RAIN ON SNOW AVALANCHE EVENTS
SOME OBSERVATIONS

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ABSTRACT

Methods of prediction of rain-induced avalanches are examined. Historical avalanche events are evaluated with respect to rainfall amounts, rainfall intensity, and days since last snowfall. A simple experiment was performed to monitor movement of water through an inclined snowpack. The mechanical effects of water movement and its relationship to avalanche activity is discussed. Observations and suggestions of explosive control for rain on snow avalanches are examined.

INTRODUCTION

Avalanches resulting from rainfall on snow are common in a maritime climate. Often this type of avalanche is defined as a wet-snow avalanche. Although some of these avalanches are similar to melt-induced wet avalanches, many have characteristics similar to dry-snow avalanches. Observations of rain on snow have shown differences between the effects of rain water on new snow versus old snow.

Considerable investigations have been performed to study the effects of rain on snow, and water percolation through the snowpack. Most of this work was targeted at studying the hydrological process of water percolation and was limited to observations of flat snow surfaces. With the exception of (Kattleman, 1986), research of the effects of liquid water on an inclined snow surface, the effects of rainfall on new snow, and the relationship of rain to avalanches has been largely neglected.

The site of this study was Alpine Meadows Ski Area. Alpine Meadows is located in the Sierra Nevada Mountains of California a few miles north of Lake Tahoe. Alpine Meadows has a maritime climate which is characterized by heavy snowfall, warm temperatures, warm snowpack and rainfall in mid-winter. Rain induced avalanches occur every winter. Some of these avalanche periods have posed a considerable hazard both within the ski area and the entire Sierra Nevada. In February 1986, rainfall followed heavy snowfall and produced wide spread avalanche activity resulting in heavy destruction to mature

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forests throughout the area. Heavy rainfall on new snow in January 1980 produced an avalanche which destroyed the Olympic Lady chairlift at Squaw Valley. On Christmas Eve 1983, rain on new snow resulted in an avalanche which buried a young boy playing on a road in the Tahoe area. These events demonstrate the importance of understanding the effects of rain on snow and the avalanche which may result.

This paper describes an analysis of twenty rain on snow events and the relationship of these events to avalanche activity. This analysis is broken down into several components comparing rainfall to the age of snow on the ground and the resulting avalanche occurrences. Rainfall amount and rainfall intensity are also compared to avalanche activity. The effects of simulated rain on new snow is investigated along with downslope liquid water transmission. The role of rain on new snow and the mechanism of avalanche release is discussed. Explosive control of this type of avalanche is described and evaluated.

ANALYSIS OF RAIN ON SNOW AVALANCHE OBSERVATIONS

A search of the Alpine Meadows weather and avalanche observation records resulted in twenty events with enough information for analysis. These events and the observations are listed in Table I. The analysis compares various snow and rainfall characteristics to determine why some rain on snow events produced avalanches and others did not. Events were broken down into two categories; Avalanche days and Non-Avalanche days. Avalanche days are defined as days with widespread avalanche activity on most exposures, with either or both natural and artificially released slab avalanches. Non-Avalanche days are defined as days with no avalanche activity. Avalanche size was not considered in the analysis.

Total Rainfall Versus Days Since Last New Snow

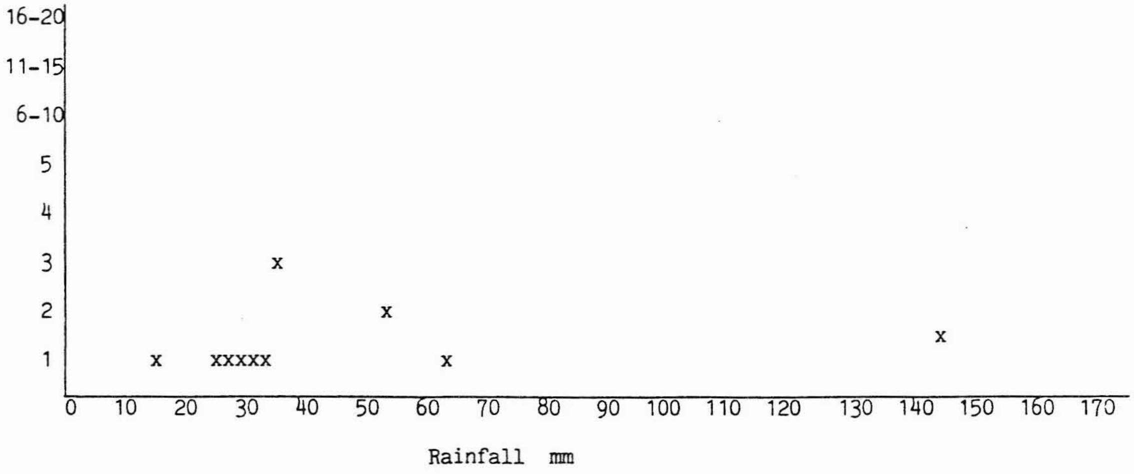
Total previous twenty-four hour rainfall amount was compared to the period of time since the last new snowfall. Twenty-four hour rainfall amount was defined as the rainfall within the twenty-four hour time interval preceding the 6:00 a.m. observation. Only the rainfall within the first twenty-four hour observation period of a rain storm was evaluated. The days since last new snow was defined as the preceding twenty-four hour periods before the rainfall observations. Day 1 was the same twenty-four hour time interval as the twenty-four hour rainfall time interval. In some events both rain and snow fell in the preceding twenty-four period. These comparisons were broken down into Avalanche Days (Figure 1) and Non-Avalanche days (Figure 2).

This analysis showed Avalanche days only occurred if there had been new snow within the preceding three days. The number of days since the last new snow for Non-Avalanche days ranged

Event #	Date	Rainfall Amount mm	Rainfall Duration hours	Intensity mm per hr	Previous Days New Snow Amount cm								Avalanche Activity	
					1	2	3	4	5	6-10	11-15	16-20	Yes	No
1	11-22-77	16.3	4.5	3.6	30	40	0	0	0	0	0	0	X	
2	1-11-79	34.5	9	3.8	0	0	22	10	0	10	0	0	X	
3	5-27-79	26.7	7	3.8	0	0	0	20	25	17	7	0		X
4	12-30-79	12.2	3	4.1	0	0	0	0	30	165	5	0		X
5	1-12-80	143.3	24	6.0	0	20	57	10	0	0	7	0	X	
6	2-17-80	30.0	12	2.5	12	25	42	5	0	0	0	0	X	
7	12-14-81	18.3	24	0.8	0	33	2	0	11	0	0	0		X
8	12-19-81	85.1	24	3.5	0	0	0	0	0	46	0	0		X
9	2-14-82	73.7	24	3.1	0	0	0	0	0	3	0	0		X
10	3-09-82	9.9	12	0.8	0	0	5	0	0	73	17	0		X
11	4-11-82	151.9	24	6.3	0	0	0	0	0	70	272	8		X
12	3-13-88	29.2	12	2.4	15	3	7	0	0	39	50	22	X	
13	12-24-83	24.6	9	2.7	16	23	4	0	0	10	82	15	X	
14	12-02-85	30.2	12	2.5	5	0	23	34	25	62	10	100	X	
15	12-30-85	38.4	18	2.1	11	0	0	0	0	0	0	0		X
16	1-05-86	42.7	24	1.8	0	4	0	0	0	11	0	0		X
17	1-17-86	52.1	24	2.2	0	20	13	0	0	0	6	0	X	
18	2-13-86	25.4	8	3.2	24	10	0	0	0	11	78	0	X	
19	2-17-86	63.0	12	5.3	48	55	19	0	24	10	11	70	X	
20	3-02-86	165.6	24	6.9	0	0	0	0	0	0	0	136		X

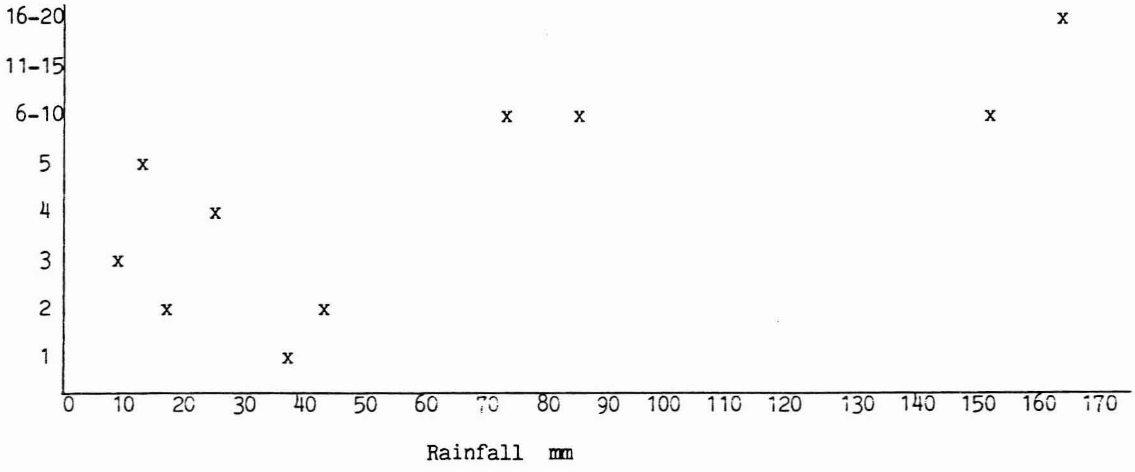
Table I

Rain on Snow Events



Avalanche Days
Rainfall Amount vs. Days Since Last New Snow

FIGURE 1



Non Avalanche Days
Rainfall Amount vs. Days Since Last New Snow

FIGURE 2

from one day to more than twenty days.

Avalanche Occurrence Versus Total Rainfall

Avalanche days, all of which had snow within the preceding three days, and the four Non-Avalanche days with snowfall within the preceding three days were compared to total rainfall (Figure 1 and 2). This analysis showed little rainfall was needed to produce avalanches if there had been snow within the preceding three days. Event #1 had only 16.3mm (.64") total rain, nevertheless, this amount produced avalanches. There was a cluster of Avalanche days around the 25 mm (1") rainfall mark. Non-Avalanche days with snow in the preceding three days had from 9.9 mm (.39") to 42.7 mm (1.68") rainfall.

This analysis demonstrated little rainfall is needed on new snow to produce avalanches. It also illustrated heavy rainfall does not always produce avalanches. Events #8, #9, #11, and #20 had large rainfall totals from 73.7 mm (2.90") to 165.6 mm (6.52") but did not produce avalanches. Three of these events had no snow within the previous 5 days and Event #20 with the largest rainfall had no new snow within the preceding 15 days.

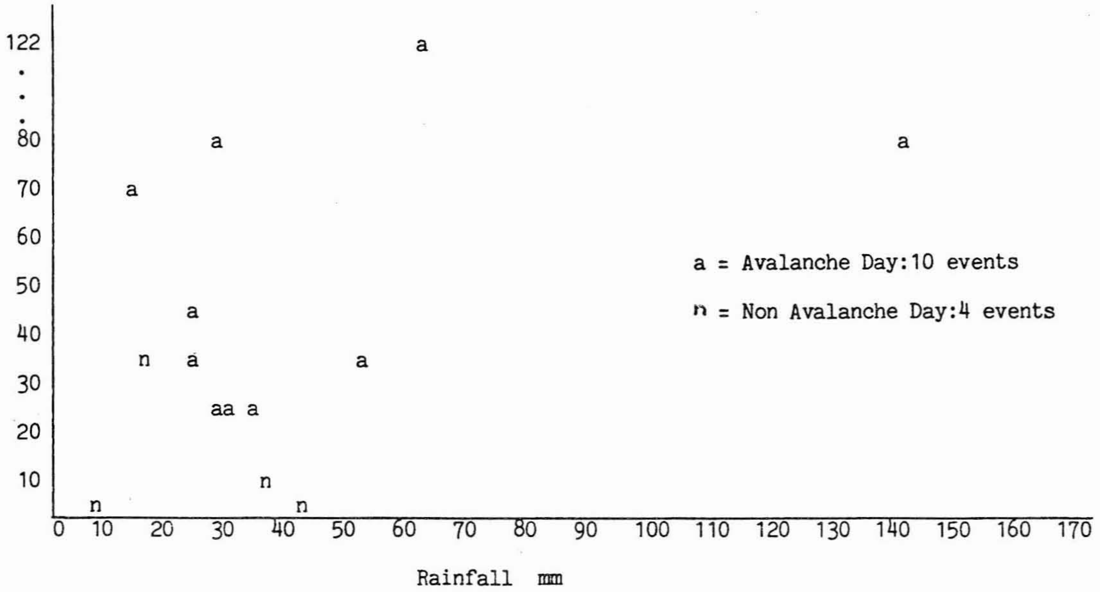
Snowfall Amount Versus Rainfall Amount

Fourteen events were evaluated with respect to the total snowfall and total rainfall within the preceding three days. Ten of these events were Avalanche Days and four were Non-Avalanche days. It appears from Figure 3 that the higher the new snow three day total, the less rainfall it took to produce avalanches. This is evident along the dashed line in Figure III. This finding must have some limit, although Event #1 with 70 cm (28") new snow produced avalanches with only 16.3 mm (.64") rain, and Event #12 with only 25 cm (10") new snow produced avalanches with 29.2 mm (1.15") rain.

Snowfall Amount Versus Rainfall Intensity

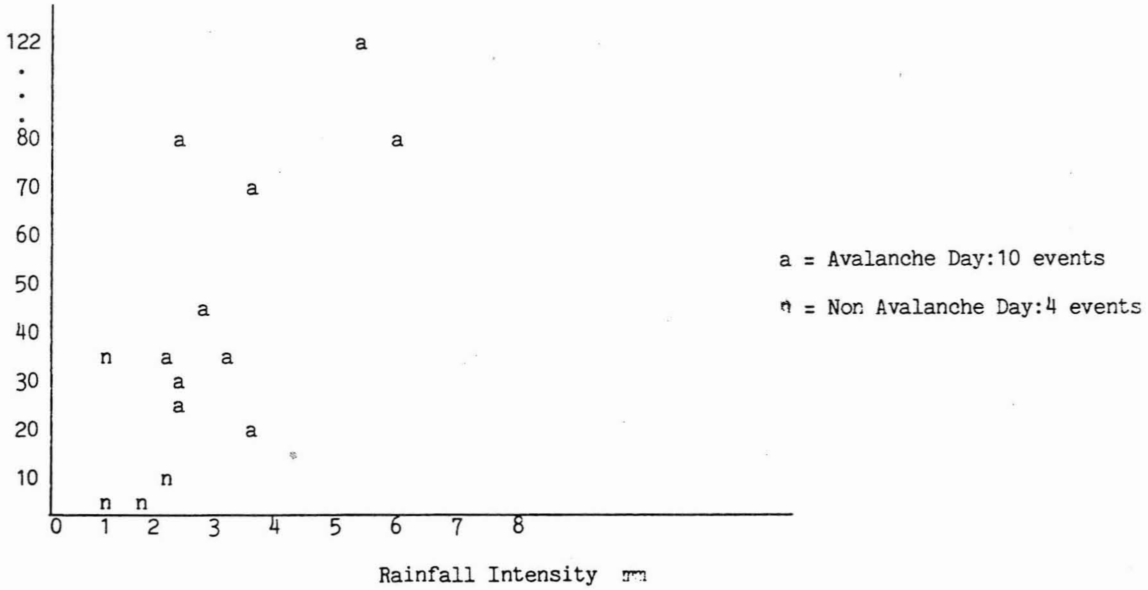
Rainfall Intensity was compared to three day snow fall amounts (Figure 4). Rainfall Intensity was defined as the amount of rain which fell in one hour. Some events had rainfall time intervals which were well documented. For those events Rainfall Intensity was calculated on the known rainfall periods. For the other events, the preceding 24 hours was used to calculate Rainfall Intensity. Fourteen events were analyzed. All had snow within the previous three days. Ten were Avalanche days and four were Non-Avalanche days.

Avalanche days only occurred with Rainfall Intensity of 2.2 mm (.09") per hour or more. There was only one event with a large snowfall total and a Rainfall Intensity of less than 2.2 mm (.09"). This was Event #7. It was a Non-Avalanche day



Previous Three Day Snowfall vs. Rainfall

FIGURE 3



Previous Three Day Snowfall vs. Rainfall Intensity

FIGURE 4

and had a snowfall total of 35 cm (14") and a Rainfall Intensity of 0.8 mm (.03").

From this analysis, it appears there may be a Rainfall Intensity below which avalanches will not be produced. Due to the limited number of events analyzed, it should not be assumed this value is 2.2 mm (.09").

EFFECTS OF SIMULATED RAIN ON NEW SNOW

To study the effects of rainwater on new snow a simple experiment was performed. A small spray bottle was used to apply approximately 10 mm (.4") of dye water to newly fallen snow. The purpose of the experiment was to track the flow of the liquid water in new snow. The dyed water was applied to 25 cm (10") of new snow on both a flat and inclined surface. The snow fell at a density of 90 Kg/m_3. The new snow contained a thin crust 5 cm (2") down from the surface. This crust was formed by a slight temperature rise during the snowfall. The water was applied the day following the snowfall by which time the density had increased due to settlement (Figure 5 & 6).

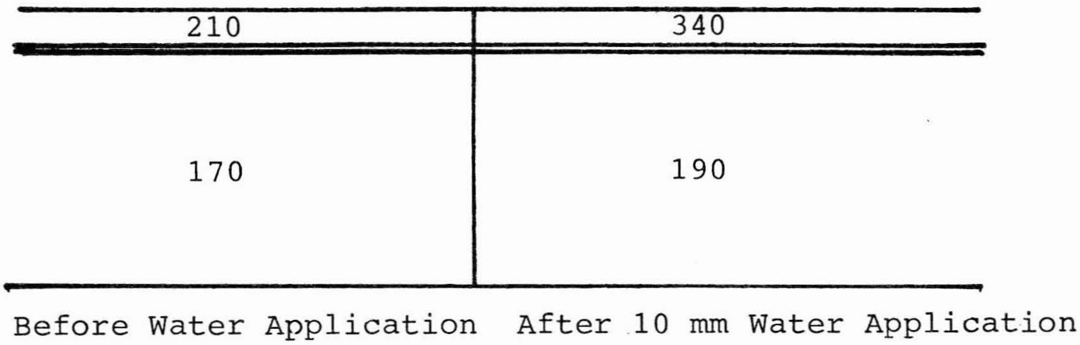
The following sequence took place on the flat surface:

Time	Observation
10:29	Begin water application
10:34	End water application
10:43	Dye pools on crust
10:56	Dye percolates to 12 cm (5") in flow channel
11:07	Snow settled 3 cm
11:29	Water percolated to old,new interface

The following sequence took place on a 20° inclined surface:

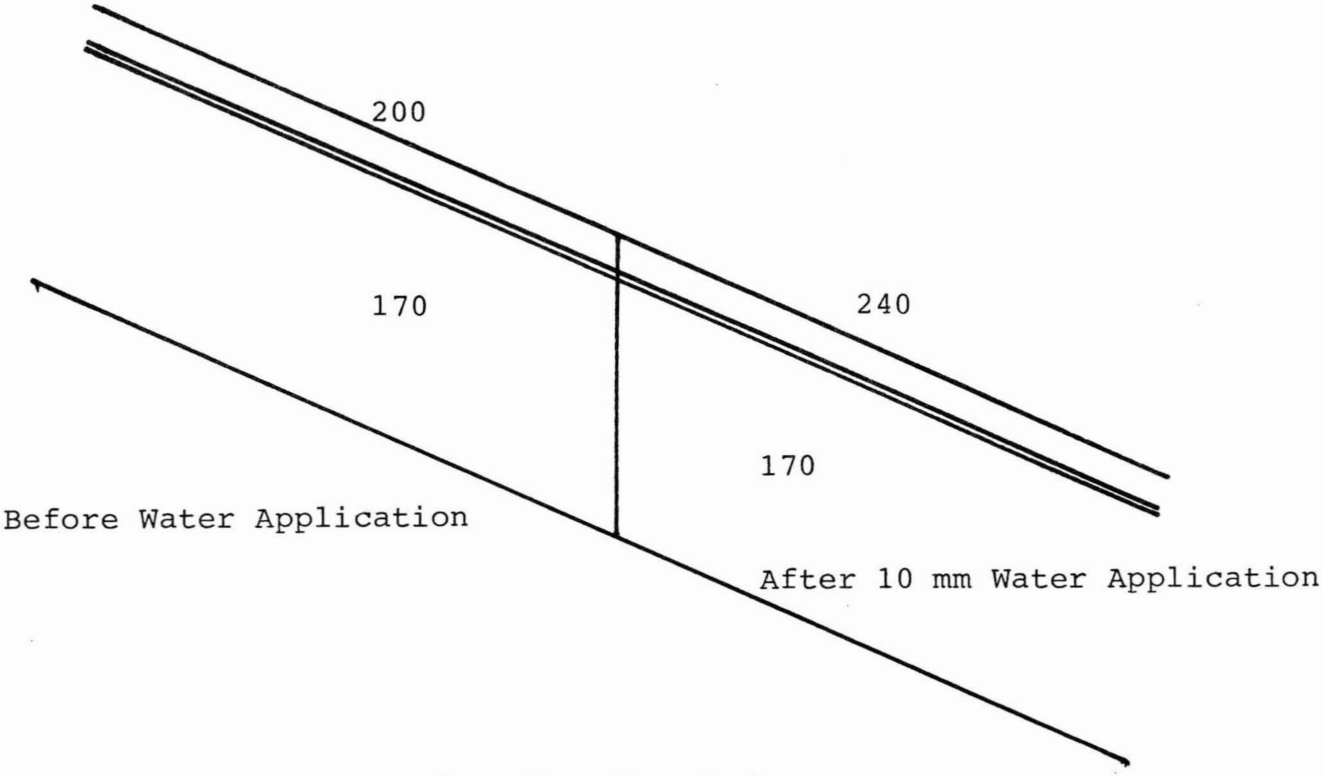
Time	Observation
11:34	Begin water application
11:39	End water application
11:47	Water percolated to crust
12:30	Dye traveled downslope 15 cm along crust No penetration below crust

As can be seen from Figures 5 & 6 there were differences in the effect the liquid water had on the density of the snow on the flat surface compared to the inclined surface. The snow above the crust on the flat surface had a density increase of 150 Kg/m_3 whereas the snow above the crust on the inclined surface only increased by 70 Kg/m_3. Below the crust the snow density on the incline showed no increase from the application of liquid water. The flat surface snow density increased by 20 Kg/m_3.



Snow Density Kg/m_3
Flat Surface

Figure 5



Snow Density Kg/m_3
20° Incline

Figure 6

Although this simple test is not conclusive it does demonstrate liquid water applied to new snow on an incline moves downslope as well as verically down. It also appears minor differences within the new snow may route liquid water downslope along discontinuities. In this case the liquid water traveled downslope along the crust and did not penetrate it. This may be the reason for the smaller increase of snow density above and below the crust. The water moved downslope and out of the water application area.

DOWNSLOPE WATER MOVEMENT AND AVALANCHE ACTIVITY

Observations of avalanches produced by the rainfall in the twenty events analyzed demonstrated many avalanches occur after the onset of rain. In some events, the avalanches ran within minutes of the commencement of rainfall. This quick response of the snowpack to rain water eliminates the possibility of rain water percolating to some lower snow layer, lowering the sheer strength and producing an avalanche.

Some mechanism other than the weakening of a basel layer may be producing these avalanches. One explanation could be the addition of the rainwaters weight increases the load, thereby increases the stress resulting in a failure. This may be the case for some of these avalanche occurances, but experience has demonstrated the equivalent weight in new snow would not have produced avalanches in some of these situations. Other causes need to be explored.

The application of simulated rain water to the inclined slope showed a tendency for water percolation to be downslope rather than vertically down. Similar observations were made by (Kattleman, 1986). He found water would move down a 5^{o} slope several meters before percolating more than a few centimeters below the snow surface. He also found slight discontinuities such as minor differences in grain size were capable of routing water downslope. This finding is similar to the water traveling downslope along the crust in the simulated rain experient.

Following a rain on new snow event in December 1987, several snow pits were excavated on inclined slopes to determine the depth and effects of water percolation. 50 cm (20") of new snow with an average density of 130 Kg/m^3 fell in a twenty four hour period. This was followed by 12.5 mm (.5") of rain over four hours. A few natural and many explosive released avalanches resulted from this storm. The profiles revealed a layer of water saturated snow 7.5 cm (3") down from the surface with the snow above noticeably less wet. Below the saturated layer at 7.5 cm (3") the snow was dry with no signs of liquid water percolation. All profiles were taken approximately six hours after the onset of rain. It appeared the rain water was flowing downslope in the top portion of the new snow with little movement vertically down.

(Perla, 1980) found as the liquid water content of snow increases it assumes a lower angle of repose. (Schaerer, 1981) states inclined snow layers experience an increase in creep and glide velocities with an increase in liquid water content. These observations may give some insight to the causes of avalanches produced soon after the onset of rain.

Some observations have illustrated rain water concentrates in the upper section of a new snow layer on an inclined surface. This liquid water also flows downslope within the same upper section of the new snow layer. For some time interval the liquid water does not percolate vertically down, thus the lower section of the new snow layer remains relatively dry. If the angle of repose of snow decreases with an increase in liquid water and the glide and creep velocities increase with an increase in liquid water, it follows that within the new snow layer the upper portion with a higher liquid water content may be traveling downslope faster than the lower dry section.

If the above assumptions are correct, the snow layer moving downslope at a higher velocity than the layer below would result in additional stresses in the snowpack possibly leading to avalanches. The accelerated creep rate of the upper section of the new snow layer could transmit stress deeper into the snowpack, particularly if there was some bond between the new wet snow and new dry snow. In effect the upper wet snow layer would be pulling the lower snow layer downslope with it. Should there be a weak layer in the new dry snow or the older snow below, this pulling may increase the stress on the weak layer and produce a shear failure.

A similar argument can be made for an increase in upper layer surface tension. In addition to an increase in tensile stress at slope transition areas due to accelerated creep in the top of the new snow layer, the additional effect of the new snow settlement due to rainfall may play a role. Tensile strength in avalanche crown areas may be decreased due to settlement producing less bond area within the potential slab.

EXPLOSIVE RELEASE: RAIN ON SNOW AVALANCES

Artificial release with explosives on wet snow avalanches has been found to be ineffective. Wet snow does not respond to explosive control as does dry snow. The physical properties of wet snow suppresses the propagation of explosive shock waves through the snowpack. Wet snow tends to be less brittle and more fluid than dry snow. This property appears to lessen the effectiveness of explosive control. Most wet snow avalanche forecasting is done for wet springtime avalanches. For this type of forecasting of wet avalanches, meteorlogical factors, particularly temperature must be used. Generally the snow cover must have a temperature of 0.0 c and liquid water must be present. Often this type of avalanche runs naturally when liquid water lubricates and weakens a basel layer.

Rain on snow avalanche events must be divided into two categories. The first category is similar to wet springtime avalanches. Rain falling on old snow can create an isothermal snowpack with snow temperatures of 0.0 c. During these conditions, water may percolate and develop lubricating layers resulting in wet slab avalanches. For this type of avalanches, explosives are usually ineffective and these avalanches must be forecast with the same methods used for springtime wet avalanches. Predicting the timing of these avalanches is difficult as the pathway of liquid water through the snowpack is often difficult to determine. Large safety margins must be used when forecasting these events.

The second category of rain on snow avalanches occurs when rain falls on new snow. In these situations explosive control is often effective in releasing slab avalanches. Timing of explosive use is critical. The snowpack during these periods often consists of wet snow on the surface with dry snow below. Explosives must be used early in the rainfall period while the snowpack is subjected to the additional stress of accelerated creep in the new snow layer. Explosive control performed later, usually will not produce avalanches. (Gerdel, 1954) found the detention of rain water on new snow high during and immediately after the precipitation period. This high detention capacity was only temporary. Four hours after the cessation of rain, most of the water had drained from the new snow. The percolation of the rain water may relieve the additional temporary stress in the new snow. Additionally, the percolating water appears to wet the snow below, thereby suppressing the propagation of the explosive shock waves.

A good example of the short time period of explosive effectiveness occurred at Alpine Meadows on December 9, 1987. 50 cm of new snow fell during the night of December 8 and the morning of December 9. This snowfall was followed by rainfall at daybreak on December 9. With the onset of rainfall, a few small natural slab avalanches fell. Explosive control was performed with an avalancher shortly after the rain began. All explosive charges brought down slab avalanches. Several hours later slopes with similar aspect and steepness were shot. No avalanches were released. There was no evidence these slopes had avalanched naturally.

CONCLUSIONS

The analysis of the twenty rain on snow events showed a relationship between the time interval since the last new snow and avalanche activity produced by rainfall. All avalanche days had new snow within the three days preceeding rainfall. It also showed the more new snow within the three days prior to rainfall, the less rain it took to produce avalanches. No avalanches were produced by Rainfall Intensities of less than 2.2 mm (.09") per hour and large rainfall totals did not always produce avalanches. New snow had to be present.

The experiment to simulate rain on new snow indicated liquid water applied to an inclined slope may travel downslope more than vertically down. There appears to be a relationship to the lower angle of repose of wet snow and increase glide and creep velocities of wet snow to avalanches caused by rain on new snow. The mechanical processes of accelerated creep, differential creep and increased tensile stress brought on by rainfall on new snow may be responsible for some avalanches evaluated. Explosive control of rain on snow avalanches was found to be effective if applied within a critical time period.

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