RELATING WET LOOSE SNOW AVALANCHING TO SURFICIAL SHEAR STRENGTH

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ABSTRACT: Wet loose snow avalanches are a significant hazard within many ski areas. Wet snow stability changes dramatically over short time periods which typically coincide with operating hours, and few quantitative tools exist for avalanche workers attempting to predict the onset of wet snow avalanching. This study documents changes in surficial shear strength during melt-freeze cycles and relates these changes to observed wet loose avalanche activity. We conducted field work at two study sites in southwestern Montana over the course of four April days in 2005 and 2006. We used a 250cm^2 shear frame to make as many as 210 surficial shear strength measurements of melt-freeze snow per day, and adjusted our results for known shear frame size effects. We also collected SnowMicroPen penetrometer profiles in conjunction with shear strength during one melt-freeze cycle. Initial results are encouraging. Changes occurred rapidly within the melt-freeze cycle as shown by highly significant changes in shear strength within half hour intervals. SnowMicroPen data shows significant positive correlations between the microstructural hardness of snow and shear strength. Most importantly, our limited data shows an apparent association between surficial shear strength and avalanche activity. On 22 April 2006 when our shear strength measurements dropped below 250 Pa we observed, and triggered, wet loose avalanches in the immediate vicinity of study slopes. Conversely, surficial stability on our study slope improved when shear strength values exceeded 300 Pa.

KEYWORDS: wet snow, shear strength, wet avalanche

1. INTRODUCTION

1.1 Background

Although wet snow avalanches are a significant hazard in many operational settings, a disproportionately small amount of research has been conducted in comparison to dry snow avalanches. There are several reasons for this, but foremost is that dry slab avalanches kill more people, cause more damage, and have therefore generated more interest and funding. In addition, experimentation with wet snow is difficult. Any model for wet snow mechanics must involve an understanding of the structural impact on snow in a three-phase system (Salm, 1982). Structural and strength parameters are highly dynamic and experiments are very difficult to reproduce.

In this study, we focus on surficial, wet loose snow avalanches (Figure 1). Avalanches of this type occur when the water content of near-surface snow increases to a point where surficial layers lose enough strength that the slope angle exceeds the static friction angle (McClung and Schaerer, 1993). With triggers such as a ‘roller-ball’, rock-fall, or skier traffic, slopes in this condition can avalanche. These avalanches are easily recognizable as point releases that form a triangular pattern on the descent, and can be differentiated from dry loose snow avalanches by the presence of liquid water in the avalanching snow, the presence of snowballs and/or levees along the flanks of the slide or in the debris pile, and well defined ‘scour’ marks and striations along the bed surface of the avalanche. In southwest Montana, wet loose snow avalanches generally occur in response to high water contents caused by elevated spring temperatures, but can occur at any time during the winter if elevated temperatures and/or rain provide sufficient free water input. Though others have measured the shear strength of

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wet snow (e.g., Perla et al., 1982; Brun and Rey, 1987; Bhutiyani, 1994), we are unaware of any research relating the surficial shear strength of wet snow to avalanche activity.

Figure 1. Example of an April wet loose snow avalanche in the Bridger Mountains of Montana.

1.2 Wet Snow

The introduction of liquid water into snow either through warming and/or rain directly affects the hydraulic properties and strength of snowpacks. Change in particle size, bond growth, and densification are not only dependent upon the presence of liquid water, but on how much liquid water is available. In this regard, it was convenient to adapt terms used in soil science (pendular vs. funicular) to formally describe wet snow (Colbeck, 1973).

Snow is 'wet' when liquid water exists between grains; it is considered to be of low water content (pendular) when the amount of free water is less than 7% by volume, and of high water content (funicular) when the free water content exceeds 7% (Colbeck, 1982). In the pendular regime air is continuous throughout the pore spaces and water is found only in isolated cells. The amount of liquid water present is greater than the capillary requirement (irreducible water content), but less than the amount needed to have capillary rings around neighboring grains coalesce and/or connect. In the funicular regime, water is continuous and air occurs only in isolated cells. This distinction between high and low water content is important because snow exhibiting funicular properties has a much lower strength than snow at lower water contents (Colbeck, 1982). In addition, infiltration rates are faster when water is continuous throughout the pore spaces, causing a marked difference in flow rates between the two regimes.

Research has repeatedly shown that wet snow loses its strength at the transition between the pendular and funicular regimes, or when its water content reaches about 7% by volume (~14% pore volume) (Ambach and Howorka, 1965; Colbeck, 1982; Bhutiyani, 1994). Wakahama (1975) recorded a drop of 2 orders of magnitude hardness in a natural surface layer from the morning before melt until noon when the water content of that layer reached 20 - 25% pore volume. In addition, when wet snow reaches higher water contents, the angle of repose decreases, and creep and glide velocities increase (McClung and Schaerer, 1993).

Several studies have measured the shear strength of wet snow (Perla et al., 1982; Brun and Rey, 1987; Bhutiyani, 1994). Perla et al. (1982) used a shear frame to quantify an index of the shear strength of alpine snow. Interestingly, they found they could correlate the shear index with all crystal morphologies except for melt-freeze grains. This phenomenon was attributed to the observation that with little discernable change in crystal morphology, the strength of melt freeze snow can change dramatically with the addition of liquid water.

Brun and Rey (1987) also concluded that an estimation of shear strength based upon the physical description (primarily density) of a snow sample is only valid for dry, fine grained or fresh snow. In addition, they discussed the influence of water content on shear strength, and found little change in wet snow shear strength at or below 6% water content by volume (they did not sample anything with a water content higher than 6%).

Bhutiyani (1994) reached similar conclusions, finding that density as a sole predictor of wet snow shear strength is inadequate. He also found that a basic assessment of grain size was a significant factor when correlating density and strength. Samples with crystal size smaller than 1mm provided a significantly better correlation than grain sizes larger than 1mm (r = 0.87 vs. r = 0.53 respectively), an observation that is plausible if the assumption is made that crystals smaller than 1mm have seen very little melt freeze metamorphism, and have more contact points between crystals per unit of snow. Bhitiyani (1994) improved the correlation somewhat for grain sizes larger than 1mm by developing a correction factor that included both density and water content that exhibited a predictive capability of r = 0.65. Study of the shear strength in relation to water content showed no significant changes up to 6%, but dropped by a factor of 2 once the water content exceeded ~7% by volume. There is some question as to why no significant change is noted in shear strength between 0 and 6% water content. Although Colbeck (1973) theorized that capillary strength is not sufficient to compensate for the disappearance of bonds by melting in the pendular regime, the fact that research has shown no appreciable change in shear strength with changes in water content (in pendular snow) suggests that even though capillary pressure is not high enough to counteract the disappearance of bonds, it may be strong enough to limit the amount of water available for bond degradation (Bhitiyani, 1994). In funicular snow, water exists continuously between contact points and bonds can be completely degraded.

As shown above, a body of work on the shear strength of wet snow exists. Further, this work demonstrates that the shear strength of wet snow can change dramatically with only small increases in the liquid water content. Such rapid changes mimic our observations of wet loose snow avalanche conditions, which often transition from relatively stable conditions to highly unstable conditions in a matter of 30 minutes or less. However, thus far we know of no research that attempts to correlate wet snow shear strength to loose wet snow avalanche activity, which is the focus of this paper.

2. METHODS

2.1 Data Collection

Changes in shear strength spanning targeted melt-freeze cycles were documented during four separate April days in 2005 and 2006. Days were chosen based upon the presence of a well developed surficial melt-freeze crust, forecasted sunny weather and above freezing temperatures. Testing began when frozen surficial snow had softened enough to allow shear frame placement. A 250 cm^2 shear frame was used in conjunction with a 5 kg Wagner force dial. In most cases, we were able to insert the frame during periods when the shear strength was greater than 5 kg pull force. Under these circumstances, the pull was given the maximum value of the gauge. In order to be as consistent as possible, we did not specifically target a weak layer, but instead attempted to measure changes in strength ~4cm below the surface (depth of a 250cm2 frame). Shear frames were inserted to the depth of the frame, and the adjacent snow (outside the frame) was removed with a putty knife (Figure 2). Pull time was 1 – 1.5 seconds. All shear frame results were adjusted for shear frame size (Fohn, 1987; Greene et al., 2004). Each study site was located in a position where neighboring slopes could be monitored for avalanche activity.

Figure 2. 20 April 2006 study site. The photograph depicts the methodology used to document changes in the surficial shear strength of wet snow.

2.1.2 – Field Day 1 and 2, 24 and 25 April 2005

Data was collected along the north boundary of the Bridger Bowl Ski Area, 24 km (15 miles) north of Bozeman, Montana. The study site is east facing with an elevation of 2438 m (8000 feet) and a slope of 32 degrees. Tests were conducted in hourly transects consisting of 12 shear frame pulls. Each transect was completed in approximately fifteen minutes. On 24 April 2005, eleven transects (132 individual shear frames) were conducted between 08:00 – 18:00. On 25 April 2005, 10 transects (120 individual shear frames) were conducted between 08:00 and 17:00.

2.1.3 – Field Day 3 - 20 April 2006

Data was collected north of Bridger Bowl Ski Area in the vicinity of Bradley meadows (Figure 2). Bradley Meadows is located 24 km (15 miles) north east of Bozeman, Montana. The study site is south east facing, has an elevation of 2316 m (7600 feet), and an average slope of ~33 degrees. The sampling scheme consisted of five 30 meter transects that allowed almost continual testing across the entire slope throughout the day. Each transect contained 3 sub-transects. Testing began at 09:55 and ended at 16:11. A total of 70 tests were conducted (210 individual shear frames). Shear measurements were coupled with snow hardness observations quantitatively recorded using the SnowMicroPen (SMP) (Schneebeli and Johnson, 1998). The shear frame was positioned 10cm up-slope of SMP locations within 1 to 2 minutes following SMP measurements.

2.1.4 – Field Day 4 - 22 April 2006

Data was collected in the Obsidian slide path at Moonlight Basin Ski Area. Moonlight is located 56 km (35 miles) south of Bozeman, Montana. The study site is east facing, has an elevation of ~2743m (9000 feet), and a slope of 40 degrees (Figure 3). Shear strength measurements were initiated at 09:45 and then conducted hourly until 17:45. Tests were conducted in transects consisting of 10 shear frame pulls and were completed in approximately fifteen minutes. Nine transects, or a total of 90 shear frames were conducted.

2.2 Data Analysis

Significant changes in shear strength by transect (significant change in strength between consecutive transects over time) were identified using the non-parametric Mann-Whitney (Wilcoxon Rank-Sum) test. Box-plots were used to graphically identify outliers and differences in central tendency. The presence or absence of avalanche activity during each field day was compared to corresponding surface shear strength measurements. In addition, shear strength changes documented on 20 April, 2006 were compared with snow hardness information derived from SMP resistance profiles. From each SMP profile, the snow hardness at the shear interface was estimated by calculating the median resistance of a 2cm segment (~4’880 resistance values) spanning the shear interface.

Figure 3. View of study site, Obsidian slide path, Moonlight Basin, 22 April 2006.

3. RESULTS AND DISCUSSION

3.1 Changes in Surficial Shear Strength during Melt-freeze Cycles

Our results show significant changes in wet snow shear strength over the course of four melt freeze cycles (Figure 4). The maximum strength recorded (mean value per test) was T_{∞} = 1273 pa (limit of instrument used) and the minimum force recorded was T_{∞} = 201 pa. The rate of weakening and strengthening varied by day though similarities clearly exist. In particular, the data shows rapid weakening of the surficial layers of the snowpack through time. In 72% of the hourly tests, changes in shear strength were

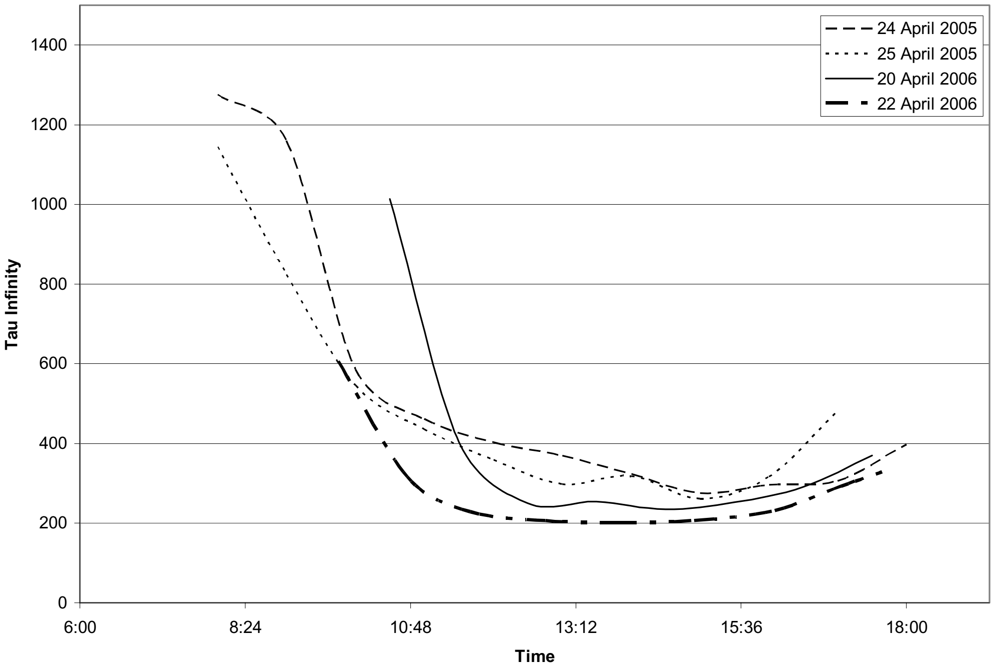

Figure 4. Graphical depiction of the mean hourly shear strength over time on Field Days 1-4 (the lines presented span a scatterplot of the data). No avalanche activity was noted on Field Days 1 and 2. Minor avalanche activity was noted around 13:40 on Field Day 3. Widespread wet loose snow avalanche activity was noted between 11:40 and 15:45 on Field Day 4. Note that in all cases there is a dramatic initial decrease in shear strength. However, our observations suggest that the shear strength might have to decrease below a critical level (perhaps in the region of T_∞ = 250 Pa) for the onset of wet loose snow avalanching (in the snowpacks we were measuring). Slope angles vary by up to 7 degrees between study sites.

statistically significant. In some cases strength drops by over 50% in less than 30 min. Unfortunately, our methods did not allow us to fully follow the strengthening trend of the cycle. In the morning we could insert frames without compression of the underlying stratigraphy, but in the evening pressure on surficial ice layers compressed the weaker underlying snow. We could, however, track the initial strengthening trend on all four field days. The minimum strength recorded on the strengthening trend was T_∞ = 336 Pa and the maximum was T_∞ = 397 Pa.

On 20 April 2006, shear strength data was collected almost continuously throughout the melt-freeze cycle and significant losses and gains in shear strength occurred in as little as 20 minutes (Figure 5). Shear strength decreased continuously until 12:11 (sub-transect 6). At this point no significant changes in strength were noted until 16:14 (sub-transect 12) when obvious strengthening began.

On 22 April 2006, significant losses in strength were noted between 10:00 and 11:00, and 11:00 and 12:00. Changes in shear strength were not significant between 12:00 and 16:00. At 15:54 there was a down-slope, cooling wind and a noticeable change in sun angle. At 16:04 surficial snow began to refreeze and significant gains in strength were noted between 16:00 and 17:00, and 17:00 and 18:00 (Figure 6).

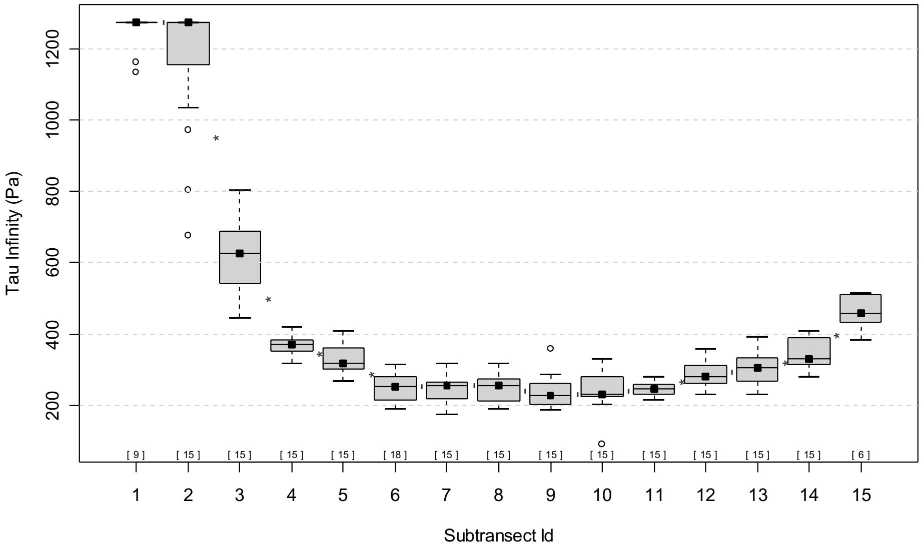

Figure 5. 20 April 2006. Shear frame data was collected almost continuously throughout the melt-freeze cycle. Testing began at 09:45 and continued until 18:11. The minimum air temperature for the day was -1°C and the maximum air temperature was 14.1°C. The groupings depicted represent the mean shear strength across the slope during 31 minute intervals (average time to complete each sub-transect). Statistically significant changes between sets of measurements (Mann Whitney $p < 0.05$) are denoted by an "*****", changes that are not significant are denoted by a "**-**". The line represents the median, the box encompasses the 25th to 75th percentile of measurements and the whiskers are 1.5 times the interquartile range. White circles denote outliers. Bracketed numbers below each group are the number of individual shear frames in the sample

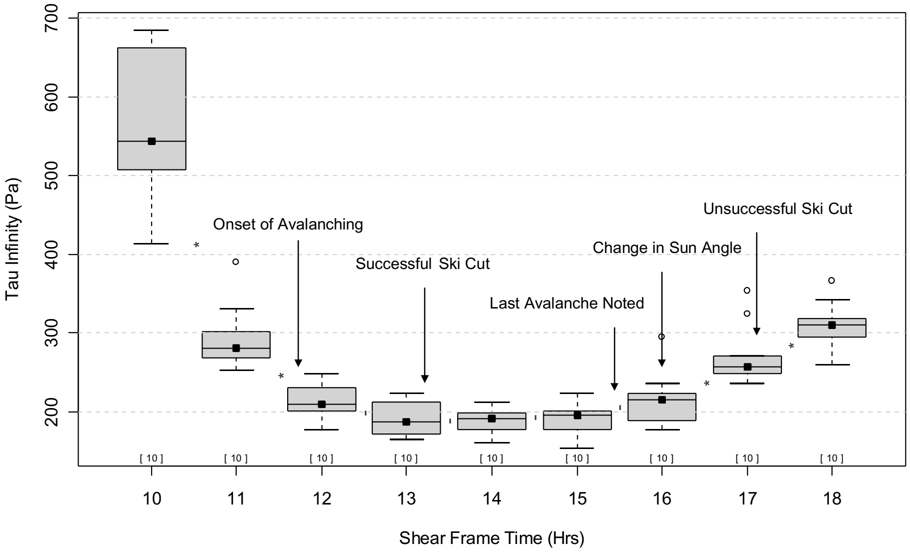

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Figure 6. 22 April 2006. Testing began at 09:45 and continued on the hour until 17:47. The minimum air temperature was -0.4°C and the maximum air temperature was 15.2°C. Widespread 'roller-balls' began at 10:45. Avalanche activity began at 11:40; the last avalanche noted was at 15:45. Statistically significant changes between sets of measurements (Mann Whitney $p < 0.05$) are denoted by an "*****", changes that are not significant are denoted by a "**-**". The line represents the median, the box encompasses the 25th to 75th percentile of measurements and the whiskers are 1.5 times the interquartile range. White circles denote outliers.

3.2 Surficial Shear Strength in relation to Avalanche Activity

No avalanche activity was noted in the vicinity of the study site on Field Days 1 and 2. On Field Day 3 (20 April 2006) 'roller-ball' activity was noted at 11:20 and two minor sluffs occurred around 13:40. The mean shear strength of the study slope was 254 Pa at 13:30 and dropped to 237Pa by 14:30; there was no significance in this change in strength. Widespread surficial wet loose snow avalanching occurred on Field Day 4 (22 April 2006). In the morning there was evidence of previous 'roller-ball' activity, but no avalanche debris was noted. Mean study slope shear strength dropped from 316 Pa at 10:45 to 229 Pa at 11:45. 'Roller-ball' activity was widespread at 10:45 and several avalanches (WL-N-D1/D2) were noted in and around the study site between 11:40 and 15:45. A ski cut within the study slope produced a small avalanche at 13:25 (WL-AS-D1). There was no significant change in strength until early evening when the mean strength increased from 232 Pa at 1605 to 293 Pa at 17:03. A ski cut on the study slope at 17:00 produced no results (Figure 6).

3.3 Surficial Shear Strength in relation to Snow Hardness

The weakening and subsequent strengthening of wet snow during melt-freeze cycles occur as two independent trends. We were able to document the full extent of the weakening trend on 20 April 2006 and have focused our analysis on it. The strengthening trend has not been considered. During the rapid weakening of surficial snow on 20 April, 2006 the snow softened considerably at a micro-structural scale. Simple linear regression revealed that 57% to 71% of the variation in shear strength could be explained through changes in the micro-structural hardness of snow located at the base of the shear frame (Figure 7). This finding suggests that, despite differing methods of observation, both types of observations are measuring related phenomenon. Further investigations need to identify how the SMP signal changes in relation to the micro-structural weakening and strengthening of wet snow.

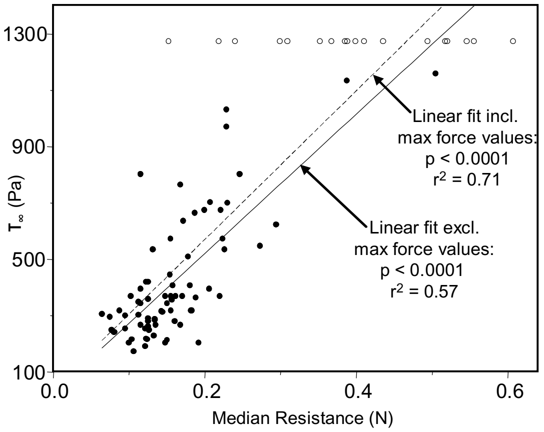

Figure 7. Association between shear strength and microstructural hardness of snow at the shear frame base. Simple linear regression reveals a significant ($p < 0.0001$) positive correlation. Microstructural hardness accounts for 71% or 57% of the shear strength variation, depending on whether the maximum shear strength values (hollow circles) are included in the regression model (dotted line) or not (solid line). A 5kg force gauge was used, the maximum strength values depicted are an unknown strength equal to, or of a higher value than the range of the gauge.

4. CONCLUSIONS

Changes in the shear strength of surficial wet snow can be documented using shear frames. The data presented shows that the shear strength of wet snow can change dramatically in as little as 20 minutes, suggesting that operationally, avalanche workers may need to monitor slopes in fifteen minute intervals. The slopes we investigated became unstable when the mean shear strength dropped below 250 Pa and showed significant strengthening when the mean shear strength increased to around 300 Pa. Significant positive correlations exist between shear strength and the micro-structural hardness of snow located at the base of the shear frame, suggesting that the shear strength of wet snow is related to its micro-structural hardness. Our data is limited, but it indicates that with additional research we can make strides toward a better understanding of wet snow processes, and the development of operational tools that will assist in the mitigation and prediction of wet snow avalanches.

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