FIELD MEASUREMENT OF SNOW CREEP IN A RADIATION SNOW CLIMATE, SAN JUAN MOUNTAINS, COLORADO

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ABSTRACT: Real-time creep data may one day be incorporated into avalanche forecasting Although numerous methods of creep data collection have contributed to the practices. understanding of snow mechanics and creep processes, no standard method has been developed that could provide strain data in all types of snow conditions. This study evaluated several methods of strain data collection in a radiation snow climate, with a focus on creep behavior near prominent melt-freeze crusts. Phase I took place at Molas Pass. CO in April and May 2003. Three different creep measurement methods were evaluated. Creep, settlement, weather, and snow stratigraphy data were collected at five-day intervals. Phase II took place at the Center for Snow and Avalanche Studies' Swamp Angel Study Plot at Red Mountain Pass, CO during the winter of 2003-2004. Weather data was available from the CSAS weather station. A Tyrolean traverse was constructed for access to the study area with minimal disturbance to the snow cover. Snow profiles were recorded and sawdust columns and ping-pong ball columns were emplaced at one-month intervals starting December 21, 2003. On March 21, 2004 the columns were excavated and total creep and settlement of the columns were observed. Major differences in creep and settlement above crustal boundaries were observed, but the behavior at those boundaries is still unknown. Settlement was found to be more dominant than creep on south-aspect slopes during winter conditions and on north-aspect slopes during isothermal conditions. Consideration should be given to the effects of heat flow, liquid water flow, and creep pressures when designing creep-measurement experiments.

Keywords: snow creep, avalanches, creep measurement, radiation snow climate, melt-freeze crusts

1. INTRODUCTION

Alpine snow-cover, to the casual observer, appears to be stationary and immobile until it melts away in the spring. In fact, snow is far from immobile, and is continually deforming through the interrelated processes of creep, glide, and avalanching.

When the snow is on level ground, it deforms through compression (settlement), as gravity causes the grains of snow to rearrange to a more dense packing (volumetric or dilational strain as result of uniaxial stresses) (Mellor, 1978).

When the snow is on a slope, rearrangement occurs in the down-slope direction. However, not all of the down-slope movement results in densification. Some movement involves shear displacement down-slope without increasing density (deviatoric strain as result of triaxial stresses) (Mellor, 1978).

The ratio of deviatoric to volumetric strain is dependent on the slope angle, and the combination is known as creep. Creep is the slow, viscous internal deformation in snowpacks, and is always occurring (McClung, 1980).

Glide, however, is the slip of the entire snow-pack over the ground or an internal layer within the snow-pack (McClung, 1980). Glide only occurs when liquid water is present to lubricate the interface, such as during the spring melt or following a rain event.

Internal deformation in the form of creep. always occurs prior to avalanche release. Recall that this deformation occurs through two primary modes: (1) discontinuous motion brought about by settlement, and (2) continuous shearing without significant volumetric strain (Mellor, 1978). During snowfall (or wind deposition), the stress on any given element of the snowpack increases with time because of surface accumulation

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(Mellor, 1978). Simultaneously, the strength of that element increases with time because of densification (Mellor, 1978). If the rate of increase of deviatoric stress exceeds the rate of increase of strength, failure, in the form of an avalanche, will occur.

2. BACKGROUND

2.1 Factors Affecting Deformation

displavs virtuallv Snow all the complications of behavior known to rheology and fracture mechanics. It is a visco-elastic material with high irreversible compressibility. Triaxial tests have shown that the viscosity of snow is highly temperature, microstructure and strain-rate dependent (Bartelt, 2000). When plotted against stress, dilational and deviatoric strains are strongly non-linear. Yield and rupture strengths cannot be described by classical failure criteria and the above mechanical properties are highly temperature sensitive (Mellor, 1978). In addition, the snowpack is composed of different layers, each with different mechanical properties that vary with time, temperature, and location in the snow-pack.

Through creep snow undergoes large amounts of irreversible volumetric straining. Volumetric straining results in an increase in density as a response to stress. If the amount of stress remains constant, the volumetric strain rate decays exponentially with time, gradually achieving a state of quasiequilibrium between stress and density (Mellor, 1978). This equilibrium is reflected by the typical increase in density that occurs with increase in depth (stress).

2.2 Creep and Avalanche Formation

Snow behaves as a visco-elastic material. Under normal conditions, snow on a slope deforms in shear and compression almost like a viscous fluid (McClung and Schaerer, 1993). In addition to the viscous deformation, a small portion of elastic, or recoverable, deformation occurs (McClung and Schaerer, 1993). The proportion of stored elastic energy increases as the deformation rate increases (McClung and Schaerer, 1993). Normally, the amount of elastic deformation is negligible, but at very high deformation rates, catastrophic brittle fracture (necessary for a

slab avalanche) becomes possible (McClung and Schaerer, 1993).

Dry snow cannot generally fracture unless a critical deformation rate is exceeded that is 100 or more times the rate of deformation experienced during ordinary creep (McClung and Schaerer, 1993). Such a deformation rate is only achievable through some type of disturbance such as a skier or falling cornice (McClung and Schaerer, 1993). When propagations occur without such a disturbance, it is believed that the critical rates are achieved through stress or strain concentrations as a result of an imperfection in the snow structure (McClung and Schaerer, 1993).

When it is failed slowly in shear, snow displays a mechanical property of granular materials known as strain-softening (McClung and Schaerer, 1993). Strain-softening refers to a peak in strength that that is reached during deformation. after which resistance to deformation decreases (McClung and Schaerer, 1993). Strain-softening results in the formation of shear bands or slip surfaces during deformation. These bands of localized deformation can be formed without prior existence of an imperfection, and the combination of imperfections and strain softening is an effective mechanism in producing the critical deformation rates necessary for brittle crack propagation and avalanche release (McClung and slab Schaerer, 1993).

Several field studies have focused on the relationship between creep and avalanche formation. Acoustic emission rates show promise as means of indirectly measuring deformation in the field, as emission rates have been found to be directly related to settlement, creep, and glide, and are an indicator of avalanche release (Watters, 1983). However, most studies have employed some time of strain gauge fixed in place in an avalanche path, with continuous deformation data accessed using a data logger and radiotelemetry.

Sommerfeld (1970) used linear position transducers to monitor creep on an avalanche path on Berthoud Pass, CO. In 1975, a large natural avalanche released at the study. Though one of the strain gauges was destroyed by the avalanche, the upslope gauge was left in place and recorded an increase in strain rate prior to the avalanche event (Sommerfeld, 1979). Conway (1998) used glide shoes and rotary potentiometers to investigate the role of creep deformation in a rain-induced wet snow avalanche event at Stevens Pass, WA. It was found that capillary pressures resulted in a rapid rate of deformation, and that slab thickness is an important factor in limiting strain rate increase (Conway, 1998).

In 1995-1996, strain data was recorded in an avalanche path on Mt. Baldy, Utah using potentiometers to record the deflection of a PVC pipe mounted to a coaxial spring. When avalanche control with explosives was conducted, the sensors were able to record a rapid increase in creep prior to avalanche release, and the elastic response of the snow-pack after release occurred (Rice, 1998).

Although the above studies suggest that real-time creep data could be incorporated in avalanche forecasting, this is not currently done in the United States. Although creep rates are often incorporated intuitively (rate of snowfalls etc.), the addition of standard method of recording snowpack deformation to forecasting practices would not only increase forecasting accuracy but would also provide valuable insights into the not yet completely understood processes of creep and avalanche formation.

Ideally this method would meet the following criteria: It would be relatively safe for the observer; it would disturb the snow cover very little; it would have sufficient resolution to record differences in strain rates between adjacent layers (i.e. creep rate of potential bed surface vs. creep rate of potential slab); and it could supply real-time data-logged and telemetry accessible data.

3. PURPOSE

3.1 <u>The San Juan Mountain Radiation Snow</u> <u>Climate</u>

Much of the previous field research on creep has been conducted in continental or maritime snow climates. The San Juan Mountains, however, exhibit characteristics of an additional type of snow climate, a radiation snow climate (see Map 1).

In the San Juan Mountains, the combination of high altitudes, low latitudes,

and predominantly continental snow climate results in a specific radiation snow climate (Armstrong and Ives, 1976). This is the result of two primary factors. First, extreme diurnal temperature fluctuations in result in gradients of a magnitude temperature sufficient to cause significant recrystallization temperature gradient metamorphism or (Armstrong and Ives, 1976).

Secondly, during the day a substantial amount of solar energy is available to slopes with a southern exposure. This daytime condition causes melt at the snow surface and at night freezes to forms a freeze-thaw crust. These two conditions influence the snow-pack throughout the winter and result in a highly complex and weak snow stratigraphy (Armstrong and Ives, 1976).



Map 1: Snow climate types in the western United States.

From this observer's experience in the San Juan Mountain snow-pack, the aforementioned freeze-thaw crusts are found on all but the most northerly and shaded aspects. Often snow failure occurs just above or below the location of these crusts in the snow-pack. Indeed, a study of fracture line profiles in the San Juan's from 1972 to 1974 revealed that in 69% of all recorded avalanches, failure initiated at or immediately below a freeze thaw crust (Armstrong and Ives, 1976).

Crusts are related to avalanche formation for various reasons. A crust can act as vapor barrier, concentrating the temperature gradient recrystallization process directly above or below the crust and weakening the adjacent unconsolidated snow. An impermeable crust, when lubricated by melt-water from above can result in glide of the upper snow-pack over that crust. If the deformation rate becomes rapid enough, this can result in wet slab avalanche release. However, the same crust, when refrozen, will act as a strong bond between the upper and lower snow-pack and may actually inhibit slab avalanche formation until melt once again occurs.

Because a crust possesses a mechanical strength considerably greater than the adjacent snow layers, with strength defined as the resistance to deformation, it can be assumed that, under the influence of gravity, a crust will deform through viscous creep considerably less than the adjacent unconsolidated layers, introducing a high velocity gradient in a relatively short vertical in the snow-pack. Because distance avalanche release is initiated by a very high rate of viscous deformation, it seems that the high velocity gradient introduced by the crust could produce the imperfection necessary for slab avalanche release.

3.2 <u>Hypothesis</u>

In addition to affecting metamorphism and providing a lubricated sliding surface, the high occurrence of crusts in the San Juan Mountains introduces additional instability which is caused by high variations in viscous shear strain rates between relatively strong, consolidated sun and wind crusts and the adjacent, unconsolidated, relatively weak snow layers.

3.3 <u>Methodology</u>

The above hypothesis was tested in research in two phases between April, 2003 and March, 2004. Phase I evaluated three creep measurement techniques, sawdust profiles, tape measures, and descending height snow stakes during the spring of 2003, with a focus on finding a method with a high enough vertical resolution record to differences in strain rates between adjacent layers. In addition stratigraphy and weather observations were recorded at each visit to the site. The sawdust column method was selected for continuing study. Phase II took

place throughout the winter 2003 – 2004. Sawdust and ping-pong ball columns were emplaced at one-month intervals and the entire transect was excavated March 21. In addition snow stratigraphy and weather observations were recorded at each visit to the site and continuous weather data were downloaded from the CSAS automated weather station.

4. PHASE I

4.1 Location

Phase I took place between April 13 and May 20, 2003. It was north-facing site at 11,200 feet at Molas Pass near Andrew's Lake. While not above treeline, the site has been cleared of trees by a relatively recent rockfall and subsequent avalanches have occurred. The site had an upper and a lower slope which were separated by a cliff and snow pillow area. The study took place on the lower slope which had an average slope angle of about 30 degrees.

4.2 Measurement Techniques

The site was visited at five-day intervals. Snow profiles and weather observations were recorded. Creep data was recorded from the snow stake and tape measure experiments, and sawdust columns were emplaced and excavated.

A height marked sawdust column experiment is a method used by Dave McClung (1980). It involves removing a vertical column of snow and filling the space with uniform sawdust. After a period of time the deformed column is excavated and the total strain is recorded. To interpret the data it must be assumed that the column has similar properties as the adjacent snow and deforms in a similar fashion, without affecting the deformation of the adjacent snow.

Because a sawdust column must be excavated in order to take a single measurement, a technique is needed that can record continuous deformation without significant disturbance of the snow-cover. Tape measures can be used as type of strain gauge for this purpose (Walker, 1994). Figure 1 shows two tape measures housed in a weatherproof box. The box is attached to a 5cm x 5cm post which is hammered into the ground to prevent movement. Wires extending from the tape measures are attached to metal plates placed on the snow surface and subsequently buried by snowfall. As the snow creeps/ glides, the plates move away from the post and movement is recorded in intervals by readings to the nearest mm.



Figure 1: Tape measure strain gauges.

Often field measurement of creep (in snow and other materials) involves placing a pole in the snow and recording its displacement. A type of this experiment was designed by the author and is shown in figure 2. The system consists of six stakes of varying heights: 120 cm, 100 cm, 80 cm, 60 cm, 40 cm, and 20 cm. The bases of the stakes are fitted with circular plastic "snowshoes" in order to minimize sinking. The stakes are placed in a line perpendicular to slope at varying depths so that all stakes initially extend 10 cm above the snow surface. The position of the stakes relative to a wire connected to two fixed points is recorded at regular intervals.



Figure 2: Variable- height snow-stake displacement experiment.

4.3 Creep Data

Table 1 shows creep data that were recorded from the snow stake experiment during the first ten days of the experiment. The experiment was terminated after ten days due to a high rate of settlement which resulted in the shortest three stakes being exposed and then falling over. Note the almost two hundred percent difference in creep between the 10 cm and 110 cm stakes.

Depth(cm)	110	90	70	50	30	10
5 day total						
creep(cm)	3.5	4.0	5.0	4.0	4.5	6.0
10 day total						
creep(cm)	4.0	4.5	6.0	4.5	6.0	-

Table 1: Creep data from snowstake experiment.

Table 2 shows creep data that were recorded from the tape measure experiment during the first ten days. This experiment was subsequently terminated due to an increasingly high settlement rate. This resulted in the wires plunging more and more steeply, recording more settlement and less creep until the plates attached to the wires were suspended in the air. Note the difference in movement in creep between the plate on a melt-freeze crust and the plate on the snow surface.

Location in	On surface	On m-f	
snowpack		crust	
5 day total creep (cm)	2.8	2.1	
10 day total creep (cm)	5.7	3.9	

Table 2: Creep data from tapemeasure experiment

The sawdust experiment recorded about 5cm of creep movement during each 5day measurement interval. Although this does agree with the data for the other experiments, it is believed that this could be error due to the difficulties associated with removing a plumb core while standing on skis. A longer measurement interval is necessary to increase the amount of creep recorded relative to the error.

4.4 <u>Problems</u>

Several problems exist with the data from Phase I. Disturbance of the snow cover was a major problem. It is difficult to extrapolate to other areas when the area at which data was collected was severely disturbed by the skier activity associated with equipment installation and data collection.

Settlement of the snow-pack was also a problem. The tape measure experiment recorded a combination of creep and settlement and as the ratio of settlement to creep increased, it became more and more difficult to infer creep rates. After fifteen days the snow-pack had settled too far and the experiment had to be terminated. With the snow stake experiment it was possible to determine settlement by noting the vertical displacement relative to the reference wire, but as settlement increased, the stakes in the upper snow-pack had settled out and were found lying on the snow surface, resulting in termination of the experiment.

Another problem with the experiments was the potential for burial by new snowfall. During the experiment a small snowfall occurred. If it had been a significant amount it would have buried the box that the tape measures were housed in and the snow stakes and their reference wire, resulting in premature termination of both experiments.

A problem with all the experiments was the heat and liquid water flow pathways that the methods introduced. Ice formation was noted on the stakes and on the plates used for the tape measure experiment. Ice also formed within the entire sawdust columns and near melt-freeze crusts prominent ice columns formed within the sawdust and the snow-pack.

4.5 <u>Results</u>

During the experiment temperatures the snow-pack reached isothermal conditions. This resulted in a dramatic increase in settlement rates and illustrated the need for a method that could measure both creep and settlement rates. The tape measure and snow-stake experiments did provide some useful data. The data indicate a major difference in strain rates between adjacent layers. However, these methods were subject to the problems detailed above and required frequent visits to the site for maintenance and data recording.

Accordingly, the sawdust column technique was selected for continuing study in Phase II. It could provide data over long periods of time regardless of burial and had a better vertical resolution which could potentially record differences in creep between adjacent layers. In addition, total settlement could be determined by recording the column's height when emplaced and comparing it to the column's height when excavated.

5. PHASE II

5.1 Location

Phase II took place between December 17, 2003 and March 21, 2004. It was a southeast- facing site at 11,140 feet at the Center for Snow and Avalanche Studies (CSAS) Swamp Angel Study Site at Red Mountain Pass. The site was near treeline on a small glade bounded by trees above it and to the left and the right and had a flat swampy area at its base. The study took place in the glade's center which had an average slope angle of about 40 degrees.

5.2 Measurement Techniques

Weather data at the site was available from the CSAS automated weather station. At each visit, snow stratigraphy was recorded by conducting snow profiles at the base of the study area and at the CSAS pit plot adjacent to the weather station (about 75 m distant). This allowed comparison of stratigraphy at the two sites.

Because of the problems with disturbance in Phase I, a Tyrolean traverse (see figure 3) was constructed at the site to emplace cores while suspended in the air. This was a steel cable approximately 30 m long, attached to two trees and spanning the transect.



Figure 3: Preparing to place a sawdust in a core while suspended from the Tyrolean traverse used for site access in Phase II

Throughout the winter the Tyrolean traverse was used to emplace sawdust and ping-pong ball columns at one-month intervals. Sawdust columns were conducted as described in Phase I but the column's width was reduced to 45 mm in a attempt to reduce heat and liquid water flow. The ping-pong ball columns were conducted in the same manner but a stack of 40 mm ping-pong balls was used in lieu of sawdust. The balls were spraved in Black Diamond's Globstopper skin wax in an attempt to reduce ice adhesion. The ping-pong ball columns were placed alongside the sawdust columns to compare the two methods. At the conclusion of the winter, the entire transect was excavated and the resultant deformation of the 3 pairs of columns was compared.

5.3 Creep Data

Table 3 shows the maximum creep recorded (in every case at the top of the column) in comparison to the settlement. Placements numbered with an "S" are sawdust columns and those with a "P" are ping-pong ball columns. Note the relatively high amount of settlement in comparison to creep in placements 2S and 2P. Only 2-3 cm of creep over an entire winter seems exceptionally small and possible reasons for this are explained in the problems section.

Placement	2S	2P	3S	3P	4S	4P
Placement	Dec	Dec	Jan	Jan	Feb	Feb
date	17	17	17	17	17	17
Elapsed	90	90	60	60	30	30
time	days	days	days	days	days	days
Max creep	2cm	3cm	12cm	10cm	8cm	7cm
Settlement	28%	19%	57%	55%	71%	72%

Table 3: Comparison of maximum creep to percent settlement (*percent settlement* = (*final height/original height*) x 100)

Table 4 (see next page) depicts the stratigraphy in standard snow profile format for the snow-pack at placements 3S and 3P, which were emplaced on January 17 and excavated on March 21. Stratigraphy depicted is that of the time of excavation. Note the substantial difference in both total creep and total settlement above the lower of two prominent melt–freeze crustal layers.



Table 4: Comparison of sawdust and ping-pong ball column deformation to stratigraphy at time of excavation

5.4 Problems

As in Phase I, in Phase II several problems occurred. One major problem was the unusually warm temperatures which occurred in early to mid March, just prior to the conclusion of the study. This resulted in isothermal snow temperatures in the study area with a substantial amount of liquid water present.

The high rate of settlement may have strengthened sawdust columns by ultimately making them more dense than the surrounding snowpack that they were designed to simulate.

Similarly with the ping-pong ball columns, the high rate of settlement and resultant high pressures crushed ping-pong balls. None of them were smashed flat, but many were indented in multiple places. In general, the amount of smashing increased towards the bottom of the columns, and only occurred in the columns that were in the snowpack for 60 days or more.

In addition, liquid water flow and subsequent ice formation may have strengthened both types of columns. Taking a core out of the snow and filling it with some other type of material provides a preferential pathway for liquid water flow, and resulted in all the columns becoming a dense matrix of ice enclosing the sawdust particles or ping-pong balls.

The various processes described above strengthened the columns relative to the surrounding snow-pack. If the snow did behave in a viscous manner, some of the snow could have been flowing around the columns rather than deforming them, resulting in less apparent creep than actually occurred. This would explain why columns in the snow longer recorded substantially less creep than columns in the snow for less time.

When the columns were excavated, the ground surface was found to be very wet and smooth and had grass blades oriented in the down-slope direction. Hence, it is believed that glide had been occurring, possibly throughout the winter. Unfortunately no reference point had been set up from which glide could have been measured.

5.5 <u>Results</u>

Results of Phase II tend to be more qualitative than quantitative. The various problems described above indicate that the columns did not behave exactly as the surrounding snow-pack did. However, a lot was learned about the relative rates of creep and settlement processes in these types of snow conditions.

Results do indicate that major differences in creep rates above crustal boundaries do occur. However, the extremely long recording intervals used and the rapid change in snow temperatures just prior to excavation make it difficult to interpret the timing of these differences in rates, with the timing being most important to the processes of avalanche formation.

Although disturbance of the snow cover was significantly reduced via the Tyrolean traverse in Phase II of the study, snow is an extremely sensitive medium and the disturbance introduced by any kind of foreign substance in the snow-pack should not be taken lightly. Great care should be taken when interpreting or extrapolating the results of any type of creep measurement experiment.

6. CONCLUSIONS

The following conclusions were made during the course of this study:

- Major differences in strain rates above crustal boundaries were detected, but the behavior close to those boundaries is still unknown.
- Settlement is a more dominant deformation process than creep on south-facing slopes during winter conditions and on north-facing slopes during isothermal conditions.
- Heat and liquid water flow is a major concern when designing creep-measurement experiments in a radiation snow climate.
- The Tyrolean traverse is a safe, low-cost way to access snow study sites with minimal disturbance to the snow cover.

7. IMPLICATIONS FOR FUTURE STUDIES

A hypothetical method of creep measurement that for use in future studies would proceed as follows:

• The Tyrolean traverse could be used for access, and reinforced with a stronger cable and/or attachment points if it were located in a major avalanche path.

- A starting zone would be preferable due to the relevant (to avalanche formation) data that would be gathered and the relatively lower avalanche velocities/pressures that would be encountered if avalanche release were to occur.
- Stratigraphy at the site could be monitored from the cable traverse with a ramsonde.
- A fixed pole in the transect could be used to place linear extension transducers along the pole at fixed heights prior to winter.
- Linear extension transducers or wireless transducers could be placed at preferred heights prior to, during, and after storm cycles and could be used to monitor strain behavior at crustal boundaries.

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