The spatial variability of snow resistance on potential avalanche slopes
by Karl Wessel Birkeland

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Earth Sciences
Montana State University

Abstract:
Since snow avalanches are believed to release from zones of localized weakness, knowledge of snow strength patterns is important for determination of slope stability and for the application of effective avalanche control measures. No previous studies have mapped snow strength over an entire inclined snow slab. In this study, the spatial variability of snow resistance (an index of snow strength) and depth were measured and compared with terrain features on two inclined slopes in Montana during two winter field seasons. An instrument that indexes snow strength by measuring snow resistance was refined, allowing the strength of an entire snow slab to be characterized in a short time. Measurements of depth and resistance were taken at 1 m intervals across and down the slopes. The spatial pattern of trees appears to affect the pattern of snow depth at the first site, where a significant linear relationship was found between snow depth and average snow resistance during both years of study (p-values <1X10^-6). When data sets were reduced to lessen the effects of spatial autocorrelation, the relationship between snow depth and average resistance continued to be significant (p-values < 7 X 10^-3). These results suggest that localized snow depth variations may be important in snow strength genesis. Although a linear relationship existed at that site, low r values for the two years (r^2 < 0.357) indicate additional factors may be critically relevant. A second site with greater complexity of terrain features and less localized wind drifting did not show a linear relationship between depth and average resistance. Complicated patterns of resistance at that site demonstrate that many factors contribute to snow resistance. In particular, the snow over rocks was found to have significantly weaker resistance than adjacent areas which were not over rocks (p-value < 1 X 10-6). Results may provide predictive information of weak zone locations in snow slabs, which would improve avalanche forecasting and control techniques.

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APPROVAL

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This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

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ABSTRACT

Since snow avalanches are believed to release from zones of localized weakness, knowledge of snow strength patterns is important for determination of slope stability and for the application of effective avalanche control measures. No previous studies have mapped snow strength over an entire inclined snow slab. In this study, the spatial variability of snow resistance (an index of snow strength) and depth were measured and compared with terrain features on two inclined slopes in Montana during two winter field seasons. An instrument that indexes snow strength by measuring snow resistance was refined, allowing the strength of an entire snow slab to be characterized in a short time. Measurements of depth and resistance were taken at 1 m intervals across and down the slopes. The spatial pattern of trees appears to affect the pattern of snow depth at the first site, where a significant linear relationship was found between snow depth and average snow resistance during both years of study (p-values $< 1 \times 10^{-6}$). When data sets were reduced to lessen the effects of spatial autocorrelation, the relationship between snow depth and average resistance continued to be significant (p-values $< 7 \times 10^{-3}$). These results suggest that localized snow depth variations may be important in snow strength genesis. Although a linear relationship existed at that site, low r^2 values for the two years ($r^2 < 0.357$) indicate additional factors may be critically relevant. A second site with greater complexity of terrain features and less localized wind drifting did not show a linear relationship between depth and average resistance. Complicated patterns of resistance at that site demonstrate that many factors contribute to snow resistance. In particular, the snow over rocks was found to have significantly weaker resistance than adjacent areas which were not over rocks (p-value $< 1 \times 10^{-6}$). Results may provide predictive information of weak zone locations in snow slabs, which would improve avalanche forecasting and control techniques.

CHAPTER 1

INTRODUCTION

The purpose of the study was to identify and quantify general strength characteristics of potential avalanche slabs and to compare areas of relative strength or weakness with geographic features. Researchers have proposed that localized weak areas (described as having weak shear strength) within a slab fail initially, triggering full slab failure and resulting in an avalanche (Gubler and Armstrong, 1983; Smith and Sommerfeld, 1985; Gubler and Bader, 1989). If failure of such weak zones is a prerequisite for avalanche initiation, then locating these areas becomes critical. Patterns of snow resistance (an index of snow strength) within potential avalanche slabs in continental climates may be related to vegetation and rock outcrop patterns, and with wind patterns related to both ridges and trees. The objectives of this study were: 1) to determine if snow resistance variations across a slab can be identified and measured, and 2) to compare geographic features (specifically, rocks and trees) of the study area with measured intervals of snow resistance of the entire inclined snow slab. Characterization of potential avalanche slabs using resistance may eventually lead to increased knowledge of the distribution of weak areas on a slope. Knowing weak zone distribution would, in turn, aid in avalanche forecasting and control. The contribution of weak zones to avalanche initiation is important based on what is known about snow failure under differing strain rates. Snow strength decreases with increasing strain rate (Brown, 1977; Narita, 1980). Strain rates induced by new snowfall, a skier, or an explosive have been shown to be relatively slow when compared to rapid strain rate increases applied by fracture propagation from a localized failure in the snowpack (Gubler and Armstrong, 1983). Typical strain rates in snowcover resulting from snowfall have orders of magnitude of 10^{-6}/second and rates associated with explosives are on the order of 10^{-3}/second, while strain rates resulting from fracture propagation approach 1/second (Gubler and Armstrong, 1983). Thus, certain areas of a slope that would fail in response to strain rates caused by fracture propagation initiating at a localized weak area may not fail under strain rates applied by the traditional avalanche control measures of using explosives or ski cutting.

The above results are important in terms of avalanche control work. Use of control techniques may not be effective unless applied to weak areas of the snow. Placing explosives in locally stronger areas may give a false sense of security about slope stability. Improper placement of explosives has been advanced as a major cause of "post-control release" avalanches (avalanches which run minutes to hours after avalanche control measures have been applied) (Williams, 1978). Since currently there is little available data, and therefore no method for predicting exactly where a weak area may occur, aerial detonation of explosives has been promoted for use in avalanche control. Aerial blasts impact the largest possible area of a snowpack, thus increasing the chance of impacting a weak area and causing initial failure to occur (Gubler, 1977). Field observations indicate that aerial explosions do cause a greater percentage of snow from avalanche starting zones to release than do in-snow blasts on adjacent slopes, presumably because the aerial blasts are impacting more weak areas of the snowpack (Juergens, 1984). Further, the use of aerial explosions for avalanche control in Switzerland has reduced the incidence of post-control release avalanches (Gubler and Armstrong, 1983). Using aerial explosives to impact every region of every starting zone, however, is neither feasible nor economic. The present study may provide important information about the location of varying strength patterns in inclined snow slabs, eventually aiding in the prediction of weak zone locations and the improvement of avalanche forecasting and control techniques.

Previous Studies

Previous studies have verified the existence of weak zones in snowpacks. Acoustic emissions data have demonstrated localized failure, and measurements of strain rates in snowcover have provided convincing evidence for weak zone failure being the mechanism for avalanche initiation. In addition, in-situ field measurements of snow shear strength on avalanche crowns and multiple Rutschblock tests (Föhn, 1987) have shown snowpack strength variability.

As a snowpack fails, certain distinguishable noise emissions can be detected with geophones. Studies utilizing these acoustic emissions have been done in various regions, including Montana, Colorado, and Switzerland. In a review of these investigations, Sommerfeld and Gubler (1983) concluded that the radii of areas of initial dislocation (or failure) were 0.l to 1.0 m. This indicated that small (0.03 to 3.1 m^2) weak areas were where initial failure appeared to be taking place.

Recent measurements of strain rates in snowcover have provided additional evidence for weak zone failure as the only plausible mechanism for avalanche release. Field observations indicate that quick brittle failure is the predominant mechanism during avalanche release (Sommerfeld, 1969). However, localized strain rates in natural inclined snow covers rarely exceed 10^{-4}/second (Gubler and Bader, 1989), and strain rates in excess of 10^{-4}/second are required for brittle failure (Smith and Sommerfeld, 1985). Thus, during the initiation of a natural avalanche small weak areas must be experiencing ductile failure (which takes place at strain rates less than 10^{-4}/second (Narita, 1980)). As that ductile failure spreads, the strain rates at the tip of the fracture are increased until they exceed 10^{-4}/second, sending the snow slab into the observed widespread brittle failure and resulting in an avalanche (Gubler and Bader, 1989).

The first attempts at in-situ field measurement of localized strength variability in snow slabs were made in New Zealand by Conway and Abrahamson (1984a, 1988) utilizing a shear strength test. Shear strength, the resistance of the snow slab to being pulled off its bed surface, is measured by isolating a column of snow, inserting a shear frame, and pulling on the frame with a force gauge. With this test the above authors measured strength variability across crown faces of recently avalanched slopes and found weaker and stronger areas. Subsequent work suggested that a "deficit", or weak area along a crown of a recent avalanche can vary in length from 2.9 to 7 m (Conway and Abrahamson, 1988). Research by Föhn (1988) conducted in Switzerland using the same strength test also indicated snow strength variability, although the fluctuations measured were two to four times smaller than those reported previously for similar sized-slopes. Föhn (1988) concluded that reduced fluctuations might be due to climatological factors (the stronger winds at the New Zealand site may have increased variability) or to measurement technique (Föhn modified the shear frame test to eliminate bending modes of failure and threw out outliers in the data). In conclusion, Föhn (1988) hypothesized that larger and/or more numerous weak areas were necessary for avalanche initiation than had been previously proposed.

Wind deposition has been proposed as a mechanism which is responsible for weak zone development. Conway and Abrahamson (1984a) hypothesized that variations in depth due to patterns of wind deposition may be a primary factor in shear strength variability along the crown of recently avalanched slopes, and suggested such variations might change weak layer thickness and gravitational forces along a slope. Föhn (1988) found that areas characterized by low shear strength values had 30 to 40% lower slab depths than adjacent stronger areas.

Weak zone measurements in previous studies (Conway and Abrahamson, 1984a, 1988; Föhn, 1988) were performed using a shear frame test. Conway and Abrahamson (1984a) took an average of 12 measurements at each site, Föhn (1988) took between 20 and 39 measurements per site, and data were gathered at the crown wall and flanks of the avalanched slopes. Shear tests are time consuming, allowing relatively few measurements to be taken at each site, and can be susceptible to human error (Perla, 1983). Concern also arises because snow at the crown of a recently avalanched slope is disturbed by the avalanche, and the resultant metamorphism may affect the measurements taken. Further, no data were collected on potentially weaker areas that may have existed within the slab before avalanche initiation.

In an attempt to collect data over an entire undisturbed slab, Föhn (1988) utilized over 100 Swiss soldiers to execute Rutschblocks (a test utilizing a large shear column which is loaded by a skier (Föhn, 1987)) across and down an entire slope. Some strength variability was demonstrated in slabs, however these tests may have been prone to human error since the large number of people taking part in the test may have made consistency between measurements difficult. Further, each test required an area of about 3 m^2, and tests were made 10 to 15 meters apart. Distances between measurements may have been too large to delineate small-scale strength differences in the snowpack. Testing the entire snow slab with many closely-spaced measurements would be more beneficial.

While the existence of weaker areas of the snowpack has been substantiated, and some measurements made of their length along the crowns of recently avalanched slopes, little data have been gathered pertaining to their cause or their spatial variability within potential avalanche slopes. Conway and Abrahamson (1984a) hypothesized that snow strength variations might be caused by wind deposition patterns of snow. Their study was conducted on a glacier and wind effects were a likely contributor to weak zone formation because the surface on which the snow was deposited was relatively homogeneous. Important potential variables for weak area formation on more heterogeneous surfaces, such as the effects of rocks and vegetation, were not addressed. Personal observations while working as a ski patroller, and the observations of others (Brown, pers. comm., 1990; Custer, pers. comm., 1990; Dixon, pers. comm., 1990; Elliot, pers. comm., 1990), indicate regions around trees and rock are often weaker than surrounding areas, and rock and trees have been loosely tied to areas of stress concentrations in snow (Schaerer, 1981). One might surmise that geographic features such as rocks and trees might affect weak zone patterns, but this has yet to be tested.

Snow studies in Montana in the late 1960's and early 1970's correlated variability in resistance (a snow strength index) of snowpack to location of early season snow using sample intervals of 15 m or more (C.C. Bradley, pers. comm., 1988). Areas retaining early season snowcover (i.e., north-facing slopes and areas under trees) were found to be more susceptible to basal weakness due to increased temperature gradient metamorphism. To date, there are no other studies correlating specific snow characteristics to geographic features.

Although studies indicate that strength variability does exist in snowpack, and several lines of evidence indicate that weak zones within snow slabs are critical for avalanche initiation, nothing is known about the spatial distribution of weak zones on a slope, or what might be influencing the formation of such weaker and stronger areas within a snow slab. The objectives of this study are to characterize the strength of an entire inclined snow slab, and to compare those strength patterns with geographic features at the site. An analysis of snow strength patterns may provide information on weak zone location and genesis.

CHAPTER 2

FIELD AREA

Two sites near Bozeman, Montana, and in close proximity to Bridger Bowl Ski Area, were chosen for study. Average annual snowfall at Bridger Bowl Ski Area (located 19 km northeast of Bozeman (Figure 1)) is approximately 675 cm. Data indicate that Bridger Bowl ranked fourth amongst United States ski areas in terms of avalanche activity in 1988-89 (U.S. Forest Service, 1989). As defined by Haas and White (1975), southwest Montana is located in the Intermountain or Middle Alpine avalanche region of the United States. This region is characterized by fairly substantial winter precipitation, low winter temperatures, varying winds, dry snow, and a changeable snowpack depending on the given winter. Snow covers vary from shallow, unstable snowpacks with depth hoar formation and climax avalanches to more stable snowpacks with extensive surface avalanches.

Air temperature, precipitation, and snowfall data, collected at a nearby National Oceanic and Atmospheric Administration (NOAA) weather station for the two seasons studied, indicate two contrasting winter years (Tables 1, 2 and 3). In 1988-89 the season was characterized by above average (106% of normal) total precipitation, with above normal amounts in November, February and March, and below normal amounts in December and January. Perhaps the most significant weather event of the season occurred in February, when a large arctic air mass moved into the region for two weeks. Extremely low temperatures from this air mass were reflected in a -12.4^0 C average temperature for the month (7.8^0 C below normal). Besides that event, temperatures were