OBSERVATIONS RELATING TO WET SNOW STABILITY

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ABSTRACT

Observations relating to wet snow avalanches in a low-elevation, maritime climate are discussed. The effects of crystal structure, water drainage, and lubricated layers on snow stability are considered.

The strength of freshly deposited snow often changes rapidly with warming or rainfall. Rather than measuring the strength at a particular time, it is more important to determine how the strength would change during a forecasted weather event. With warming or rain, snow consisting of intricately shaped crystals weakens and avalanches much more rapidly than snow containing more rounded crystal types.

The movement of liquid water through snow is influenced by the structure of the snowpack. Coarse-grained snow allows water to drain easily and makes for a relatively stable snowpack, while fine-grained snow inhibits drainage. On numerous occasions, saturated layers were observed at different depths within snowpacks. The strength of these layers was usually stronger than adjacent layers and avalanches did not release at the saturated layers, but rather within layers above or below them.

INTRODUCTION

To be effective, avalanche control must be performed when the snow is sufficiently unstable so that it can be released with explosives or by ski-testing and yet before avalanches occur naturally while the highway is open to traffic. This time interval is often very short but needs to be better defined in order to know when to control.

In this paper, we document some observations from Snoqualmie and Chinook Passes in Washington State. Snow temperatures at Snoqualmie Pass, 915 m (3,000'), are often close to $0^{o}C$ and midwinter rain is common. Rain falling on significant amounts of new snow frequently causes avalanches which threaten Interstate 90. The Chinook Pass highway, 1,658 m (5,440'), is closed in the winter. Snow clearing operations and avalanche control do not begin until mid April. New snowfalls into June are common while

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rain is rare. The avalanche paths above the highway (U.S. 410) are generally of southerly aspect, and most avalanches release after snow is warmed by solar radiation.

Wet snow avalanches are usually predicted by monitoring changes of weather (Perla and Martinelli, 1976). In a low-elevation maritime climate, we have found that atmospheric warm-ups and rain directly influence snow stability. We expected that the multitude of variations in snow crystal type and structure would complicate simple temperature based forecasting, and that both snow and weather conditions would vary with spatial location as well as with time. Measurements at the starting zones would be likely to yield the most useful information.

We had previously thought that wet snow avalanching occurred when liquid water had penetrated the snow and lubricated a sliding surface. However, early observations using dye to trace water movement showed that some avalanches occurred long before water had penetrated very deeply into the snowpack.

METHODS

Measurements of Weather

Weather parameters were measured hourly at different locations using sensors connected to data loggers. Air temperatures were monitored at five locations: the pass study plot, 915 m (3,000'), the gun-tower near the top of the Summit ski area, 1,160 m (3,800'), Alpental base, 975 m (3,200') the top of chair 16 at Alpental, 1,310 m (4,300'), and the top of chair 17, 1,645 m (5,400'), Wind speed and direction were measured at the top of Denny Mountain, 1,685 m (5,520'), and also at the gun-tower at the Summit ski area. Precipitation was measured at the Pass and at Alpental base using a heated tipping-bucket rain gauge. At any time we could graph past and present information as a time-series using a personal computer at the avalanche office.

Measurements of Snow Properties

(a) Snow structure and stratigraphy were measured in accordance with procedures outlined in UNESCO/IAHS/WMO (1970). Measurements from snow pits were made at various locations before, during, and after storms, and also during periods of melting. In experiments designed to simulate rain on snow, we made measurements before and after distributing water using a garden sprinkler. The rate of water distribution from a sprinkler exceeded that from natural rain.

(b) We spread a water soluble dye on the surface to trace the movement and distribution of liquid water through the snowpack. Initially Rhodamine B was used, but this is toxic, and we later used Malachite Green. The presence of dye in the water will depress the freezing point of ice and may also absorb solar radiation and enhance melting. However, we did not notice any differences in drainage patterns when comparing situations where dye had been introduced with those which occurred naturally.

(c) A particular effort was made to measure liquid water content of the snow. Wet snow is a mixture of ice, air, and water. The high frequency dielectric constant of ice at $0^{\circ}C$ is about 3.1 which is substantially different from that of water (88.0) but not too different from air (1.0). The large difference between the constants of the components makes dielectric techniques particularly suitable for determining the liquid water content of the snow (Colbeck, 1980a; Denoth et al., 1984).

We built a device to measure dielectric properties in the frequency range 400-500 MHz (Conway, 1988). The instrument requires further calibration to yield a measure of moisture content. We also used a sling centrifuge (Wilbour, 1986) but changed the screen size from 14 to 80 mesh/inch screen to restrict contamination of the extracted water by fine-grained snow. For a qualitative estimate of water content, we used the squeeze test outlined in UNESCO/IAHS/WMO (1970).

(d) Monitoring snow temperatures at different depths defines the time at which liquid water could first exist within the snowpack (the temperature would have to reach $0^{\circ}C$). We used four thermistors set in voltage divider circuits to measure snow temperatures. The thermistors were buried at different depths in the study plot and connected to a data logger which could be programmed to take measurements at any desired time interval. We encountered several problems:

- Setting the probes disturbed the snow. We usually inserted the probes into the side of a pit which we then backfilled. Other times, new snow was allowed to accumulate around the probes which were fixed to a stake, but the probes affected settlement of the snow. We suspect that any disturbances would change the drainage patterns.

- Solar radiation, which penetrated the snow, often heated the probes above the temperature of the snow and also melted the surrounding snow. To minimize this, we covered the probes with white tape, but this was only partly effective. In the future, we will wrap the probes with reflective mylar.

- During periods of snowfall, the depth of the sensors from the surface continually increased which made it difficult to locate the probes at all times. Further, temperatures varied across slopes as well as with depth, and an array of thermistors would yield a more representative profile than a single row buried at different depths.

CASE STUDIES

Below, we have outlined several case histories showing measurements of weather and snow parameters taken during the 1987-88 winter.

Case 1

At 11 a.m., January 9, snow profiles from Bald Knob and Airplane Curve showed 18 and 12 cm, respectively, of low density (100 kg/m^3), relatively cold (-2 to -3.5$^{\circ}C$) snow overlying harder layers. The surface layers were very soft and contained mainly large stellars and broken crystals. At this time, the snow responded poorly to ski-checking. The snow was relatively well bonded, and only a few small sluffs were released.

Snowfall continued through the morning and the air temperature at 1,645 m (5,400′) started to increase slowly at 1 p.m.. Four hours later, the temperature at 1,160 m (3,800′) increased rapidly (about 12^{o}C between 5 p.m. and 6 p.m.). Avalanche activity began immediately after the air temperature at the starting zones first reached freezing (at 6 p.m.).

Snow conditions at pass level, 915 m (3,000′), were similar, but the air temperature did not reach freezing until some time between 7 and 9 p.m.. Thermistors at 24 and 34 cm in the snowpack did not start to respond until 1 hour after the air warmed. The upper probe first reached freezing 4 hours after the air, and temperatures deeper in the snowpack increased more slowly. A profile at the pass study plot taken 3 hours after the air had first warmed to freezing showed that only the upper 5 cm of snow had reached 0^{o}C. Liquid water had not penetrated beyond that depth. Although conditions in the avalanche starting zones would have differed from those at the pass, it is unlikely that liquid water had penetrated more than a few centimeters at the time of avalanching.

<u>Case 2</u>

Air temperatures had been cold, but between midnight and 1 a.m. on January 14, precipitation increased (4 mm water equivalent/hr. at the pass), and the temperature at 1,645 m (5,400′) started to increase, reaching freezing between 2 and 3 a.m..

At 3.30 a.m., rain started at Bald Knob and explosives were used to release avalanches. Just prior to this, several small (Class 2) avalanches released naturally. A snow profile at Bald Knob at that time showed a thin freezing-rain crust overlying 54 cm of soft, low-density snow. The surface snow temperature was 0^{o}C, but temperatures deeper in the snowpack were colder (-1.6^{o}C at 5 cm and -3.0^{o}C at 30 cm). Liquid water had not penetrated far into the snowpack.

<u>Case 3</u>

Slab type conditions persisted at Chinook Pass for almost the entire month of April and early May. Sudden settling and "whumping" noises were frequent on approach routes and during safe skiing. These settlements were similar to those experienced in snowpacks containing depth hoar. The frequency of "noisy" snow to actual slab release was low. The slabs which released were commonly 0.2-1 m deep and most occurred at breakovers or in steep chutes. They were often triggered by small, wet loose slides which had been ski-released. Once released the avalanches moved fast and were very powerful. These conditions could have been serious had an unwary skier ventured into the middle of the deeper slabs.

One of these avalanches was skierreleased on April 19. The upper 25 cm of the snowpack consisted of coarse-grained (2-3 mm), wet snow with a density of 400 kg/m^3. A saturated layer existed between 25-26 cm. Under these conditions we expected rapid grain growth (Wakahama, 1968; Raymond and Tusima, 1979; Colbeck, 1986), but grains within this saturated layer did not coarsen over a period of weeks. The ice particles were rounded, small (<.1 mm) and very closely packed. The volume of water extracted with the sling centrifuge was about 26% and when exposed in a snowpit, water flowed freely from the layer. Beneath this slush layer, crystals were coarse-grained (2-3 mm) and rounded. Immediately beneath the slush, the large crystals were loose and cohesionless, but deeper in the pack, they were well bonded and pencil to knife hard. It seems likely that liquid water had seeped from the slush layer, lubricating and weakening the bonds below.

The sliding layer for the avalanche was the thin layer of cohesionless grains (rather than the more saturated layer above). Other profiles indicated that this stratigraphy was common during that period, and avalanches always failed in layers beneath the layer of highest water content. Similar conditions have been reported by Kattelmann (1984). It is clear that some measure of structure as well as liquid water content is required to estimate the strength of snow.

Case 4

New snow fell between May 16-19, and warming on May 17 caused the surface snow to settle and densify. In a 4hour period, the depth of new snow decreased by about half (7.5 to 4 cm), the density doubled (120 to 240 kg/m^3), and the snow became wet (about 2% by volume of water was extracted with the sling). At this time, rolling snowballs did not enlarge or entrain sufficient snow to cause avalanches.

Conditions did not change significantly the next day (May 18); although the water extracted from the surface snow increased to 3%. However, at 11 a.m. on May 19, avalanches could be started on slopes greater than 30^{o} by rolling snowballs which entrained the upper 7 cm of snow. At that time, we extracted up to 5.5% liquid water from the surface layers. An avalanche released naturally down East Main and blocked one lane of the highway at 11.30 a.m.. At 12.50 p.m., several avalanches which almost reached the highway were released down West Main on Knob 1 while placing charges for control work, and those released by explosives crossed the highway. By evening most slopes in the area had avalanched.

The next day (May 20), the weather was still warm and sunny. A profile taken in an area which had avalanched the previous day showed 16 cm of soft, coarse-grained (2 mm) rounded snow overlying harder snow. Although the surface snow was again wet (about 5% water content), areas which had avalanched the previous day had stabilized, and avalanches did not occur.

These measurements indicate that avalanching occurred only after the volume of water extracted by the sling reached 5.5%. However, this value is not unique for all snow but depends on the structure and snow type. For example, on May 20 the water content was still high, but the crystals were rounded, and the snow did not avalanche.

SYNTHESIS AND DISCUSSION OF OBSERVATIONS RELATING TO STABILITY

Drainage Patterns

Several studies have described structures in snowpacks after rain. For example, Gerdel (1954) showed with dye tracing experiments that large spatial inhomogeneities may exist within snow after rain. He described vertical drainage tubes, subsurface as well as surface channels, through which liquid water preferentially drained. More recent studies (Wankiewicz, 1978; Marsh and Woo, 1984) described water penetration of snow and distinguished between a background wetting front (above which all the snow was wet) and a finger wetting front (the deepest penetration of liquid water).

We found that watering or rain on new snow wetted the surface layers, and continued rain caused water to penetrate unevenly. Preferential drain channels were established rapidly and these often extended to the ground. Widths of the channels commonly varied from 15 to 30 cm, and the distance between channels was 70 to 130 cm. Outside a channel, snow was often dry and the snow surface developed a hummocky topography--drain channels always existed beneath dimples while relatively dry snow existed under the high-points. Extended rain or melting caused the channels to enlarge and the snowpack to become more homogeneous.

On slopes, water flowed downslope as well as vertically into the snowpack. It was common to observe water flowing downslope along layers or layer boundaries which were buried between dry snow layers. During a period of surface melting in the spring, we traced the movement of water using dye; water flowed almost 4 m down a 26° slope in 4 hours. We expect flow would be even faster during rain. The water usually flowed within layers of relatively high liquid permeability, such as graupel or other coarse-grained crystals. This was more common than the frequently documented situation--that of water flow along the upper surface of an impermeable ice layer. Flow concentrated in channels, and this was reflected in the surface micro-topography as a series of almost linear ridges and troughs. The troughs were up to 10 cm deep and followed the fall-line; the wave length varied from 20 to 200 cm.

We expect the time for the initial fingering and their spatial distribution to be governed by the snow above and below the wetting boundary as well as the relative flux rates. Once flow-fingers developed, the presence of liquid water would enhance the rate of grain-coarsening and rounding (Colbeck, 1986) and increase liquid permeability in that region. The rate of densification and settlement would be greater inside than that outside channels which explains the hummocky surface topography. Dimples at the snow surface would serve to route any subsequent surface water into the vertical channels which would allow drain channels to form rapidly.

After the hummocky surface topography had developed (indicating that drainage patterns were established), avalanche activity usually diminished. We are not certain whether this is typical--it is possible in some areas that water may not drain from the base of the snowpack, and the hummocky topography might mark the onset of climax type avalanches.

During the 1987-88 winter, drainage channels developed early in the season at the pass and remained well established. Once water had penetrated the most recent snow, the old channels were reused and water was routed rapidly through the lower layers. We felt that this tended to stabilize a snowpack. Because drainage has not been established at the time of the first rain induced avalanche cycle of the winter, the snow may slide a number of times as water works its way down through the layers.

In past years we have observed drainage channels to freeze, this was also reported by Marsh (1987). In our experience, frozen channels stabilized the snowpack. However, refreezing of drainage channels may cause subsequent water to pond and reduce stability.

At Chinook Pass in the late spring and summer, the snow becomes homogeneous consisting of coarse-grained, melt-freeze (MF) crystals which efficiently route water to the ground. In these circumstances (except where snow overlies steep and smooth rock), the snow is relatively stable. The end of avalanche hazard to the highway occurs after the final snowfall has stabilized. Even on a day when air temperatures reach 25°C, a sluff starting on a 40° slope will soon stop because the depth of loose, wet, coarse-grained snow is insufficient (less than 7 cm, Wilbour, 1986).

When snow temperatures are below freezing, we expect any liquid water within the snowpack will freeze and release latent heat which would warm the surrounding snow. Temperatures and temperature changes varied spatially and with time, depending on water flow patterns, and did not increase uniformly. On some occasions, snow temperatures increased rapidly to 0°C and we attribute this to a large flux of liquid water which flooded the area. When the snowpack was already 0°C (for instance during the spring), liquid water could not be traced in this manner.

Unsteady flow patterns may also explain why in some cases the snow temperature increased slightly and then decreased before increasing again The initial warming would have been caused by a pulse of water through a flowfinger. If flow stopped for a time, heat would dissipate to surrounding colder snow and the temperature would decrease until flow started again. It is also possible that the decrease was due to instrument effects, and we plan to investigate this anomaly further.

Lubricated Layers

Several hours after the onset of warming or rain on snow, the surface layers (up to 12 cm thick) were wet, and thin bands (up to 2 cm thick) of saturated snow often formed at different depths. The saturated layers always existed at textural boundaries due to either a difference in liquid permeability or a mismatch of capillary pressures between layers (Wankiewicz, 1978). For example, when fine-grained snow (where pore sizes are small) overlies coarse-grained snow (with larger pores), flow will initially be impeded above the fine-grained snow because the liquid permeability is low. However, capillary pressures are greater in the fine-grained snow (because of the smaller pore size) and once water has penetrated, it will accumulate within the fine-grained layer until pressures across the fine-/coarse-grained boundary equalize. At that time, liquid water will begin to seep into the coarse-grained snow. Wakahama

(1974) measured up to 30% free water content at such a boundary, and we have measured values in excess of 26%.

Colbeck (1982) discriminated between wet snow with a high-liquid water content and wet snow with a low-liquid water content (less than about 7% by volume). He described snow of low-liquid water content which consisted of tightly packed clusters which were relatively strong. In contrast, he described snow at high-liquid water contents consisting of well-rounded, cohesionless particles which were weak.

On numerous occasions, we observed avalanches which did not fail within the very wet layers, but rather within layers which were comparatively dry. We are particularly interested in this phenomenon since we had expected the strength to decrease as the water content increased past about 7% by volume (Armstrong, 1976; Colbeck, 1982; Kattelmann, 1984). We discuss this in more detail below.

Snow Stability at the Onset of Warming or Rain

The emphasis in current literature is that wet snow avalanches occur when snow layers are "lubricated" by liquid water (Perla and Martinelli, 1976). This is a likely mechanism, but on a number of occasions avalanche activity began at the onset of warming or rain, particularly when the snow contained a buried weakness or consisted of intricately-shaped crystals. We know that water had not penetrated very deeply because the moisture content of most of the snow which avalanched had not changed. Further, although the temperature at the snow surface was $0^{o}C$, temperatures deeper in the snowpack had not changed significantly and were commonly less than $0^{o}C$. This implies that liquid water did not exist at that point in time or position. However, even small temperature changes can cause relatively large changes in pressure (Colbeck, 1980b) which may affect the rate of metamorphic processes.

Newly formed snow crystals often have very unstable shapes, particularly when the initial shapes are complex. Perla and Sommerfeld (1986) described sintering processes which cause the surface area to mass ratio of an ice crystal to diminish with time. As well as this smoothing and rounding process, the branches and arms of dendritic type crystals tend to thin at their roots and break from the nucleus of the crystal (Yoshida, 1954; LaChapelle, 1969). An initially large and intricate grain will break into a number of smaller rounded ice grains.

On the other hand, initially rounded grain shapes change more slowly and are less likely to break during metamorphic processes. There is some evidence that grain-bonds can form rapidly (Montmollin, 1982), but if bonds or crystals break faster than they form, then snow strength will decrease. The rate of bond formation compared with the rate of bond breakage will determine whether warming will cause the snow to avalanche or to settle and stabilize. The processes which control this rate depend strongly on the structure and the temperature of the snow. Other factors, such as additional loading from the rain and changes in surface properties, may also need to be considered.

The shapes of crystals falling at cold temperatures are likely to be more complex and fragile than those at temperatures close to freezing. These tend to have rounded shapes and be well bonded. Further, the rates of mass transfer processes are slowed at colder temperatures, and we expect metamorphic processes and bond formation to be slowed. Following the above reasoning, we expect that instability from warming is likely to develop more rapidly in cases where snow has been deposited at colder temperatures.

For example, preceeding the warmup on January 9, air temperatures had been cold (about -8^{o}C) and the new snow consisted of fragile crystals. Avalanching started immediately after the temperature at the starting zones rose above freezing. On the other hand, temperatures throughout a storm on March 24-25 were close to freezing, and natural avalanches did not start until about 8 hours after the temperature at the starting zones reached freezing. In this case, the newly deposited snow was already rounded, and it is likely that the avalanches occurred only after grain boundaries were lubricated.

In some conditions, sudden warmups over short time periods produced surface crusts, either by rain freezing on cold snow or from freezing rain. If avalanches did not occur immediately, the crust served to inhibit or delay avalanching. This complicated the timing of control work. Even large amounts of explosives did not consistently trigger avalanches. After continued hard rain, post-control releases have been known to occur on slopes of all elevations and aspects.

Snow falling from trees or off steep rock outcrops also affect avalanche initiation. It is common for large amounts of snow to accumulate in these places near the starting zones. Limbs often hold snow at its maximum angle of repose, and additional loading will cause the limbs to bend even further. Such snow falls early in a warming cycle. Falling chunks of snow (which may be up to table size), transfer considerable energy to slopes below. This may cause unstable snow to avalanche earlier than it would otherwise. Gusty winds associated with frontal passage further intensify these effects. These conditions are less common at Chinook Pass. We have also observed water-soaked snow to fall off the underside of cornices and trigger avalanches.

We have found that large quantities of explosives, 23 kg (50 lbs,), elevated above the snow surface to be the most effective avalanche control technique. It may take up to 12 hours to control all the potential hazard to the highway at Snoqualmie Pass. During warming, conditions may change much faster than this. The period of time during which avalanche control is effective can be extended by using large aerial bombs.

CONCLUSIONS

With the onset of warming or rain, new snow strength often changed rapidly. The rate of change depended on structure and type of snow. The final crystal type tends toward large rounded grains. The greater the change in crystal shape necessary to achieve this final state, the more quickly the snow became unstable with the introduction of water. We make a distinction between avalanches which released before significant lubrication had occurred, and those which released after bonds had been weakened by the presence of liquid water.

In the first case, we think that avalanching occurred after snow was weakened when crystals and bonds collapsed more rapidly than they formed. We are not certain of the mechanism by which warming at the surface caused the strength deeper in the snowpack to decrease. However, when the snow contained a buried weakness or consisted of intricately-shaped crystals, avalanching occurred as soon as the air temperatures in the starting zones reached freezing.

In the second case, avalanching did not occur until liquid water had lubricated grain boundaries sufficiently to cause slip between grains. This condition occurred when the original crystal shapes were more rounded. It is important to distinguish between these mechanisms because instability by the first mechanism can occur much sooner than predicted by a saturated/unsaturated criterion (hours after the air temperature reached $0^{o}C$).

To forecast the time of avalanche release during rain or warming, we, therefore, need to consider how the snow strength would change. We found that the weakest layers were not always those with the highest water content. Many avalanches of new snow occurred well before the moisture content reached 7% by volume. In order to anticipate changes in the strength, it was important to consider the shape and structure of the crystals as well as the liquid water content.

Vertical drain channels in midwinter snowpacks effectively routed water through the snowpack without allowing the lower layers to become wet enough to avalanche. This tended to make for a relatively stable snowpack. Once drainage had been established, instability from rain was usually limited to the most recent snow layers. For these reasons, deep slab instability is uncommon in low-elevation maritime snowpacks. When the spring snowpack becomes all well drained MF, it can be considered quite stable.

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