Prediction of Snow Avalanches in Maritime Climates

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Avalanches in Maritime Climates

PREDICTION OF SNOW AVALANCHES IN MARITIME CLIMATES

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16. ABSTRACT

The study examined avalanche release mechanisms in a maritime snow climate to improve hazard assessment and prediction at Snoqualmie Pass. Hazard level and potential release times depend on weather conditions and snow stratigraphy in the starting zones of avalanche paths.

Most avalanches release less than one hour after the onset of rain and before liquid water or a thermal wave has penetrated more than a few centimeters into the snow. Prediction of the timing of these immediate avalanches requires observation systems that give advance notice of the onset of rain. New instrumentation installed at nearby mountain sites, with a telemetry link to Snoqualmie Pass, improved predictive capability.

In some conditions, avalanches can be delayed and the hazard can remain high for at least a day. Prediction of the timing of delayed avalanches is more difficult and requires information about the mechanical response of the snowpack to the penetration of liquid water and heat. A new method based on observation of strain-rate in the snow was developed to quantify the effects of changes of temperature and precipitation on the snow structure. This technique may prove useful for predicting avalanche release but requires additional research before it can be used operationally.

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SUMMARY

In a maritime climate such as exists at Snoqualmie Pass, it is common for air temperatures to rise above freezing and for precipitation to change from snow to rain during mid-winter storm cycles. These conditions frequently cause avalanches to release. The physical processes leading to natural release of these type of avalanches were examined in order to improve hazard assessment and prediction of the time of release.

The time of avalanche release depends on the distribution of stress and strength in the snowpack. These can change rapidly during times of rain. The researchers found that most natural avalanches occurred less than one hour after the onset of rain; in these cases the snowpack was initially weak. If the snowpack was stronger, the stress to strength relationship did not become critical so rapidly, and avalanche activity was delayed or did not occur. The time of delay for a particular avalanche path depended in part on the properties of the snow and the rate of rainfall; in one case avalanche activity was delayed 13 hours after rain had first started.

Both weather conditions and snow properties may vary strongly with spatial locations and time. It is not possible to determine these conditions in the starting zones from measurements at a single, low level station. A network of automated weather stations was established around Snoqualmie Pass to obtain real-time measurements representative of conditions at the elevations of avalanche starting zones. New experiments were designed to measure snow properties. During storm and avalanche cycles, sequential measurements of snow properties were made to determine the events leading to avalanche release.

By using the weather station network to monitor spatial and temporal changes of weather, it was often possible to predict about two hours in advance the time that the air temperature in the starting zones would increase above freezing.

This information could be used to define the time that natural avalanche activity is likely to increase.

However, it is not possible to accurately predict the time of release for delayed avalanches from measurements of weather alone. It is necessary to have supplementary knowledge of the stratigraphy and texture of the snow in the starting zones, and how these change with warming and rain. Such information is difficult to obtain and interpret.

Measurements of strain-rate versus depth indicated abrupt changes associated with the penetration of a thermal wave and liquid water into the snow. Measuring strain-rate over short time intervals is a newly discovered method for quantifying the response of a snowpack to external changes of temperature and precipitation. The technique may prove useful for defining the time that a snowpack could become unstable and avalanche.

CONCLUSIONS AND RECOMMENDATIONS

(1) Most avalanches release less than one hour after the onset of rain. Avalanches may also be delayed after rain has started, and hazard can remain high for at least one day.

(2) Real-time measurements of weather conditions to the west of and near the starting zones are important for predicting times of high avalanche hazard. Monitoring snow depths in the starting zones would further improve predictions.

(3) Predictions of snow stability from weather conditions alone are not sufficiently dependable for determining the hazard or the timing of delayed avalanche releases. To obtain the accuracy required, supplementary knowledge about the structure of the snow and how it will evolve with warming or in the presence of liquid water is needed. Conditions may vary

with spatial location, and it is best to have this information from near the starting zones of the avalanches.

(4) Measurement of strain-rate in the snow is a new method for predicting avalanche activity. It is based on the combined effects of external changes in temperature and precipitation and the internal state of the snow. Further experiments with the technique are required before its full potential can be determined, and before the method can be used operationally.

BACKGROUND INFORMATION

Little is known about the release of avalanches in maritime climates, and only a few measurements have been documented (Kattelmann, 1984; Ambach and Howorka, 1965). This study examined the physical processes leading to natural release of avalanches in order to improve hazard assessment and prediction of the release time. Specific focus was on the Snoqualmie Pass highway corridor.

In the Snoqualmie Pass region it is common for air temperatures to increase above freezing with the approach of a warm front. Temperatures can change several degrees within minutes, and it is common for precipitation to change from snow to rain during mid-winter storm cycles. These conditions frequently cause avalanches to release. These types of avalanches were the main concern of this study.

Avalanche paths that threaten the highway through Snoqualmie Pass have been mapped by LaChapelle and others (1974). A certain amount of snow cover is required to smooth the terrain in the avalanche paths before avalanches will affect the highway. In the past, avalanches have reached the highway once the snow depth (at Pass level) exceeded 34 in.

In some situations, new snowfalls of only 3.2 in. (measured over the previous 24 hours at Pass level) have resulted in avalanches onto the highway. Given these conditions, regular avalanche control is necessary to minimize the hazard, and an active control program has been in operation since 1973.

To be effective, avalanche control needs to be done when the snow is sufficiently unstable so that avalanches can be triggered artificially, but not so unstable that avalanches release naturally while the highway is open to traffic. The time of natural release is often difficult to predict, and at Snoqualmie Pass the time interval available for effective control may be a few hours only. This combination has potential for hazard to the traveling public, and in the past, it has resulted in unnecessary highway closures.

MEASUREMENTS OF SNOW AND WEATHER

Avalanching is likely when the stress from the overburden and any other loading exceeds the strength of the snowpack. To determine the stability of a snowpack, a measure of stress and the relevant strength and how they change with location and time is required. Strength is determined by the structure of the snow. Significant structural changes may occur over periods of minutes when snow is warmed, either by the penetration of a thermal wave or by melt or rain water.

Weather Stations

Information about the time of a warming can be obtained from measurements of weather. It is common for conditions to vary considerably along the Snoqualmie Pass highway, and they cannot be predicted reliably from a single, low level location. Weather conditions, and in particular air temperature, need to be known with high time resolution in the starting zones of avalanches.

The researchers established a system to monitor weather at eight sites in the mountains surrounding Snoqualmie Pass. Data from the remote sites were transmitted either by radio or telephone to the computer at the WSDOT office on Snoqualmie Pass. The researchers recorded hourly measurements of temperature, wind speed, wind direction, and precipitation, and the data could be graphed at any time as a time-series.

Two sites wee about 25 km west of the crest at Mt. Washington (4400 feet) and the Fire Training Center (1600 feet -- see Figure 1). These sites offered warning of warm frontal passage from the west. Other sites were located at three different elevations on Denny Mountain (5400 feet, 4300 feet, 3200 feet -- marked DM in Figure 1); at Snoqualmie Pass (3000 feet -- WSDOT); at the top of the Summit ski area (3800 feet); and at the East Shed (3700 feet -- ESS). Precipitation (water equivalent) was measured at the Pass and at the Alpental ski area base station.

Winds in mountainous topography affect the areal distribution of precipitation, and snow accumulation can vary widely over scales of a few meters. It would be more appropriate to measure depths in the starting zones rather than at the Pass (3000 feet) or the Alpental base (3200 feet). The study team tested a device that sonically ranges the distance from a fixed point above the snow to the snow surface to measure snow depth at remote sites. The device was only partly successful (see the technical report). If some of the scatter in the measurements could have been eliminated, instruments located in the starting zones would have provided information about the potential hazard at any time.

Sequential Measurements of the Structure of the Snow

To understand how the snow structure evolves with warming and in the presence of liquid water, and how the strength of the snowpack changes, the researchers made sequential measurements of snow properties including stratigraphy, density, hardness, and crystal size and shape and related these to observations of snow stability. Measurements were made during storms and controlled experiments. Measurements were made both in the study plot at Snoqualmie Pass (3000 feet), and at higher elevations in the starting zones.

Distribution of Liquid Water in the Snowpack

Measurements were made during times of natural and artificially induced rain. A garden sprinkler was used to distribute water over snow to study the effects of watering in controlled experiments. Before watering or rain, a water-soluble dye (Malachite Green) was spread over the snow surface. The dye made it easier later to map the path of liquid water through the snow. The liquid water content of snow can be determined from its dielectric constant (Denoth and others, 1984; Colbeck, 1980). The researchers built a device to measure the dielectric constant of snow and also used a sling centrifuge (Wilbour, 1986) to determine water content. For a qualitative estimate, the squeeze test was used (UNESCO/IAHS/WMO, 1970).

Snow Temperature

Thermistors were buried in a vertical line to measure snow temperature versus depth. Measurements were made at 15-minute intervals at the Pass study plot. A three-dimensional array of thermistors would provide a better understanding of warming processes in snow than the single line of thermistors used in this study. To minimize heating from solar radiation that penetrated the snow, the thermistors were wrapped with reflective mylar. Accuracy of the measurements was 32.36°F.

Snow Settlement

Settlement was measured by running a cord vertically from a shoe (a thin plastic plate 2 in. with holes drilled through it) embedded in the snow to a 10-turn rotary potentiometer fixed above the snow surface. The potentiometer turned as the shoe settled with the snow. The resolution of the displacement transducers was about .008 in. The rate of movement was calculated from the change in resistance measured at 15-minute intervals. During storms, shoes were set on the snow surface and allowed to be buried by further snowfall. Settlement at different depths was measured, and strain averaged over depth intervals between the shoes was calculated. Strain-rate was averaged over half-hour intervals.

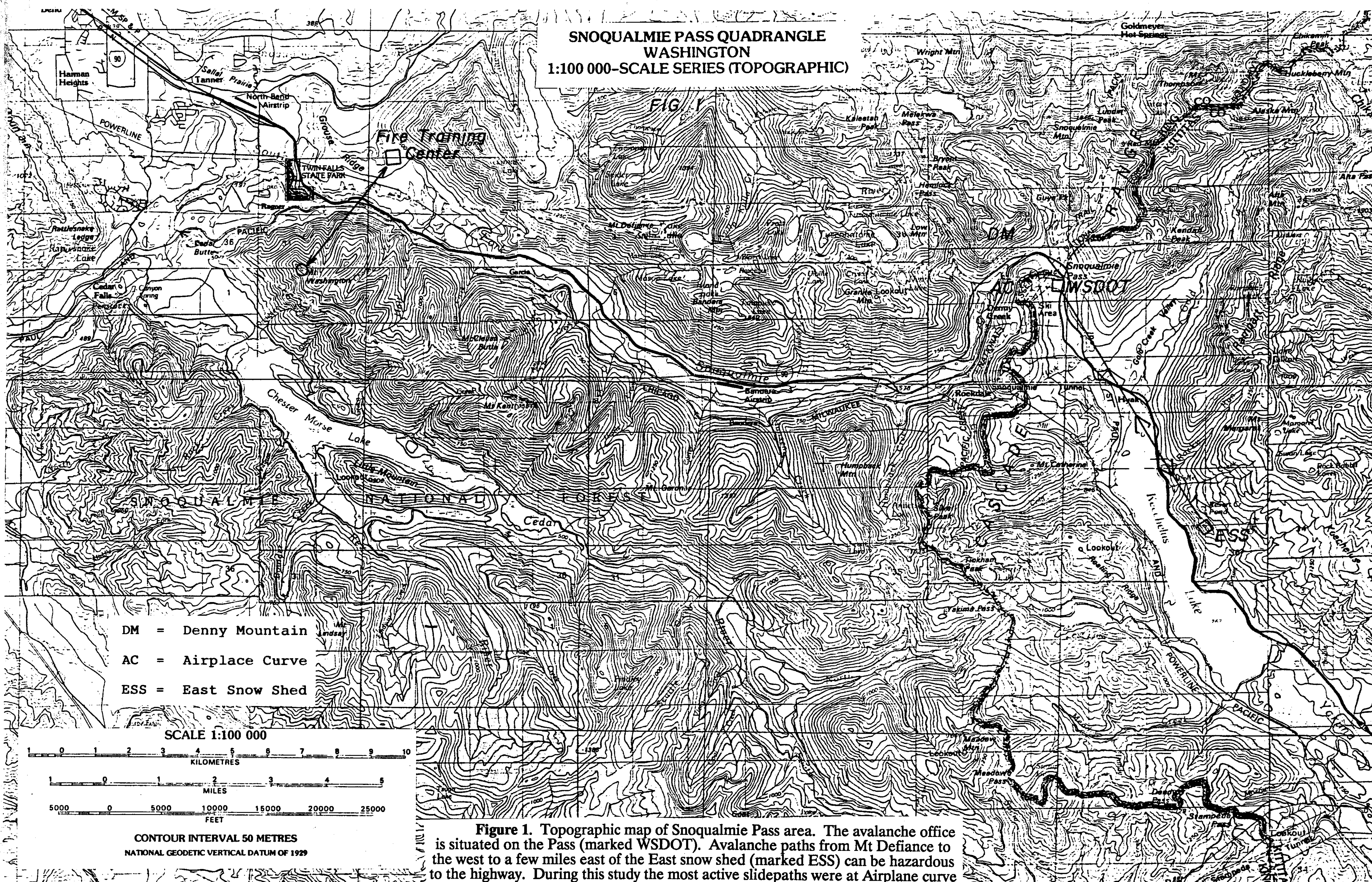


Figure 1. Topographic map of Snoqualmie Pass area. The avalanche office is situated on the Pass (marked WSDOT). Avalanche paths from Mt Defiance to the west to a few miles east of the East snow shed (marked ESS) can be hazardous to the highway. During this study the most active slidepaths were at Airplane curve (marked AC) and west snow shed areas, Denny Mountain slide paths (DM), and the East Shed and Slide curve paths (ESS).

Some short-term fluctuations in the measurements occurred when winds buffeted the cord attached to the shoe. This extended the potentiometer and was followed by a time of no apparent movement as the snow settled sufficiently to take up the slack. Measuring errors also caused some noise.

Measurements from the starting zones of avalanches would provide the best information, but the measurements discussed below were made on flat snow in the study plot at the Pass.

DISCUSSION AND SYNTHESIS OF MEASUREMENTS

Case Histories

Two examples of temperature and precipitation time-series data are shown in Figures 2 and 3. In both of the cases, precipitation changed from snow to rain when a warm frontal system moved into the area from the west. These, and other storm and avalanche cycles are discussed in more detail in the technical report.

On January 9, 1988, the vertical distribution of air temperatures was complex and changed significantly over periods of minutes (Figure 2). At 5 p.m., a wedge of cold air (at 3800 feet) was sandwiched between two warmer layers; the air at 5400 feet was warmer than the air at 3000 feet. However, in the next hour, the temperature at 3800 feet increased 10°F and soon after 6 p.m. it warmed above freezing. During the same hour, the temperatures at the other two stations remained unchanged, but two hours later, the air at 3000 feet warmed abruptly above 32°F at 9 p.m.

The elevation of the starting zone of Airplane Curve #1 is 3350 feet. When the air temperatures were less than 22°F, avalanche control produced only a few small surface sluffs from that path. However, less than one hour after the temperatures in the starting zones reached 32°F, avalanches released naturally in the same area. Further, an avalanche from Airplane Curve #1 slid to the highway at 8 p.m., which was about the same time that the air temperature at the starting zone reached 32°F.

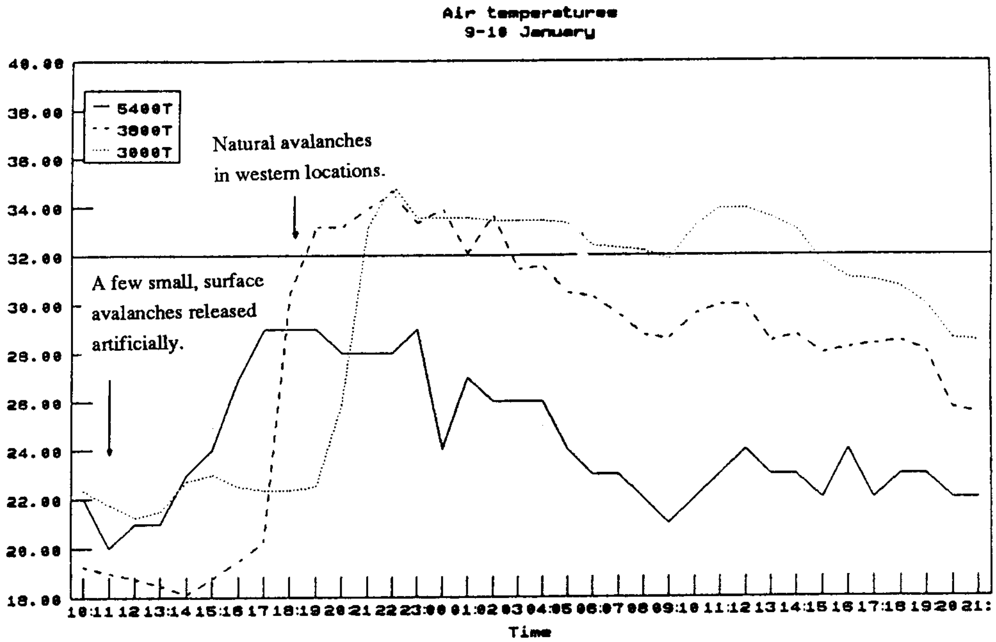
The air temperature record is also interesting in the second example (Figure 3). More stations were added in the second year of the study to improve knowledge of the spatial distribution of air temperature. In the second case (January 15th to 16th, 1989) there was an abrupt warming of 8°F in two hours starting at 4 a.m. on the 15th, but temperatures did not reach freezing. Although 15.6 in. of new snow had accumulated in the previous 24 hours (at 3000 feet), avalanche control between 5 a.m. and 3:30 p.m. released only a few surface avalanches. However, about nine hours after rain had started, numerous large, wet slab avalanches released naturally from paths that had not been controlled earlier in the storm cycle.

Predictions of Snow Stability from Weather

Snow stability often changed rapidly when air temperatures increased above 32°F, and it was common for avalanches to release within an hour of that time (as occurred on January 9, 1988). The researchers suspect that the time of onset of rain is more critical than the time the 32°F threshold is first crossed, but this is more difficult to measure. An instrument that distinguishes between rain and snow at remote sites is required.

Prediction of the critical line of crossing at the starting zones was complicated by the influence of mountainous topography on the weather. Both sets of data showed large spatial and temporal gradients in the air temperatures. It was common for temperatures at the starting zones to warm two to three hours before those at Pass level (3000 feet). Given these conditions, measurements from a single location did not usually represent conditions at other locations.

By using the network of stations, it was often possible to predict when the air temperature at the starting zones would warm above 32°F. The signal of warming was not always clear. For example, the only warning of the abrupt warm-up at



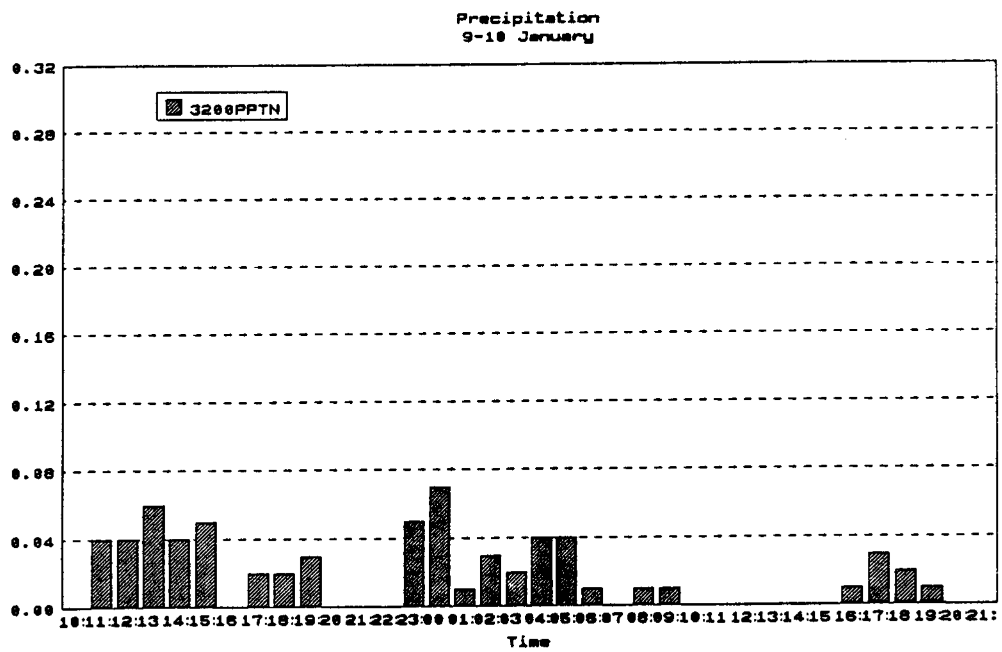


Figure 2. Hourly measurements of air temperature and precipitation from 10 a.m. January 9 to 9 p.m. January 10, 1988. Temperatures were measured at the top of Denny Mountain (5400 feet), the top of the Summit ski area (3800 feet) and at Pass level (3000 feet). Precipitation (inches of water equivalent) was measured at the base of Alpental ski area (3200 feet).

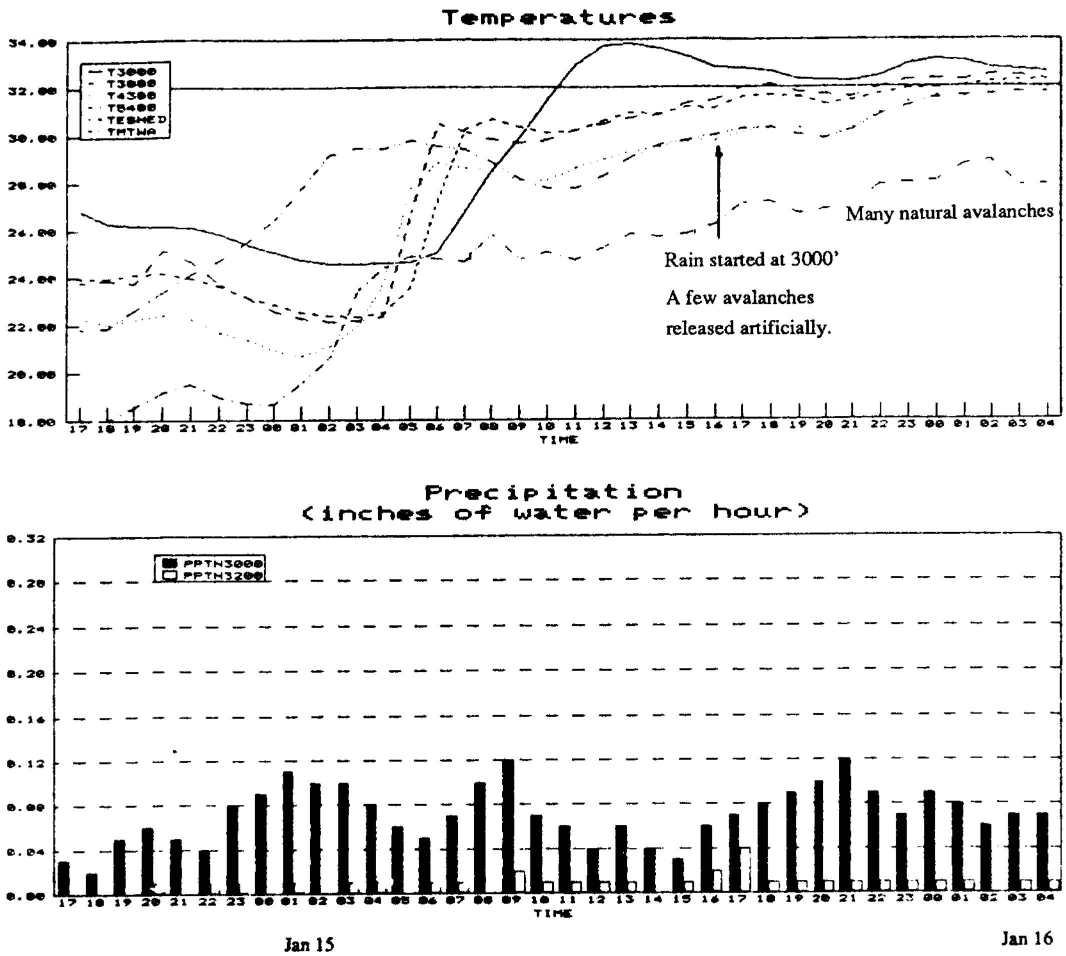


Figure 3. Hourly measurements of air temperature and precipitation from 5 p.m. January 14 to 4 a.m. January 16, 1989. Temperatures were measured at the top of Mt Washington (TMTWA), the East Shed (TESHED), the top of Denny Mountain (T5400 feet), partway up Denny Mountain (4300 feet), the top of the Summit ski area (T3800 feet) and at Pass level (T3000 feet). Precipitation (inches of water equivalent) was measured at the Pass (PPTN3000). Precipitation measurements from the base of Alpental ski area (PPTN3200) are incorrect.

3800 feet on January 9, 1988 was from the temperature at 5400 feet on Denny Mountain, which had started to increase slowly six hours earlier. In real time, it would have been difficult to interpret this as a precursory signal.

On some occasions measurements of wind speed and wind direction showed changes associated with frontal passage (see technical report), but these were not dependable when used alone. By combining all of the available weather parameters, and with more experience, it should be possible to recognize patterns that recur and obtain an accurate estimate of the onset of rain. It is interesting to note that on January 15, 1989 (Figure 3), the warm-up at Mt. Washington started about seven hours prior to that at 5400 feet on Denny Mountain. Although the data are limited, the data available suggest that this site will give early warning of fronts approaching from the west.

For all of the cases studied, the time of known natural avalanche cycles in relation to the crossing of the 32°F threshold temperature were documented (Figure 4). The data showed that there is a high probability that avalanches will occur at the onset of warming or rain. The data also showed that avalanches occurred up to 13 hours after rain had started. This hazard interval is long, so the motivation is strong to further refine predictions of the time of avalanche release. Knowledge of weather conditions in the starting zones is not sufficient, and supplementary knowledge of the structure and location of potential sliding surfaces in the snowpack is also required.

Warming and Liquid Water in the Snow

Rapid metamorphic and structural changes occur when snow is warmed or liquid water is present (Perla and Sommerfeld, 1986; Raymond and Tusima, 1978; Wakahama, 1968, 1975). An understanding of how these processes affect the stability of a snowpack is required.

When rain first falls on cold snow it freezes, and the latent heat released warms the snow to 32°F rapidly. When the snow temperature reaches 32°F, any further rain causes the liquid water content to increase. In the study, soon after rain had started it was common to observe liquid water concentrated in the upper snow (usually in a layer less than 4.8 in. thick). The snow below the wet layer remained dry; the liquid water content changed sharply and the boundary was clearly defined.

With more rain, liquid water started to penetrate vertically through the boundary in flow fingers, and with time, these increased in size and formed channels through which water preferentially flowed. Drain channels allow water to pass rapidly through the snowpack. In our experience, avalanche activity decreased after drainage had developed. Details of observations are given in the technical report.

The penetration of liquid water into a snowpack is not homogeneous, and snow is not expected to warm uniformly. Two series of measurements of temperature were taken at different depths in the snowpack at Pass level (3000 feet) during rain events (Figures 5 and 6).

On January 9, the temperature 9.6 in. below the surface increased slowly for seven hours after rain had started, and then it warmed abruptly between midnight and 1 a.m. (Figure 5). This occurrence indicates that a pulse of water wet the snow at that depth. During the period shown, temperatures deeper in the snowpack (13.6 in. and 21.6 in. below the surface) warmed gradually and remained below freezing.

Measurements on January 13-14th are also interesting (Figure 6). The temperature 6 in. below the surface warmed steadily for five hours and then slowed. About 10 hours after the rain first started (intensity averaged 0.14 in./hr.), temperatures deeper in the snowpack increased rapidly to 32°F while the snow above remained below freezing. Water apparently flowed through channels and warmed the deeper layers first.

One implication of these measurements is that it is possible for liquid water to penetrate (and perhaps weaken) a layer deep in the snowpack before the snow above has been saturated. This is an important consideration for predictions of the time of natural avalanche release.

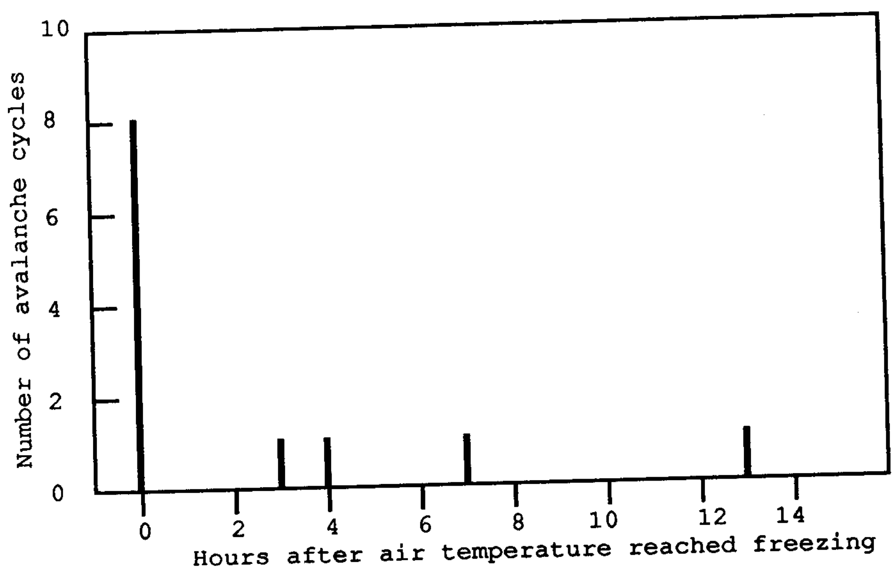


Figure 4. Timing of natural avalanche cycles. Times shown are hours after the air temperature in the starting zones first reached freezing. In some cases we were uncertain of the exact time of the avalanche cycles and the times are estimates.

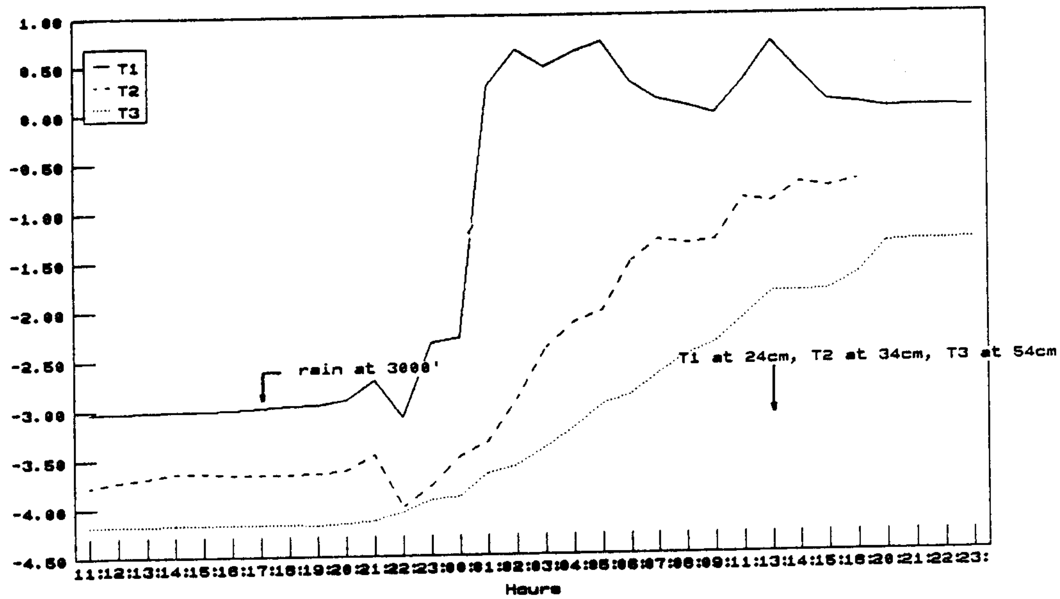


Figure 5. Hourly measurements of snow temperature measured at different depths in the snow at the Pass study plot (3000 feet) between 11 a.m. January 9 and 11 p.m. January 10, 1988. Rain started at 5 p.m. January 9 and continued throughout the period shown (see Figure 2). At the end of the measurements, the thermistors were located 24, 34, and 54 cm below the snow surface.

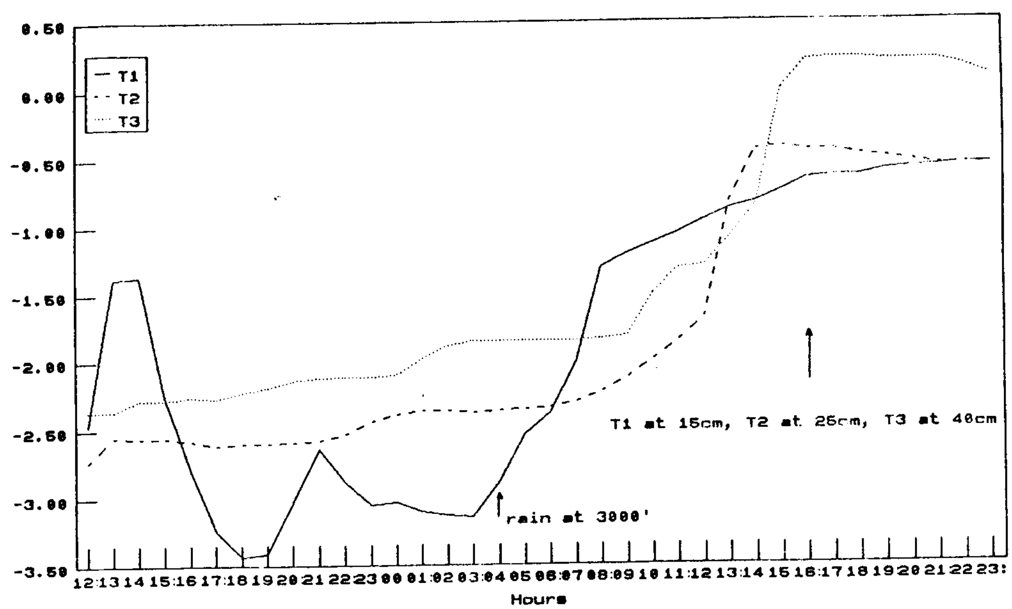


Figure 6. Hourly measurements of snow temperature measured at different depths in the snow at the Pass study plot (3000 feet) between 12 noon January 13 and 11 p.m. January 14, 1988. Rain started at 4 a.m. January 14 and continued throughout the period shown. At the end of the measurements, the thermistors were located 15, 25 and 40 cm below the snow surface.

Snow Instability

Immediate Instability. Avalanches were likely to release soon after the onset of rain if the snowpack was initially weak; activity was highest when the snow was very weak and when warm-ups were rapid. Weak, newly deposited snow is typically low density (less than 264 lb./1.1 yd.^{3}) and contains crystals that are fragile and easily broken (Yoshida, 1954). Small perturbations of stress are likely to fracture the snow. Further, although sintering processes can be rapid (Montmollin, 1982; Perla and Sommerfeld, 1986), during rapid warm-ups, the snow does not have much time to gain strength.

The researchers are not certain of the mechanism of release of these type of avalanches, but measurements showed that they released before the thermal wave or liquid water had penetrated more than a few centimeters into the snowpack. The snow that avalanched was usually more than a few centimeters deep, which implies that the instability was not caused by the sub-surface snow weakening in the presence of liquid water. It is more likely that these avalanches released when the stress increased in some way.

The weight of new precipitation increased stress, but the avalanches released either during times of no extra precipitation (solar induced warming), or soon after rain had started. However, the presence of liquid water near the surface of the snowpack could have altered the distribution of stress significantly. Before vertical drainage has been established, some water will flow downslope, and discontinuities in the topography will cause the water to be unevenly distributed. Stress could have concentrated rapidly in this manner, and this may have been sufficient to initiate failure, especially if the snow was initially weak.

Loading could also have been redistributed if the surface snow slipped downslope. Further, any snow falling from trees or nearby cliffs could have added sufficient dynamic load to cause slope failure.

Delayed Instability. Avalanche activity was often delayed (or did not occur at all) when the new snow contained rounded, well bonded grains. Rounded grains are less susceptible to collapse and are capable of sustaining higher stress than branched shapes. Thus, with rounded grains, the snowpack is stronger (or able to gain strength by sintering processes during a slow warm-up). Further, rounded grains are more permeable to liquid water, and vertical damage could develop rapidly. This inhibits stress redistribution by the process of water flow downslope described in the previous case.

Avalanching does not occur until the stress increases and/or some critical sub-surface snow layer is weakened and the stress/strength relationship becomes critical. It is likely that the time of release is influenced in part by the time taken for water to penetrate to the slip surface. Avalanches that occur late in a rain storm are likely to release from deep layers and be destructive.

Snow Settlement

Volumetric changes occur as the structure of the snow evolves either from metamorphic processes or from external forces. The rate of change reflects grain and inter-grain stability, which are directly related to snow strength. If bonds break faster than they form, the strength decreases. Snow exhibits viscous behavior at low rates of strain (Narita, 1983), but at higher rates it displays ductile or brittle fracture. The probability of crack formation increases with strain-rate.

The study's measurements of strain-rate versus depth were designed to monitor changes of the internal structure during periods of warming, rain, and extra loading. A high strain-rate occurs during periods of grain rearrangement and fracture. Bonding is poor and the snow weak. Once the strain-rate returns to low values, a state of relatively high snow strength may exist.

The structure of low density snow containing intricately shaped crystals changes rapidly, particularly in the presence of liquid water (Wakahama, 1975); volumetric changes are rapid. More dense snow containing grains that have rounded will densify more slowly. The rate of densification decreases as the grains become closely packed.

Measurements of settlement strain-rate within two snow layers during rain are shown in Figure 7. The compressive strain-rate in the near surface (0 to 7.2 in.) snow increased rapidly to a peak of $2x10^{-5}s^{-1}$ when rain first started. However, within two hours, the rate had decreased to less than $5x10^{-6}s^{-1}$ (Figure 7). Structural changes had been rapid in the presence of liquid water.

The strain-rate deeper in the snowpack (7.2 to 15.2 in.) did not change until about seven hours after rain had started. Apparently it took that time for liquid water or the thermal wave to penetrate to that depth. The strain-rate increased from less than $5x10^{-6}s^{-1}$ to a maximum of $10^{-5}s^{-1}$ about 12 hours after rain had started.

So far the researchers have only measured strain-rate at two depths, but with more gauges one should be able to distinguish more details of a propagating strain wave associated with the penetration of water into the snow.

It is interesting to note that avalanches released at the onset of rain on April 4, 1989 but not on January 16, 1989 (see technical report). In the first case, the maximum strain-rate measured (in snow from 0 to 7.2 in.) was $2x10^{-5}s^{-1}$, but in the second case the maximum rate (in snow from 0 to 17.2 in.) was $8x10^{-6}s^{-1}$. More measurements are required to confirm whether there is some threshold between these two values that can be used to predict whether avalanches will release at the onset of rain.

In two cases, the time that the strain-rate in the sub-surface snow increased corresponded with the time of delayed avalanche release. This phenomenon was probably coincidental, since it is unlikely that the rate of settlement in the study plot accurately represented those in the starting zones. However, the results are encouraging and suggest that high strain-rates in the snow might be related to avalanche activity. Further measurements are required to verify these observations.

Weakening of the Snowpack

It is likely that snow may weaken by a number of different mechanisms in the presence of liquid water, and below are discussed some new observations.

Current available literature suggests that downward flow of water in impeded by ice layers that are impermeable (Perla and Martinelli, 1976), but in the study water always penetrated ice layers rapidly. It is possible that flow is impeded if the ice is thick and cold. When the temperature of the ice is warmer than about 31.82°F, the presence of water melts the grain boundaries and increases permeability (Langham, 1974, 1975).

The tests found that water was likely to accumulate either in snow of relatively high permeability (such as graupel), or at a stratigraphic boundary of fine-grained snow overlying coarse-grained snow. In this situation, the low permeability of the fine-grained snow first impeded flow above the layer, but once water had penetrated, flow was inhibited by the relatively high capillary pressures in the fine-grained snow. Water accumulated at the lower boundary of the fine-grained snow until the pressure across the boundary equalized (Wankiewicz, 1978), and then the water started to seep into the coarse-grained snow below.

On a number of occasions the researchers observed thin bands of saturated snow in the stratigraphy at crownwalls. When exposed, water ran freely out of the layer, but it was relatively strong in shear; the sliding layer for the avalanches was always immediately below the saturated layer and consisted of coarse grains that lacked cohesion (see technical report). This finding was surprising because it was expected that such large amounts of liquid water (in excess of 25 percent) would weaken the snow (Colbeck, 1982). Below are discussed the stratigraphy of this situation in terms of grains and their structure.

Saturated Layer. In all of the cases, the grains in the saturated layer were small (less than 0.0004 in. in diameter) and closely packed. In most cases the grain size did not increase over a period of weeks. Grains usually coarsen in water-

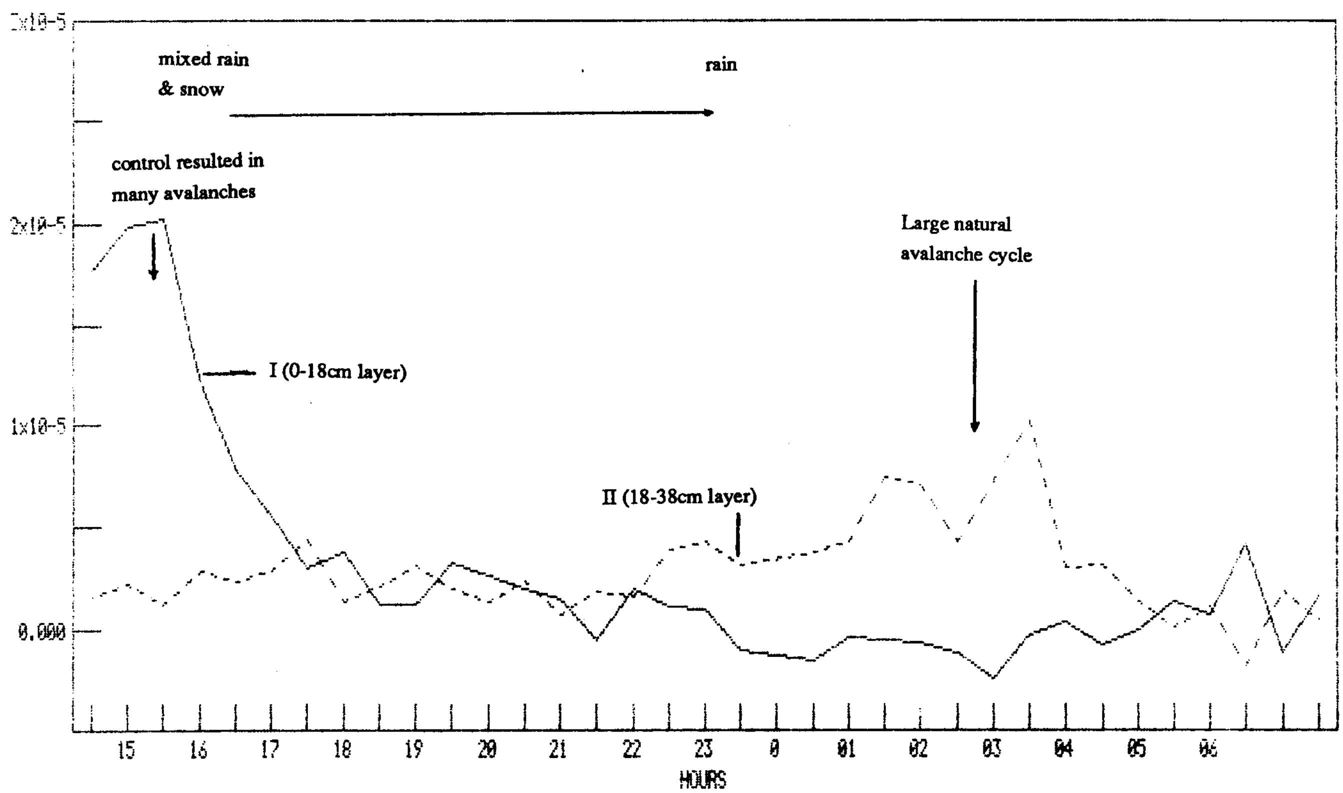


Figure 7. Strain-rate measured over two depth intervals in the study plot at the Pass (finishing on 4/5/89). Curve I is the strain-rate between the surface and 18cm; the rate increased to $2x10^{-5}s^{-1}$ as the snow surface warmed to 0°C. Curve II is the strain-rate between 18 and 38 cm; the rate started to increase about 6 hours after the rate in upper layer had decreased, and reached a peak ($10^{-5}s^{-1}$) 12 hours after the rain had started.

saturated snow (Colbeck, 1986), but growth is inhibited when grains are closely packed (Voorhees and Schaefer, 1987). The stress from the overburden may compress a wet, deeply buried layer rapidly and this may inhibit grain growth. This contrasts with wet snow near the surface, where rapid grain growth may be expected.

The combination of small grain size and high packing density may allow this layer to resist relatively high shear stresses.

Coarse-Grained Layer. Coarse-grains (0.08 to 0.12 in. in diameter) always existed directly below the saturated layer in the crownwall stratigraphy. Vertical flow was impeded above the boundary, but as the flux increased, some water seeped from the saturated layer into the coarse-grained snow. As the volume of water in the coarse-grained snow increased, solid bonds between grains melted and the grains became cohesionless. The thickness of the layer of cohesionless grains changed with the amount of melt water present. It was difficult to measure the irreducible amount of water in the cohesionless layer, but it probably would have been close to 7 percent (Colbeck, 1982).

Shearing of closely packed grains that cannot deform requires some void space for the grains to move around each other. The shear layer either needs to dilate to create space or, if it is constrained, the space is created by a number of grains each moving a small amount. This implies a minimum thickness for the shear layer, which is thought to be about 10 particle diameters (Bridgwater, 1980). For the above case, the shear strength could decrease significantly when the thickness of the cohesionless layer increased to 0.8 in. to 1.2 in.

The observation that the weakest layer in the snowpack was not the one with highest liquid water content is contrary to current avalanche literature (Perla and Martinelli, 1978); it is thought that snow strength decreases when the liquid water content exceeds about 7 percent (Colbeck, 1982). A measure of liquid water content is not sufficient to determine strength, but the grain structure also needs to be considered.

IMPLEMENTATION

In order to have sufficient time to do avalanche control along the I-90 highway through Snoqualmie Pass, it is necessary to be able to predict the time that rain will begin in the starting zones at least two hours ahead of time. A local network of mountain weather stations is needed to achieve that accuracy.

Weather Stations

The network of eight stations already established is adequate for most areas that threaten the highway, but it needs to be expanded to cover the starting zones near the west snow shed. The avalanche paths at Airplane Curve and Bald Knob are particularly active and often are the first to threaten the highway. It is difficult to predict weather conditions in this area from the existing network, and instruments near the starting zones of these avalanche paths would fill this gap in knowledge.

Work is necessary to develop instruments to measure snow depth and precipitation type. These two types of instruments should eventually by added to the existing stations on Denny Mountain and at the East Shed and also incorporated into the new station near Airplane Curve.

Interpretation of Weather Record

Analysis of weather conditions from the network of weather stations is required to make full use of the available information. With experience, it should be possible to recognize patterns that recur and to predict how different storms influences different locations.

Other information such as the likely structure of the snow can be interpreted from the temperature and precipitation history. When snow is deposited at cold temperatures, crystals are likely to be intricately shaped and weak. At temperatures close to freezing, new snow is more likely to be rounded and relatively strong. Furthermore, if the air warms slowly from sub-freezing temperatures, sintering processes are likely to strengthen the snowpack. Field checking is needed to determine the level of confidence that can be placed on these interpretations.

Measurements of Snow Properties. It is necessary to know how the snow structure will evolve and how its evolution will affect stability. Field observations of snow stability and measurements provide important information for estimating present and future stability. The following measurements are needed with high time resolution in the starting zones:

(a) snow stratigraphy

(b) crystal shape and size

(c) snow temperature, density, liquid water content, and hardness.

Measurements of strain-rate have not yet proved to be useful as an operational tool. More research is needed to develop the potential of this method.

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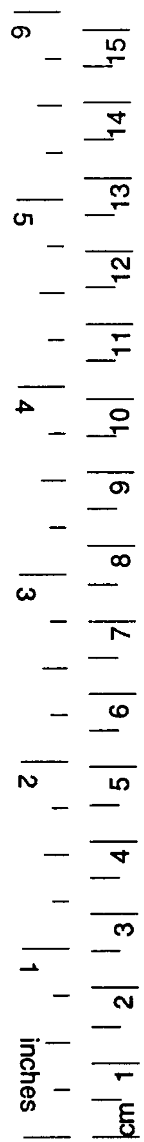
METRIC CONVERSION FACTORS

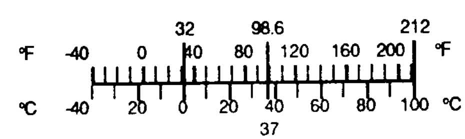
Approximate Conversion to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
	LENGTH			
in	inches	2.54	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
	AREA			
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
	MASS (weight)			
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
	VOLUME			
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
	TEMPERATURE (exact)			
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C



Approximate Conversion from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
	LENGTH			
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
	AREA			
cm^2	sq. centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	sq. kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
	MASS (weight)			
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
	VOLUME			
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
	TEMPERATURE (exact)			
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



II: Data: Adm: TRAC Adm: Metric

12/12/89

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