PREDICTING WET SNOW AVALANCHES AT THE ARAPAHOE BASIN SKI AREA

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ABSTRACT: Premature terrain closures, due to wet snow instability, lead to unhappy skiers during the annual snowmelt period. Furthermore, wet snow avalanches are destructive and remove the snowpack from ski runs. Previous research shows that wetting fronts which infiltrate a continental snowpack for the first time result in a sudden loss of snowpack strength. Therefore, wetting fronts that penetrate the ski-compacted slab and underlying depth hoar are central to predicting wet snow instability. To investigate this concept, wetting front characteristics have been measured with dielectric probes. The study site is situated on a north aspect in an avalanche start zone that also serves as a ski run. Integrating these measurements with standard weather and snowpack observations indicate that the most important forecast parameters are: (1) Air temperature (2) Crack propagation pathways (3) Depth hoar texture (4) Ice structure characteristics (5) Radiation and (6) Snowpack temperature. For example, the first wetting fronts that fully penetrate the snowpack require air temperatures in excess of 15° C, total daily solar radiation near 32 MJ and a snowpack at 0° Celsius. Also, ice bodies that signify vertical migration of meltwater over broad areas are an important indicator of potential wet slab instability. Now forecasters supplement conventional avalanche forecasting skills with analysis of wetting front characteristics that indicate an impending loss of snowpack strength. Thus, steep terrain closures are based, in part, on predicting the concentration and timing of diurnal wetting fronts which rapidly infiltrate the ski-compacted slab and underlying depth hoar.

Key Words: wet snow instability, wetting fronts, crack propagation pathways

1. INTRODUCTION

Avalanche forecasting and risk management procedures are essential for successful ski area operations. At a ski area, forecasting procedures are notably different when compared to regional backcountry and transportation corridor forecast centers (Uehland, 1996). For instance, during early season conditions ski area customers are accustomed to brief closures while active avalanche control measures are applied. Terrain management during snowmelt is based on a different strategy. Rather than the application of explosives as a primary tool for testing and releasing avalanches, risk management relies exclusively on terrain closures.

A prescient submission to the ISSW (Fierz and Föhn, 1994) identified a poor understanding of wet snow instability and accurately described the need for “long term observation of the water content of the snowpack.” A later investigation (Carran et al, 2000) suggested a need to understand water infiltration as a “key to improving prediction of snow stability during rain and melt.”

Furthermore, previous studies have attempted to establish forecast parameters to assist ski area workers with wet snow stability assessment (Romig et al, 2004), though a study of shear and stability tests concluded that “no established procedure exists to assess wet snow stability” (Techel and Pielmeier, 2009). Nevertheless, earlier papers (Techel, et al. 2008), (Hartman and Borgeson, 2008), identified wetting fronts at low concentrations as a primary factor influencing wet snow instability.

Our investigation is ongoing and continues to diversify. After six years of study at the Arapahoe Basin Ski Area in Colorado, we have begun to understand the intricacies’ of wet snow instability. Our findings point toward the need to observe a number of key parameters. Today, forecasters supplement conventional avalanche forecasting skills with analysis of wetting front characteristics that indicate an impending loss of snowpack strength and increased fracture propensity. This paper builds

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upon our earlier research and summarizes our efforts to help ski area avalanche forecasters predict wet snow instability.

2. DATA

A series of remote weather stations (hereafter ABP, ABS, and ABW) are used at the ski area to collect daily weather and snow data (Hartman and Borgeson, 2008). A number of sensors target data specific to understanding meltwater production and the ensuing wetting fronts. For instance, snow cover energy balance research (Marks and Dozier, 1992) concluded that most snowmelt is a result of radiation, and more specifically “during melt season, solar radiation predominates.”

Consequently, during the 2009-2010 ski season, an all-wave radiation sensor was added to the ABP study site. Additionally, a simple change in programming allowed avalanche forecasters to monitor net incoming and net outgoing all-wave radiation.

Based on the authors’ earlier studies, avalanche forecasters track three important trends by remote sensing. These are (1) Air temperature (2) Snowpack temperature and (3) Radiation. Moreover, field observations of (4) Ice structure characteristics (5) Depth hoar texture and (6) Crack propagation pathways help forecasters confirm the timing and characteristics of diurnal wetting fronts. Monitoring stream discharge rates and increases in irreducible water content using in-situ dielectric probes also confirm the presence of diurnal wetting fronts.

3. DISCUSSION

3.1 *Forecasting procedures*

Daily avalanche control procedures are based on the program goal stated in the Arapahoe Basin Ski Area Avalanche Control Manual. It is “for avalanche control personnel to be informed when making decisions about the likelihood of avalanches when opening and closing ski runs in avalanche areas.” To this end avalanche forecasters collect and inspect data from the remote sites beginning at 0500 h each morning. They use this information and other observations to formulate a daily ski area specific weather forecast.

An avalanche hazard forecast for the ski area is produced each morning. This encompasses open ski terrain and terrain slated to open or close in the near term. These forecasts utilize a five level hazard scale specifically written for the ski area. It starts at NONE and progresses through LOW, MODERATE, HIGH, and EXTREME. Each level notes probable avalanche size and triggering sensitivity. Operational impacts are outlined as well. For instance, during periods of HIGH hazard the ski area will experience: “Temporary closure of lifts and trails. Active control measures include hand charges and avalauncher rounds.”

3.2 *Wet snow stability forecasting*

Wet snow avalanches can involve the entire seasonal snowpack or at least leave the surface unsuitable for skiing. Although hazard ratings above LOW call for the use of explosives, now risk management procedures during periods of wet snow instability are limited to terrain closures. Avalanche forecasters and snow safety workers want to avoid a repeat of a destructive avalanche triggered with explosives during snowmelt at the ski area in May 2006.

To avoid dissatisfied customers and a decrease in revenue, the ski area strives to close steep terrain based on standard weather and snowpack observations supplemented by the parameters identified earlier. Customers generally understand the efforts of active avalanche control during early season and mid-winter. Terrain closures due to wet snow instability, though, can be misunderstood since it may appear that the ski area is closing the terrain without reason. A further lack of visual or audible active avalanche control measures may erroneously confirm this misconception.

Following six seasons of study, a wet snow observational scheme has been developed. Results presented at the ISSW in Whistler BC (Hartman and Borgeson, 2008) illustrated the correlations between air and snow temperature and changes in irreducible water content in depth hoar. Qualitative and quantitative analysis of all-wave radiation and daily solar radiation flux revealed an additional correlation to a spike in irreducible water content in depth hoar. In the end we have identified the following meteorological indices that tell the avalanche forecaster to suspect increased chances of melt-water penetration of the snowpack.

The key thresholds for these indices are: (1) 10 MJ of incoming all-wave radiation as measured at ABP (2) Air temperature approaching 10° C at all remote sites (3) Relative humidity in the 20-30 % range (4) Hourly average mid-day wind speeds in the 10-15 m/s range at ABP and (5) Daily solar radiation flux approaching 30 MJ as measured at ABW.

3.3 *Wet snow observations*

Snow melt at the Arapahoe Basin Ski Areas has proved remarkably similar from year to year. Due to its location and elevation along the western edge of the continental divide, the ski area typically enjoys winter-like conditions into April. However exceptions have been noted. For instance, dielectric probes measured wetting front penetration of the deep snowpack at mid-mountain on March 2, 2009.

Nonetheless, forecasters begin systematic observations of snowpack characteristics when air temperatures approach 10° Celsius. In addition to temperature gradient observations, forecasters seek information about crack propagation pathways, depth hoar texture and ice structure characteristics. Also, ski patrollers look for typical signs of wet snow instability that include: surface softening, deep penetration, collapsing, meltwater, and wet snow movement like roller balls and point releases.

Regular data pits as well as hasty pits give avalanche forecasters an empirical understanding of ice structure characteristics that indicate the location of wetting fronts in the snowpack. Also, as noted in 2008, ice structures typical of preferential flow increase in frequency and vertical orientation as snow temperature approaches 0° Celsius. Rarely has this type of ice structure been observed in depth hoar.

Persistent depth hoar and layers of faceted crystals are structures commonly encountered in continental snowpacks. The consistent basal snow stratigraphy pattern, noted by Hartman, (2004) appears to be a contributing factor to wet snow instability. Our earlier research indicated that the probability of wet snow avalanching increased when coarse grained depth hoar dominated snow pack height. Continuing observations have not indicated otherwise.

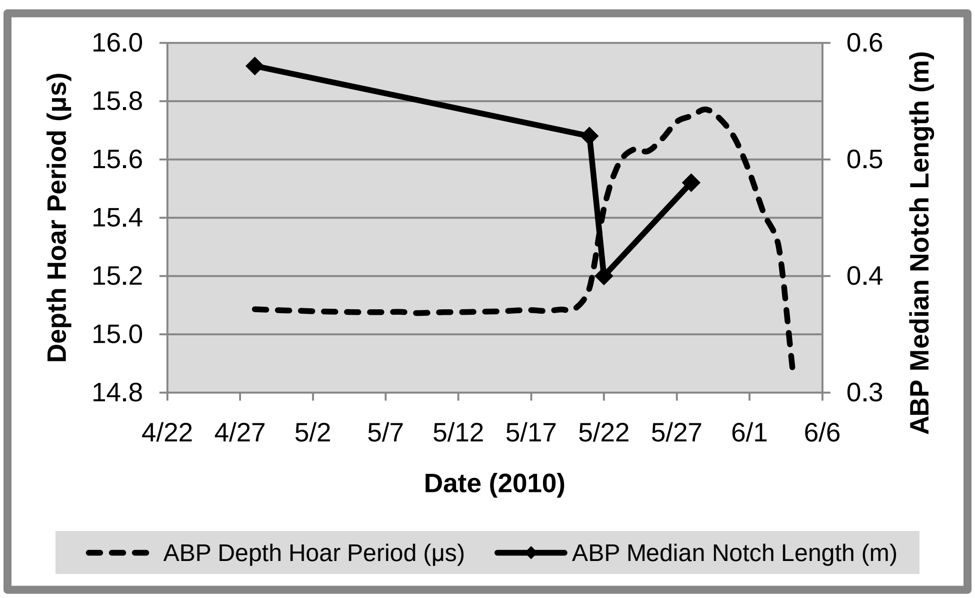

Figure 1: The trace scaled on the left axis shows the hourly irreducible water content in depth hoar underlying the ski compaction. The trace scaled on the right axis shows the median notch length, prior to midday, in the same layer of depth hoar.

In addition to the relative thickness of depth hoar, observations into crack propagation during snowmelt provided clues about the behavior of wet snow instability. Unfortunately testing deep instabilities in wet snow has been problematic. While the earlier citation was succinct, a more in depth conclusion from Techel and Pielmeir (2009) notes that "[s]tability tests (RB, ST, ECT, and ECTmod) may provide additional information, yet there is still much uncertainty in interpreting the test results in wet snow." This paper additionally indicates the data set for test results "should be expanded primarily with unstable profiles."

During the 2010 snowmelt period, 97 PST tests (Gautier and Jamieson, 2008) were conducted in a layer of depth hoar underlying the ski compacted slab at the ABP study site. The layer of depth hoar was approximately 15 cm thick and was comprised of 6 mm cup crystals. Concurrently, 89 PST tests targeted the same layer of depth hoar at a backcountry site with similar terrain characteristics 0.9 km beyond the ski area boundary. Sampling days were determined by weather and snowpack conditions which impel the annual spike in the irreducible volumetric liquid water content during snowmelt (Hartman and Borgeson, 2008). While sampling, at least 10 consecutive PST tests were recovered from each site by working across the fall line. Median notch lengths at both sites were studied through graphical analysis as well as non-parametric significance and equality of variances tests. In some instances PST tests were recorded using a high definition video camera.

Six important findings are: (1) At ABP, notch length reached a minimum coincident to the annual spike in irreducible water content in depth hoar (see Figure 1). (2) Terrain features at the backcountry location permitted test site selection based on slope angle. As snowmelt proceeded, slope angle was incrementally decreased each day. Subsequently, the kinetic friction angle of wet depth hoar was 22° ± 1° when crack propagation was scored END on May 27th. On this day the snowpack shed approximately 65 mm of water. (3) The distribution of crack propagation behavior was constrained in two directions. For example, at ABP 53% of crack propagation behavior was scored END (Gauther and Jamieson, 2008) whereas a new scoring criteria "BF", describing cracks diving to the ground, totaled 43 percent. At the backcountry site, only ratios differed. Here, 90% were scored END while 8% fell into the BF category. The remaining balances were classified as ARR or NR for no result.

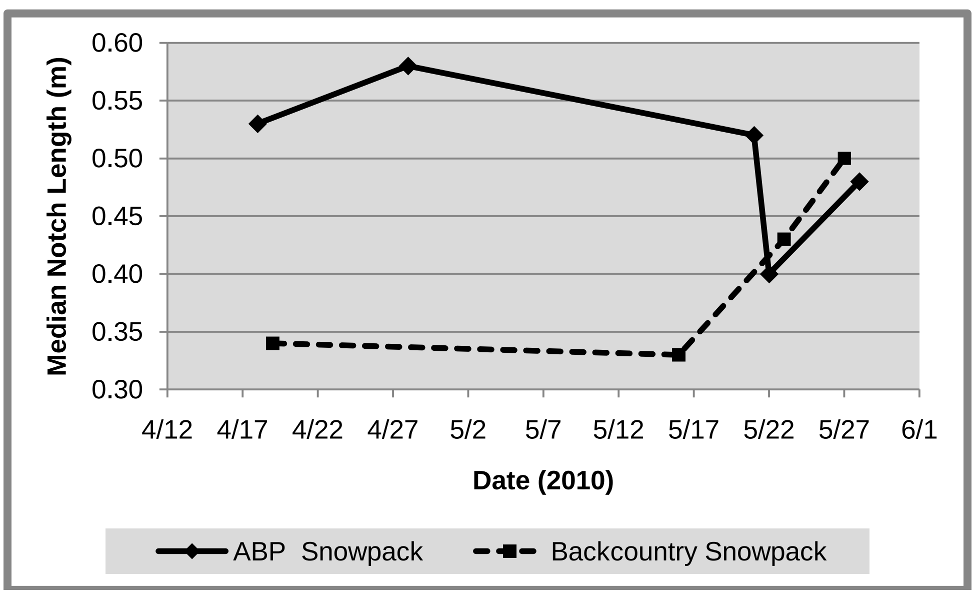

Figure 2: Median notch lengths, prior to midday, over time in depth hoar underlying ski compacted snow at ABP and within the natural snowpack adjacent to the Arapahoe Basin Ski Area.

(4) A crisp failure process in the depth hoar, best described as a “crack, collapse, slide” sequence, required a well defined propagation pathway bounded above and below by textually different and stiffer snow. As textural features and stiffness characteristics at the upper and lower boundaries began to wash away during snowmelt, the score BF became more likely and interrupted the “crack, collapse, slide” sequence. For example, 82% of crack propagations scored END at ABP resulted in a sliding block compared to 69% at the backcountry site. Conversely, if crack propagation direction was scored BF then the “slide” phase was absent approximately 8 of 10 times at both sites. (5) Notch length, within the same layer of depth hoar, was remarkably dissimilar when comparing the ski compacted slope to the backcountry snowpack (see Figure 2), though rapid change in notch length occurred simultaneous to the initial spike in the irreducible water content in both snowpacks. Following the initial spike in the irreducible water content, notch lengths increased. (6) The timing of PST tests seems to influence the results. Empirical findings indicate the greatest propensity for fracture occurred in the morning. Conversely, the kinetic friction angle decreased in the afternoon.

4. CONCLUSIONS

Personnel at the Arapahoe Basin Ski Area continue to investigate wet snow instability and strive to keep steep terrain open for its customers. Monitoring several key parameters has helped avalanche forecasters understand wetting fronts and anticipate a rapid loss of snowpack strength and an increase in fracture propensity during snow melt. With the exception of in-situ dielectric probes the key parameters are typically monitored at remote sensing locations at other ski areas.

We would like to see the results of wet snow instability investigations made more readily available. This would help foster an understanding of wet snow and provide ski area customers with added insight into risk management practices.

Field observations that investigate depth hoar, ice body and crack propagation pathway characteristics have also proven useful to avalanche forecasters. While the data set is young and small, (n = 186), the PST test seems to show a correlation between fracture propensity and the initial presence of diurnal wetting fronts. The dissimilarity between test results in the ski area and in the backcountry suggests that active avalanche control measures which seek to disrupt early season shear planes and propagation pathways have long lasting effect. During the 2010-2011 season further PST tests will target the effects of changing volumetric water content on notch length during the daily melt cycle.

Decisions to close steep terrain at the Arapahoe Basin Ski Area during snowmelt must incorporate a variety of factors. Aside from the input of avalanche forecasters, ski area management considers seasonal business strategies, historical perspectives, and the growing probability of localized climate change. It is the authors’ goal to clearly define key parameters that will make the job of forecasting wet snow instability easier.

In conclusion, the problem statement mentioned 6 years ago reads: Although rare, crack propagation or wet slab avalanches which involve the entire snowpack are most likely to occur at the onset of sustained snowmelt. Based on findings presented here, we fail to reject this statement.

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