

![Figure 9: Measured coefficient of friction varying with the snow properties density (a) and snow temperature (b).](image-url)
Figure 9 (a). In the snow temperature - coefficient of friction plot (Figure 9 (b)) we show direct snow temperatures inferred from the measurements of a close by automatic weather station for experiments No.6 and 7 and directly measured values for the rest of the experiments. The correlation coefficient between this set of snow temperatures and the coefficient of friction is 0.69. Taken a closer look a Figure 9 (b), we can observe that the coefficient of friction is increasing slightly with temperature until approximately -1.5 °C, while its increase is much stronger from -1.5 °C to 0 °C. This suggests that the dependence of the coefficient of friction on the snow temperature is not linear, which is consistent with the findings of Steinkogler et al. (2013, 2014), who observed an abrupt transition of the behaviour of snow flows at a temperature of -1°C and -2°C respectively. The correlation between air temperature and the coefficient of friction was high as well ($r = 0.89$), which is not surprising since the correlation between air and snow temperature was high.

In comparison with the fit for the temperature dependence of their dry coefficient of friction obtained by Casassa et al. (1991) ($\mu(T) = 0.001T + 0.47$), which was inferred from extrapolating measurements of the total coefficient of friction to zero velocity, our measured coefficient of friction shows a much stronger dependency on the snow temperature. Here one has to keep in mind that the frictional processes taking place between to sintered snow blocks, where a shear layer in the order of magnitude of millimetres was observed, and a highly fluidized snow flow on a rough running surface are very different. In our experiments the interaction with the running surface does not only consist of sliding but also of (inelastic) collisions of snow particles which generally will move in a chaotic way.

Naaim et al. (2013) also observed a much less pronounced dependency of the parameter which relates retarding stress to normal stress in their model on the snow temperature. And no temperature dependence of their second model parameters which quantifies the velocity dependent part of the retarding stresses was found. Their data had very much scatter and the coefficient of determination of their fit was very low ($R^2 = 0.1$). This might indicate that natural avalanches show a frictional behaviour, which is more complex than assumed in their model.

Although no quantitative agreement was found for the snow temperature dependence of the coefficient of friction determined with different methods, it is still encouraging that the trend observed was the same for all methods: higher snow temperatures implicated higher coefficients of friction!

A dependence of the coefficient of friction on the density of the granular material snow, is intuitive, since higher density means more particles per unit volume and therefore more frictional contacts with the running surface are possible. It seems that this additional frictional contacts make the shear increase more rapidly than the normal stress due to the additional weight.

The effect of increasing coefficient of friction with increasing temperature is probably more difficult to explain. However it
is also intuitive that collisions between snow particle get more inelastic with higher temperatures. Especially when reaching zero degree, where the liquid water content is rapidly increasing and the snow particles easily stick together. So if more kinetic energy of snow particles is lost in every collision this will translate to increasing retarding stresses in the snow flow. Additionally, in high-speed recordings of the shear layer of snow flows (Schaefer et al., 2010), a change of flow behaviour from dryer less dense snow flows to wetter denser snow was observed: whilst in the dryer snow rotational movements of clusters was frequently observed, in the wetter flows the snow tended to slide more regularly (Schaefer et al., 2010).

The correlation between the mean avalanche velocity and the coefficient of friction was $r = 0.61$. Increasing shear stresses with increasing velocity are intuitive as well, since frictional contacts are more frequent, which means that the volume element loses kinetic energy at a higher rate. The correlation between the coefficient of friction and the avalanche volume was negative ($r = -0.53$). This is consistent with the common practice in avalanche modelling to use smaller coefficients of friction for larger, catastrophic avalanches (Salm et al., 1990). However, here it is important to keep in mind that the volume of our artificial snow flows is several orders of magnitude lower than the volume of avalanches observed in nature.

6 Summary and outlook

We present measurements of shear and normal stresses in 12 snow flows on the SLF Snow Chute on a straight incline of 45 degrees as well as directly after a slope deviation. We find that the maximum normal stresses measured at the straight incline predominately agree with the maxima of flow-normal component of the column weight using snow densities measured before the experiment. After the slope deviation, in most of the experiments, the normal stress was much higher than the flow-normal component of the column weight. This disagreement was stronger for higher flow densities.

Measured coefficients of friction were generally lower as expected for flows of constant velocity which might indicate the importance of other frictional processes as side-wall friction and friction at the snow-air interface.

Analysing the dependence of the coefficient of friction on parameters varying between the experiments, we found higher coefficients of friction for higher densities, snow and air temperatures and average avalanche velocities. The total avalanche volume correlated negatively with the coefficient of friction. The Pearson correlation coefficient was highest between the coefficient of friction and snow density. The variation of the measured coefficient of friction with snow temperature suggested a non-linear dependency. When searching for the dependency of the coefficient of friction on avalanche parameters it is important to remember that contributions to retarding stresses that do not depend on the normal stress (like for examples turbulent only velocity-dependent friction) are excluded form the analysis.
Although our experimental data give several hints for the dependence of the coefficient of friction on avalanche parameters, more experiments could help to improve our understanding of snow flows: the bend in the chute should be removed in order to obtain two stress measurements at the same inclination angle. These point measurements should be complemented by a tracking of the flow evolution with photogrametric techniques which include a precise quantification of snow deposits on a well-defined run-out zone. Also a quantification of erosional processes on a beforehand prepared bed are thinkable. Measurements of velocity profiles and velocity fluctuation could help to distinguish different flow regimes. International collaborations of different work groups are desirable to gain large amount of data in intensive collaborative measurement campaigns.

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