SNOW CREEP AS A MODEL FOR POSTCONTROL RELEASE

by Thomas E. Pratt
Geophysical Technician (Electrical Division)
CGG American Services, Inc. Denver CO

Abstract.--Field experiments indicate that the compressional blast of an explosive can cause a substantial reduction in the rate of snow creep (10-45%) in the immediate area of the bomb crater. Thus a weak point in the slab (caused by differential creep) may be artificially produced and vulnerable to postcontrol release.

INTRODUCTION

Preliminary research indicates explosive stability tests may increase strain within the snowpack if an avalanche is not triggered by the explosive. It is thought that the compressional blast of an explosive causes a reduction in the rate of snow creep in the immediate area of the explosive test. Therefore, differential creep rates may occur simultaneously in the vicinity of the bomb crater and the resulting strain build-up increases snowpack instability.

The following definitions are provided for clarity:

snow creep: time-dependent plastic deformation;

postcontrol release (PCR): an avalanche, most often a slab (depth of fracture often exceeds 1m) which occurs either naturally or artificially after an explosive test has failed to release the slope.

PCR may be further categorized by the following:

long term PCR: PCR in which one hour or more has lapsed between time of explosive control and time of avalanche.

The proposed snow creep model is most valid for cases of long-term PCR. Because snow creep is a time-dependent process, sufficient time must pass before the induced differential creep rates attributed to the explosive test can produce enough strain to increase snowpack instability.

PAST RESEARCH

Field research undertaken in 1981 involved the monitoring of surface snow creep over a short time span (one to three days). Measurements were taken twice a day (once in the morning and once in the afternoon) before and after an explosive (1 kg HDP cass primer) was detonated 46 hours into the experiment. Measurements were made by triangulation using two Kern six-second theodolites and triangulating from base line to surface targets[1] on the test slope (average slope angle approximately 26°). As the snowpack moved, the targets were carried downslope and distances could be calculated by the changes in horizontal and vertical angles.[2] Before the explosive was detonated, various weather data were collected in hopes of distinguishing the effects of the explosive from the fluctuating weather conditions that affect the rate of snow creep (table 1). Figure 1 shows the results of two targets that were placed on each side of the bomb crater on the same horizontal line across the slope.

CURRENT RESEARCH

Because the 1981 experiment measured surface creep only, there was a need to determine what effects an explosive has on snow creep below the surface and what size area is affected in general. Sawdust columns were chosen for this purpose and placed at distances ranging from 3.5m to less than .5m from the bomb crater at two different test sites. Both test sites were very similar to each other in elevation (approximately 2400m), steepness (33°-35°), and length of slope (approximately 100m), but varied in aspect (one northeast and one due south). Temperature and density profiles were taken periodically during the three weeks that the sawdust columns were in place (see figs. 2 and 3).

---

[1]The targets were constructed with a tripod-like configuration with a plumb bob for siting purposes hung from the top center point.

[2]In using surface targets and triangulation as a method to determine movement it is impossible to distinguish snow creep from glide. Also if the three legs of the target settle into the snowpack at different rates, the resulting translation of the plumb bob will cause false measurements. This was not considered a problem because the experiment was designed to measure only the relative movement before and after an explosive test. In addition, the temperature 20 cm below the snow surface increased after the explosive test (Table 1) and this should have caused an increase in movement, yet there was a sharp reduction.

Table 1.--Daily weather conditions monitored for five days during the surface snow creep experiment.

	Sunday 3-23-81	Monday 3-24-81	Tuesday 3-25-81	Wednesday[1] 3-26-81	Thursday 3-27-81
MAXIMUM TEMPERATURE °C	4.4	1.6	3.3	6.6	3.3
MINIMUM TEMPERATURE °C	-3.9	-6.6	-4.4	-1.1	-3.3
TEMPERATURE °C 20 Cm. BELOW SNOW SURFACE	-2.0	-5.0	-4.0	-1.0	-1.0
PRECIPITATION Cm.	12.7	0.0	0.0	Trace	12.7
WATER EQUIVALENT Cm.	.38				

[1]The explosive was detonated late Wednesday afternoon, after the last set of readings were recorded for the day.

The sawdust columns were placed in the snowpack (vertically[3]) immediately following detonation of the explosive (1 kg two-component Kinepac). In addition to the sawdust columns surrounding the bomb crater, a control column was placed 10-12m from the crater in order to determine the creep rate at an undisturbed portion of each test site (fig. 4).

DATA INTERPRETATION AND EXTRAPOLATION

Reduction in Creep Rate Following Explosive Test

The 1981 experiment recorded an approximate 50% creep reduction at a distance of 2m from the bomb crater 16 hours after the explosive was detonated (fig. 1). In most[4] of the cases that sawdust columns were used, creep reductions of approximately 10-45% were recorded relative to the control column[5] (figs. 5 and 6). The reduced creep rate is thought to be caused by the compressional blast of the explosive which does two things: (1) it removes the uppermost portion of the snowpack where the compound effect of creep is greatest; and (2) the associated heat causes spontaneous sintering which bonds the base of the crater to the slower creeping snow beneath it, in effect, retarding the creep at a point in the slope. It is evident from 1981 and 1984 experiments that the reduced rate of creep initiates either at, or shortly after the explosion (50% reduction 16 hours after explosive test) and persists for a considerable length of time (10-45% reduction after three weeks).

Propagation of Reduced Creep Rate

The type of propagation pictured is thought to be a chain reaction effect. The snow grains comprising the crater will creep more slowly because of the anchoring effect attributed to the compressional blast of the explosive. This reduction in creep rate is then acquired by the adjoining snow grains through the bonds (sintered grains) which interconnect the snow grains found at the crater with the snow grains located some distance from the crater. Thus, the reduced creep rate which initiates at the bomb crater is propagated through the internal bonding of the snowpack.

Subsequent Strain Redistribution

The redistribution of strain is caused by a reduction in the creep rate which occurs at the bomb crater. The reduced creep rate, which is initially localized at the crater, spreads radially from the crater through the internal bonding of the

[3]Because the sawdust columns were placed in the snowpack vertically, the true creep displacement was not recorded. Instead, relative creep rates were recorded at variable distances from the bomb crater.

[4]In one case at the northeast site, column (6,4) recorded more creep than the control column. In addition, columns (3,4), (4,2) and (7,4) recorded relatively insignificant creep reductions of approximately 3-8%.

[5]Each sawdust column was fitted with a second-degree polynomial regression model in order to estimate the amount of creep at 40, 80, 120 and 160 cm. Each of the fits had a R^2 of at least .95 except column (4,5) at the northeast site. The coefficients in the models were significant at $\alpha = .05$ level.

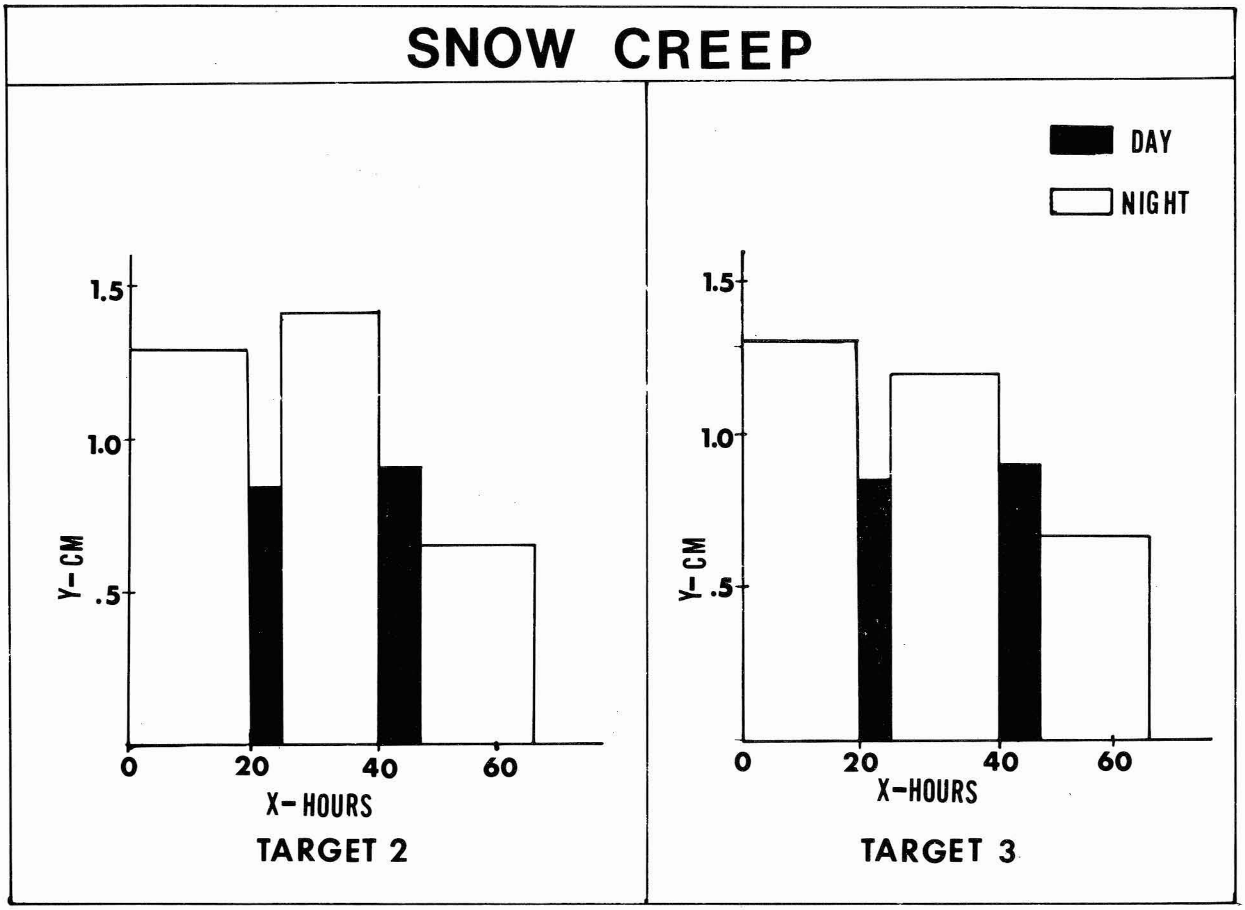

Figure 1.--The Amount of Surface Snow Creep Before and After an Explosive Test. Both targets were located approximately two m. from the edge of the bomb crater. The explosive was detonated after 46 hours (end of the second day of the experiment). The amount of surface creep recorded on the third night was much less than either of the two previous nights even though the snowpack temperature 20 cm below the surface increased (table 1).

snowpack. With increasing distance from the crater, the creep rate increases. This is because the entire snowpack in inter-bonded and at some distance from the crater the snow creep will continue at its normal rate, unaffected by the explosive. Thus, at any given point between the bomb crater and some point distant enough to be virtually unaffected, there will be two opposing creep rates; the reduced rate which is propagated from the crater and the normal rate which is propagated from points distant enough to be unaffected by the bomb blast.

At this time the net result of this strain redistribution is not clear. It is assumed that a compressional zone would develop up-slope of the crater, and a tensional zone would develop either at, or directly down-slope of the crater. In addition, a zone of shear strain may develop laterally on each side of the crater. It is believed that all of these various zones of strain would be concentrated in a relatively small circular zone, perhaps 10m in diameter.

Snowpack Most Susceptible to Creep Reduction and Subsequent Propagation

Creep Reduction

The percentage of creep reduction following explosive stability tests appears to be dependent upon the total snowpack depth. The more shallow the snowpack the greater the effect of the explosive in causing a reduction in the creep rate. This is because a larger percentage of the snowpack is affected by the compressional blast of the explosive. Although field data is limited, the significance of snowpack depth is implied in table 2.

Propagation

It would appear that the most critical factor affecting the propagation of a reduced creep rate from the crater to areas surrounding the crater would be the strength of the internal bonds; i.e.,

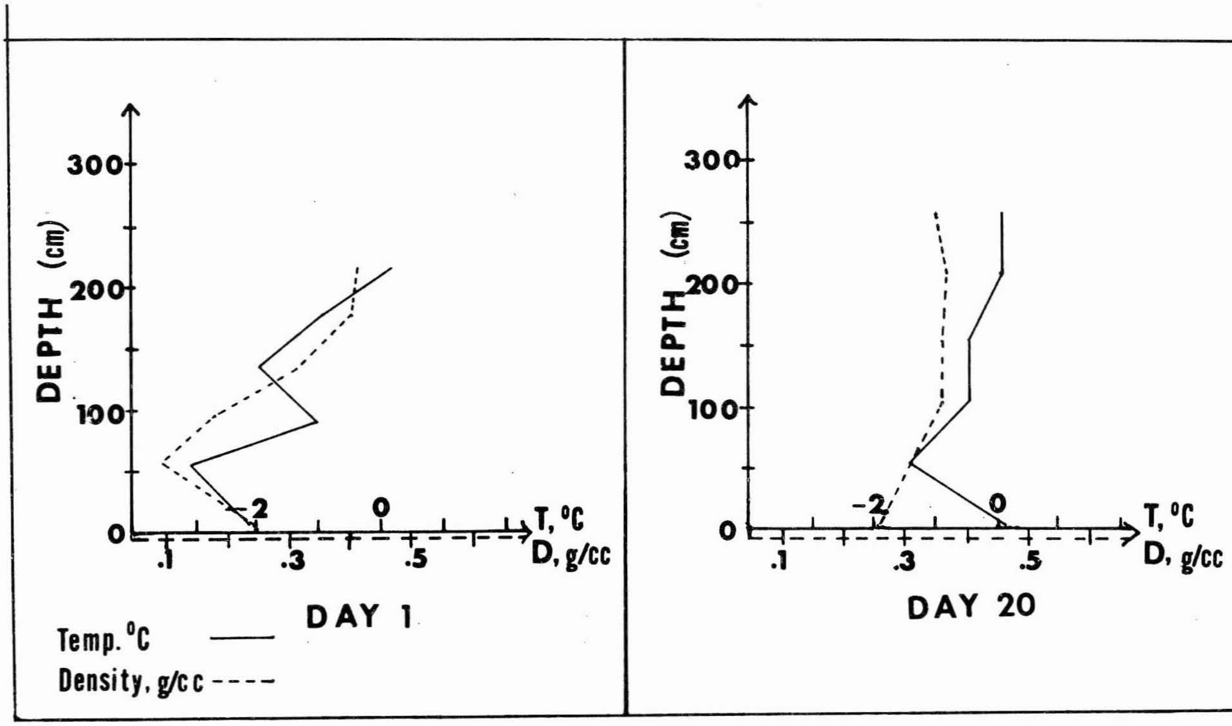

Figure 2.--Temperature and Density Profile Northeast Aspect.

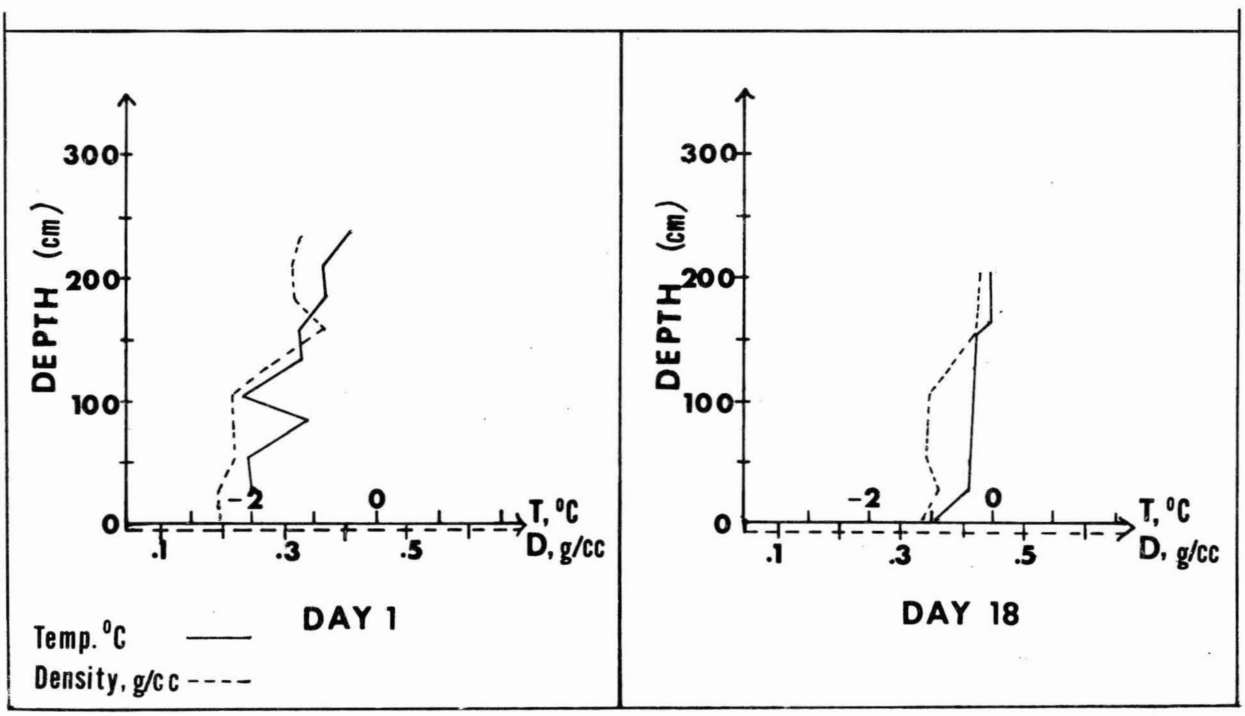

Figure 3.--Temperature and Density Profile South Aspect.

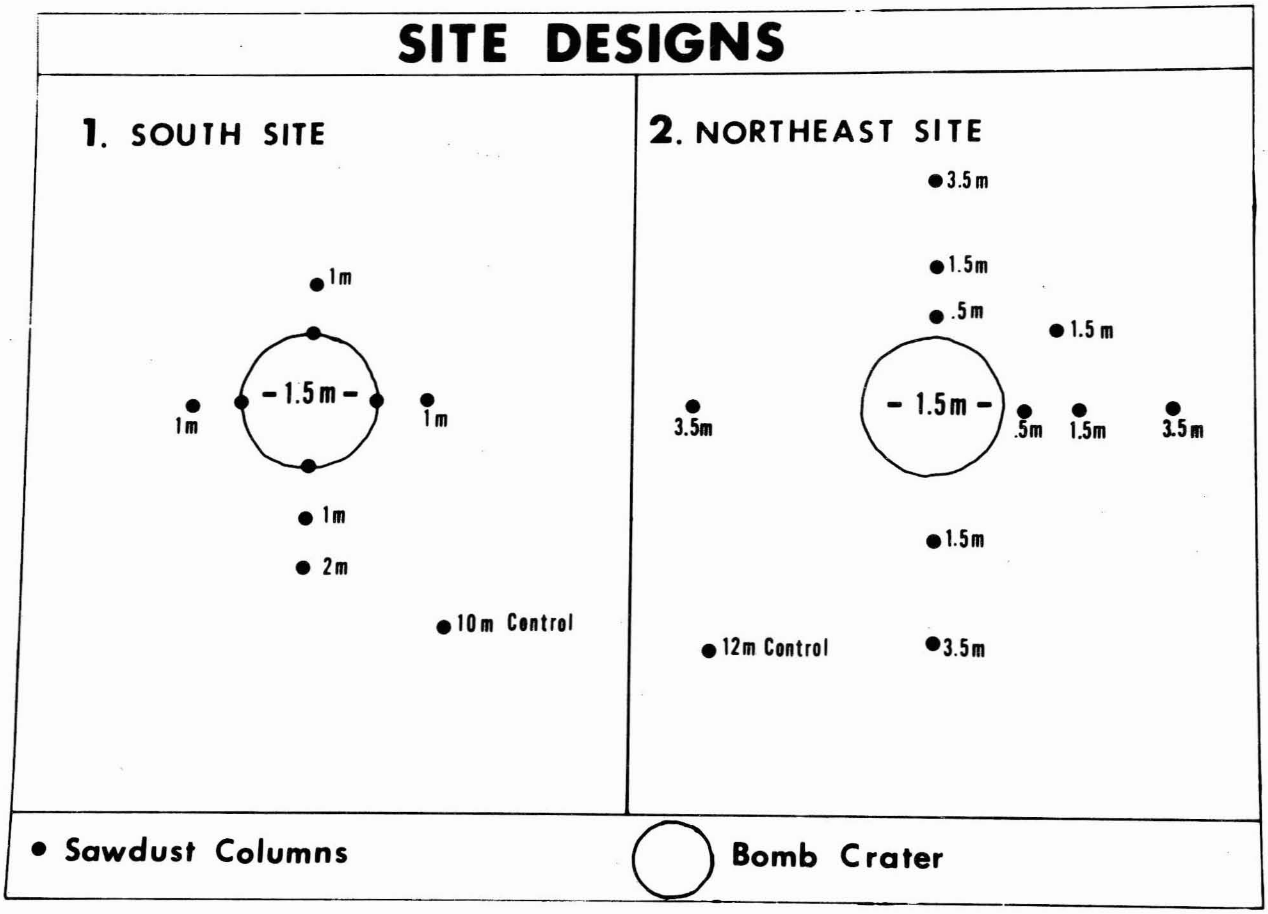

Figure 4.--Sawdust Column Pattern for South and Northeast Site.

Table 2

Field Site	Approximate Distance From Crater	Average Snow Depth	Average Creep Reduction
1981 South Aspect	2m	178 cm	50%
1984 South Aspect	1m	203 cm	40%
1984 Northeast Aspect	1.5m	228 cm	20%

how well the snowpack is sintered. Under conditions of poor sintering, as would be found in a dry, low-density snow, or very wet isothermal conditions, propagation would be expected to be minimal. On the other hand in a well sintered snowpack, such as a slab, one would expect propagation to be enhanced. This would result in a larger area being influenced by the bomb crater.

POSTCONTROL RELEASE: CHARACTERISTICS AND CASE HISTORIES

Postcontrol releases are most common in the Rocky Mountain region in the early season (20 of

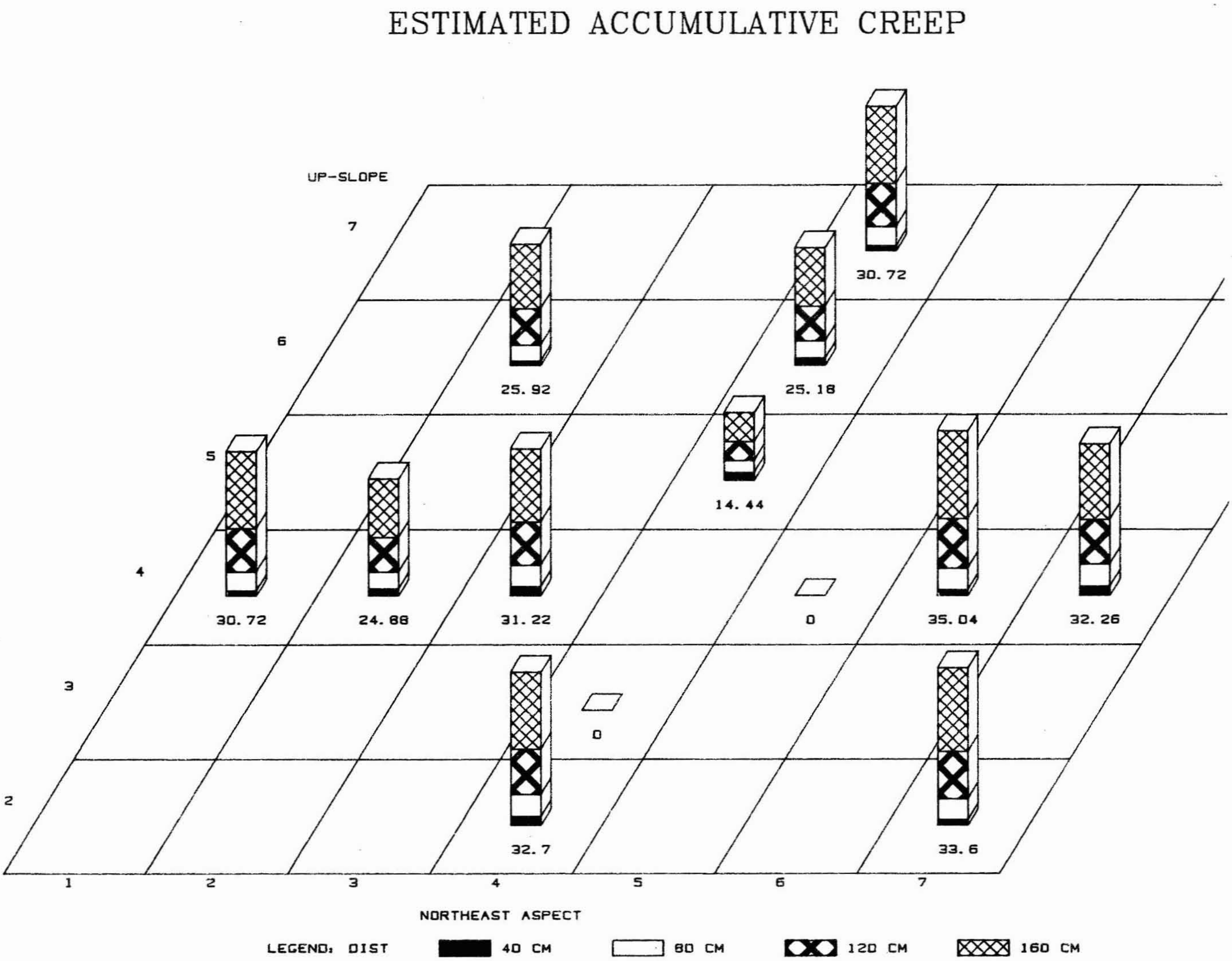

Figure 5.--Estimated Accumulative Creep Northeast Aspect. The number at the base of each bar graph represents the sum of the estimated accumulative creep at 40, 80, 120 and 160 cm. The various patterns in each bar graph represent the relative amount of estimated creep at four distances (from ground to snow surface) shown in the legend. The bar graph representing the control column is located at the lower right corner of graph (column 7, row 2, i.e., 7,2). Center of graph (4,4) represents the location of the bomb crater. For scale, refer to figure 4.

29 study cases occurred between November 1 and January 30). The shallow snowpacks combined with cold temperatures generate high temperature gradients which produce TG metamorphism. In addition, the snowpack rarely undergoes compaction because of limited skier traffic (5 of 27 cases[6] of PCR are known to have occurred on opening day) and this causes an increase in vapor transport, creating an ideal environment for the growth of mature TG grains. Additional snowfall and wind loading may create a situation of deep slab instability in which the TG grains at the base of the slab act as the failing weak layer. This situation can be quite unpredictable (as far as explosive control measures are concerned) and is the environment most commonly

[6]Although 29 cases of PCR have been studied, two did not involve ski areas.

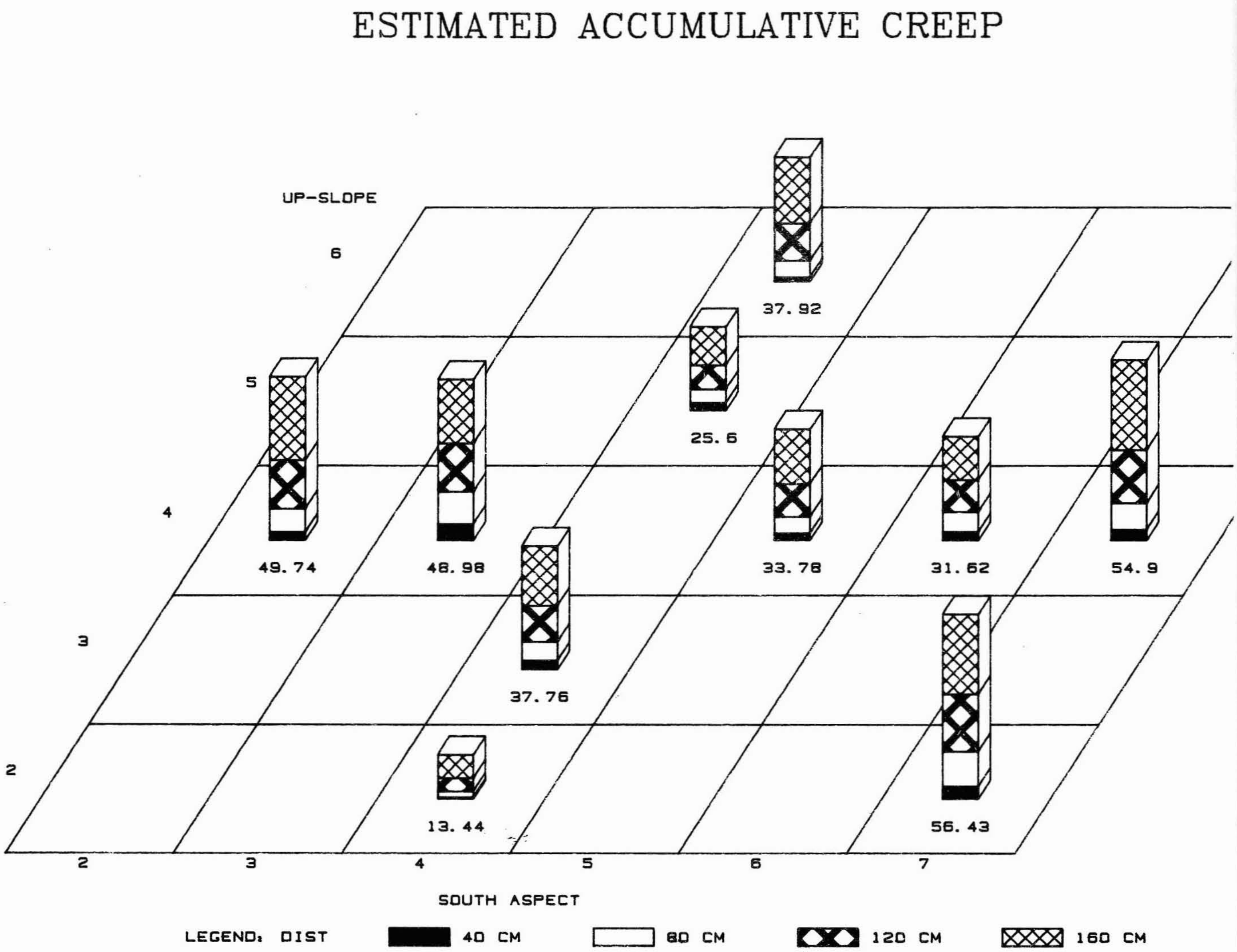

Figure 6.--Estimated Accumulative Creep South Aspect. The same description as in figure 5.

associated with the PCR[7].

In this study the cases of PCR that are associated with changing weather conditions (i.e., snow and/or wind loading) which occur between the time of avalanche control and the time of PCR have been ignored. This is because changing weather conditions may play a significant role in affecting the stability of the slab. Therefore in developing a snow creep model for PCR, it was decided to eliminate weather-related cases and study only those cases in which there are no acceptable explanations for increasing instability resulting in slope failure following explosive tests.

[7]Of 11 cases of PCR in which the running surface is identified, TG grains were present in 9.

For the past two years, a questionnaire on postcontrol avalanches has been distributed to approximately 50 ski areas in the United States and Canada in order to compile much needed information concerning the characteristics of post-control releases. Because their occurrence is quite rare, there is a tremendous lack of well-documented cases. Due to the problem of rare occurrence, the questionnaire served to include any instances in which the effectiveness of explosives was questionable as a means of controlling deep slab instability.

The following eight cases are considered to be possible examples of explosive-induced strain build-up, resulting in increased instability and slope failure:

1. Jackson Hole, 1971. On opening day of the upper mountain, Rendezvous Bowl was bombed with 28 kg of explosives with no results. After nearly three tram-loads of skiers had made runs down the bowl, the slope avalanched. The crown line split several of the shot holes.

2. Steamboat, 1972. Five 1 kg and three .5 kg charges were used in the upper Big Meadow with negative results. After five hours the slope avalanched. The crown line was six meters below three of the shot holes.

3-4. Bridger Bowl, 1978. Two postcontrol releases occurred on the opening day of the upper mountain, one soft slab, and one hard slab. Two skiers triggered the release of the soft slab avalanche two hours after explosive control. The crown face was one meter deep and was located less than five meters down-slope of the bomb crater. The hard slab avalanche was also triggered by a skier, two hours after explosive control, when he jumped off a small cornice and landed approximately five meters below the bomb crater. The crown face was 1.5 meters deep and fractured the crater.

   Running surface: Mature TG on rain crust.
   Control measures: Ski cut and 1 kg hand charge in each case.
   Total snow depth: 150 cm.

5. Snowbird, 1982. On opening day of the upper mountain, approximately 150 skiers had made runs down the slope before two skiers finally triggered the release of a large (class 4) soft slab avalanche. The crown face was 110 cm deep and occurred three to ten meters below three craters which were 24 hours old and fractured two craters which were less than three hours old.

   Running surface: Beginning TG.
   Control measures: Ski cut, and a total of 5 hand charges--two 2 kg, and three 1 kg.
   Total snow depth: 150 cm.

6. Jackson Hole, 1982. A class 2 soft slab avalanche occurred two hours and 45 minutes after explosive control. A snow ranger triggered the slide while skiing down-slope from one of the bomb craters. The crown face was 60 cm deep and fractured the crater from a 1 kg hand charge.

   Running surface: Surface hoar layer.
   Control measures: Ski cut, two hand charges--one .5 kg, and one 1 kg.
   Total snow depth: Approximately 125 cm.

7-8. Alta, 1982. In both cases the avalanches were triggered by explosives after explosives had already been attempted once. In each case when the explosive worked effectively it was placed directly down-slope of the pre-existing crater. In one case a 1 kg hand charge proved effective in releasing a soft slab (depth of fracture 60 cm). The second case involved a hard slab with a fracture depth of 130 cm in which a buried 2 kg charge proved effective. The difference in time between the old craters and the explosives which proved effective ranged from 90 minutes for the soft slab to two days in the case of the hard slab. The control personnel did not feel that weather was a contributing factor.[8]

   Running surface: Beginning to intermediate TG on fog crust.
   Control measures: One 1 kg charge, one 2 kg buried charge.
   Total snow depth: 150-180 cm.

9. Mürren (Switzerland), 1983. Following a two week period of no precipitation, 30-40 cm of snow fell overnight. A skier triggered a soft slab avalanche in the Shilterhorn area two hours after a hand charge had been used on the slope. The slide ran on the old snow surface and the crown line occurred approximately three meters below the crater. Two more avalanches adjacent to the PCR were triggered by use of additional explosives (one hand charge in each case).

   Running surface: Hard sun crust.
   Control measures: One hand charge, size unknown.
   Total snow depth: 120 cm.

A SUGGESTION FOR FUTURE AVALANCHE CONTROL PRACTICES

While explosive tests remain very efficient (over a wide range of snowpack conditions) as a means of avalanche control and hazard assessment, their effectiveness in determining the stability of deep slabs remains questionable. These deep slab conditions often result in the use of more numerous explosive tests and/or larger explosives, depending upon the individual philosophy of the avalanche control personnel.

Bomb Placement

When attempting to control deep slab instability, it is the author's opinion that the creep reduction and subsequent strain redistribution resulting from explosive tests may be used to the advantage of the ski patroller. This is because a zone of tensional strain is suspected to develop either at, or directly down-slope of the explosive test if an avalanche is not triggered by the explosive. The zone of tensional strain is a vulnerable weak point in the slab and may be subject to failure if a second explosive is used (directly down-slope of the preexisting crater). In addition, the vulnerability of this area to

---

[8] Although weather was not a contributing factor, the control personnel reported that the "tidal effect" (earth tides) was a contributing factor. In addition, they believed that buried charges were the most significant factor during this particular avalanche cycle.

explosives is increased because the suspected tensional zone is located near the surface of the slab. Therefore, it is subjected to much more of the initial shock of the explosive, compared to the weak layer at the base of the slab which is partially insulated from the explosive by the thickness of the overlying slab.

Time Allotment for Maximum Strain Development

The optimum time required between the initial explosive and the second explosive in order to create maximum instability (tensional zone development) is not known. It is believed that two primary factors are involved: (1) the time-dependent nature of snow creep; and (2) the self-stabilizing quality of the snowpack. Because snow creep is a time-dependent process, sufficient time must pass before the reduced creep rate attributed to the explosive test can produce enough strain to increase snowpack instability. This period of strain build-up is thought to be dependent upon two factors: (1) total snowpack depth; and (2) to less of a degree, internal snowpack temperatures. The total snowpack depth is critical because the more shallow the snowpack, the greater the effect of the explosive in causing a reduction in the creep rate. It is suspected that the more drastic the reduction in the creep rate, the quicker the development of the tensional zone. The internal temperature of the snowpack is important because a warm snowpack will creep faster than a cold snowpack and this may also cause a more rapid development of the tensional zone.

The strain build-up, resulting in tensional zone development, is thought to eventually subside with increasing time. This is attributed to the visco-elastic properties and self-stabilizing quality of the snowpack. With increasing time, the various zones of strain are thought to be distributed over a larger area, creating a more uniform distribution and resulting in increased stability.

In summary, time is required for the initial strain build-up that results in increased instability. It is suspected that several hours to a day is required for maximum strain build-up, depending on snowpack conditions; more shallow, warm snowpacks are likely to build up strain more quickly. With increasing time (in excess of two days), the snowpack is believed to undergo self-stabilization and the instability created by the bomb crater will correspondingly dissipate.

CONCLUSION

Although more data is necessary, the author believes that the proposed snow creep model is a reasonable possibility for explaining the occurrence of postcontrol releases. Certainly more field experiments and analysis are needed to either lend support to, or disprove the hypothesis.

The possible incorporation of the snow creep model for controlling deep slab instability (described in the preceding section) is warranted only in rare instances of avalanche control when the results of explosive tests are most questionable. It is believed that the degree of instability created by explosive stability tests is very small and insignificant in nearly all cases, otherwise postcontrol releases would be common occurrences. Only when a slab is in a very critical state can the small degree of suspected instability attributed to explosive tests become a significant factor. The snow creep model may be one additional factor to be included in the extensive list of variables associated with avalanche control and forecasting. It is the author's opinion that the instability caused by differential creep rates is the least significant factor to be considered when evaluating stability. The snow creep model is offered as an experimental alternative to larger, more numerous explosives which are all too often the accepted means of controlling deep slab instability.

BIBLIOGRAPHY

Williams, Knox, 1978. Postcontrol Avalanche Release Report. Deuxiemme Rencontre Internationale sur la Neige et les Avalanches. Grenoble, France.

ACKNOWLEDGMENTS

Richard Allan, Statistical Consultant, Montana State University, Bozeman, Montana.

Bridger Bowl Ski Patrol, Bozeman, Montana.

Dr. John Montagne, Professor of Geology, Montana State University, Bozeman, Montana.

Departments of Civil Engineering/Engineering Mechanics and Earth Sciences, Montana State University, Bozeman, Montana.