SNOW DENSIFICATION DURING RAIN

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Abstract: Observations and measurements indicate rain often has a major impact on snow slope stability. Measurements to investigate the effects of wetting of low density, alpine snow were made at Snoqualmie Pass, Washington, U.S.A. Results indicate that on first wetting the densification rate can increase by three orders of magnitude. This initial burst of densification occurs independently of the gravitational load and is probably a result of rapid structural changes and grain rearrangement that occurs when liquid water is first introduced. The rate decreases rapidly with time, although it remains about two orders of magnitude higher than that for dry snow of the same density. The rate of densification decreases as density increases. We assume snow behaves as a linear viscous fluid and that the metamorphic and gravitational components of compaction are additive. A simple model of compaction is derived empirically using the measurements. The model fits the measurements very well, although more experiments are needed to determine the dependence of the model parameters on liquid water content.

Keywords

Snow, snow compaction, rain on snow

1. Introduction

Widespread avalanche activity is often observed immediately following the onset of rain. Previous work has shown that the avalanching occurs both before the rain has reached the sliding layer, and before the increase in overburden stress due to the additional weight of water would have caused the slope to fail [*Conway and Raymond*, 1993]. The failure layer is dry at the time of avalanching, and apparently surface perturbations caused by the rain are sufficient to alter slope stability. Here we present and discuss measurements of compaction of natural snowpacks during rain and also experiments in which water was introduced artificially.

Compaction of dry snow at low strain rates has been the subject of numerous studies, many of which have been discussed in reviews such as [*Bader*, 1962], [*Mellor*, 1975], [*Salm*, 1982], [*Shapiro et al.*, 1997]. Accurate descriptions of micro-structural properties are needed to formulate a realistic physical model of snow densification [e.g., *Keeler*, 1969; *Hansen and Brown*, 1987] but application of this type of model is difficult because micro-structural properties are not easily measured. Empirical models are easier to apply and often provide a better fit to measurements than do physical models [*Colbeck et al.*, 1978; *Herron and Langway*, 1980], although caution is needed when applying these models outside the range of the experimental data used to formulate them. Empirical models continue to be used in practical applications [e.g., *Schweizer*, 1993; *Bader and Salm*, 1990] and it is likely that they will remain in use until an easily measured micro-structural parameter is identified.

The vertical rate of compaction $\dot{\varepsilon}_{zz}$ (for positive z in the downward direction), or densification rate $\frac{1}{\rho(t)}\frac{d\rho}{dt}$, of natural snow in response to stress from the overburden $\sigma_{zz}(t) = \int \rho(t) g dz$ is often described by a one dimensional constitutive relationship for a linear viscous fluid [e.g., *Kojima*, 1967]. Metamorphic processes also cause snow density to change independently of gravity and it is convenient to think of the metamorphic component $\sigma_m(t)$ as a stress that is additive to the gravitational stress:

$$\dot{\varepsilon}_{zz} = \frac{1}{\rho(t)}\frac{d\rho}{dt} = \frac{1}{\eta_{zz}}(\sigma_m(t) + \sigma_{zz}(t)) \qquad (1)$$

Experiments show the compactive viscosity $\eta_{zz}(t)$ varies exponentially with density [*Kojima*, 1967], temperature T and liquid water content w of the snow [*Yamazaki et al.*, 1993] and can be written:

$$\eta_{zz}(t) = A_1(w)\, A_2\, e^{A_3 \frac{\rho(t)}{\rho_i}}\, e^{E/RT} \qquad (2)$$

where $A_1(w)$ decreases exponentially from 1.0 for dry snow to 10^{-5} at 14% water content [*Yamazaki et al.*, 1993], $A_2 = 1.1 \times 10^{-8} Pa \cdot min$, $A_3 = 19.3$, the density of ice $\rho_i = 917\, kg\, m^{-3}$, the activation energy $E = 67.3\, kJ\, mol^{-1}$, and the gas constant $R = 0.00831\, kJ\, mol^{-1}\, K^{-1}$.

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2. Observations and measurements during rain on snow

We have made high resolution measurements of compaction of natural snow at the Washington State Department of Transportation snow study site (915 m a.s.l.) at Snoqualmie Pass, Washington U.S.A. Mid-winter storms often deposit up to 1 m of new snow which may then be followed by rain. Widespread avalanching is often observed immediately following the onset of rain [*Conway and Raymond*, 1993].

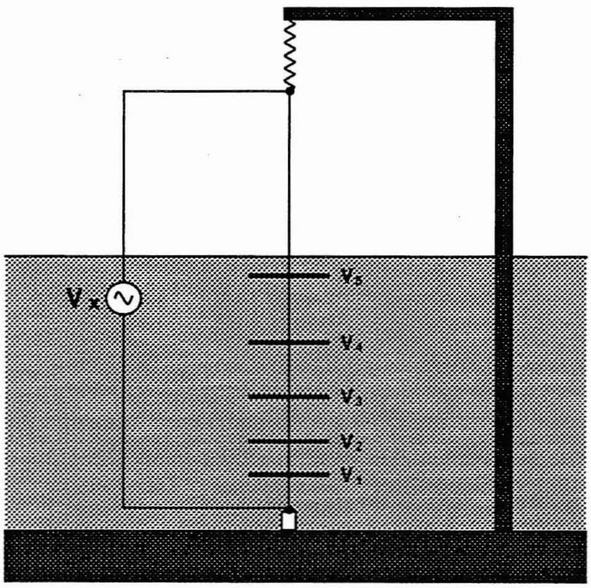

Figure 1. Apparatus for measuring settlement within snowpacks.

Fig. 1 shows the apparatus used to measure settlement within snowpacks. Velocity shoes made from light-weight aluminum screening were placed sequentially at the surface after 10 to 30 cm of incremental snow accumulation. A sliding contact mounted on each shoe made electrical contact with a resistance wire strung between a support above the surface and the ground. We configured this as a voltage divider circuit to calculate the shoe position with an accuracy of $\pm 2\,mm$. Thermistors attached to the shoes measured the temperature in the snow at each shoe position. Measurements, usually made at 15 minute intervals, were recorded using a datalogger and storage module. The evolution of layer density was calculated from measurements of the initial snow density and changes in layer thickness.

Other things being equal, the increased stress from the overburden should cause layers at depth to densify more rapidly than layers near the surface (Eqn. 1). However in reality the snow at depth is

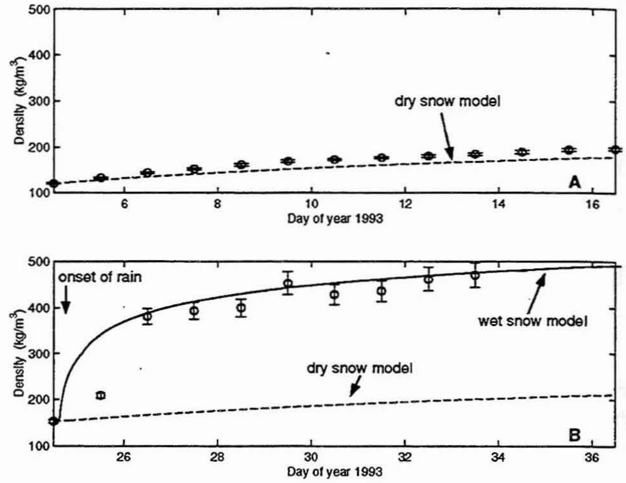

Figure 2. Densification of two layers of natural snow using the apparatus shown in Fig. 1. Fig. 2A shows a layer which was dry throughout the measurement period, while figure 2B shows a layer which became wet after rain started. The error bars for Fig. 2A are within the symbols. For comparison, in both cases the dashed lines show results from the dry snow model (Eqn. 1). The solid line (Fig. 2B) shows results from the wet snow model (Eqns. 4 and 5).

likely to be more dense (and hence more viscous - Eqn. 2), and/or during rain, the surface layers will be wetted first (because of the time lag of infiltration). Both effects complicate interpretation of measurements of settlement in natural conditions.

Fig. 2 shows measured compaction rates in natural snow for two layers in 1993. Both layers were near the surface during measurements; Fig. 2A shows a layer which was dry throughout the measurement period ($-5.4 < T_{snow} < -3.5°C$). Fig. 2B shows a layer that was wetted by rain which started at 1500 hr on day 24. The uncertainty in the estimate of density was calculated using propagation of errors [*Bevington and Robinson*, 1992], assuming the error in velocity shoe position was $\pm 2mm$, the error in the measurement of water equivalent was $\pm 0.25\,mm$, and that the two errors were uncorrelated. For comparison, model predictions for dry snow (Eqn. 1) are also shown. We expect values of $\sigma_m(t)$ will range from being positive (equilibrium metamorphism) to negative under large temperature gradients (kinetic growth metamorphism). Here for dry snow we use a constant value evaluated by fitting measurements of density of dry snow near the surface ($\sigma_{zz} \approx 0$) to Eqn. 1. Results from four such experiments yielded an average $\sigma_m(t) = 75 \pm 35\,Pa$ which is equivalent to about 7.5 mm (water equivalent) overburden. The solid line (Fig. 2B) shows results from the wet snow model discussed later.

Results show the dry-snow layer (Fig. 2A) densified slightly faster than the model prediction (assuming $\sigma_{zz} = 0$). However the difference is well within the model uncertainty (uncertainties in $\rho(0)$, $\sigma_m(t)$ and temperature) and further, some snow accumulated during the experiment making $\sigma_{zz} > 0$. In contrast, the wet layer densified more than 100× faster than the model prediction for dry snow (Fig. 2B). Introduction of liquid water has a major impact on the rate of densification and below we discuss experiments to investigate this effect.

3. Experiments to investigate the first wetting of dry snow

Experiments were done during the 1996-97 winter at Snoqualmie Pass. Undisturbed samples of freshly deposited snow were collected by pressing a cylindrical container into the new snow, sliding a sheet of plywood underneath and then inverting it. The average initial density $\rho(0)$ was obtained by subtracting the weight of the empty container from the weight when filled with snow, and dividing by the sample volume. A known volume of water at 0°C was sprayed evenly over the surface. Changes in height of snow in the container were measured as a function of time for up to five hours and used to calculate changes in density. The change in height at a given time was taken to be the average of five measurements across the center of the sample (Fig. 3). A large can ($h = 160\,mm$, $diam. = 155\,mm$) was used for four of the experiments, and plastic containers ($h = 70\,mm$, $diam. = 167\,mm$) were used for the others. In each experiment about 14% (by volume) of water was distributed evenly over the surface within ~ 30 seconds.

The experiments were done outdoors and were therefore subject to changing environmental conditions. When the air temperature was lower than ~ -5°C the water froze at the surface and infiltration was impeded. At temperatures higher than $\sim +1$°C the snow melted, and measured changes in height were the combined effects of loss of ice mass and densification. To reduce melting during warm conditions we buried the container (with the top level with the surface) within the natural snow. A total of 20 experiments were successfully completed within the range $-5^o < T_{air} < 1^o C$.

We are not certain how the container size affects the measurements. In most experiments the change in volume was caused by changes in height with little shrinkage from the sides and we suspect that edge effects were minor. However it would be useful to

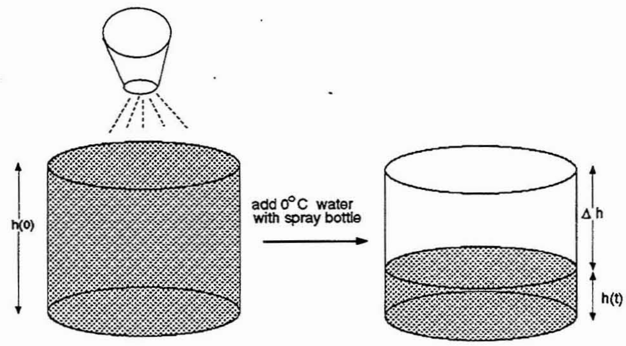

Figure 3. Densification experiments. Water was sprayed uniformly onto a volume of snow with initial height $h(0)$ and density $\rho(0)$. The height at time t after first wetting $h(t)$ was calculated by measuring $\Delta h(t)$ at 1 minute intervals for the first 10 minutes, and every 10-30 minutes thereafter for up to 5 hours. $\Delta h(t)$ was the average of 5 measurements across the center of the sample.

do more experiments with containers of varying diameter to determine when edge effects become important.

The standard deviation of each measurement of density $S_{\rho(t)}$ was calculated from the uncertainty in the measurement of mass ($S_M = \pm 1g$), radius of the sample cylinder ($S_r = 0.5mm$) and height ($S_h^2 = S_{hp}^2 + S_{ha}^2$ where the accuracy of height measurement $S_{ha} = 0.5mm$ and the precision of height measurement S_{hp} is the standard deviation of the five measurements). Assuming the errors are uncorrelated, the uncertainty in density is [*Bevington and Robinson*, 1992]:

$$(\frac{S_{\rho(t)}}{\rho(t)})^2 = (\frac{S_h}{h(t)})^2 + (\frac{S_M}{M})^2 + (\frac{2S_r}{r})^2 \qquad (3)$$

where M= the total mass of the sample, r is its radius, and $h(t)$ is its height. Because the surface becomes more irregular with time, and h(t) decreases, the standard deviation increases with time.

Fig. 4 shows results from two experiments. One ($\rho(0) = 125\,kg\,m^{-3}$) is typical of fourteen experiments in which the initial density ranged from 100 to 190 $kg\,m^{-3}$. Low-density snow always densified rapidly in the first few minutes after wetting, and the rate decreased as densification proceeded. On the other hand, changes were too small to be detected over the period of measurements when the initial density was high such as in the other experiment ($\rho(0) = 360\,kg\,m^{-3}$). The rate of densification for snow of low initial density was much faster than that predicted by the dry snow model. This is not surprising since we expect rapid structural changes and grain rearrangement when liquid water is first

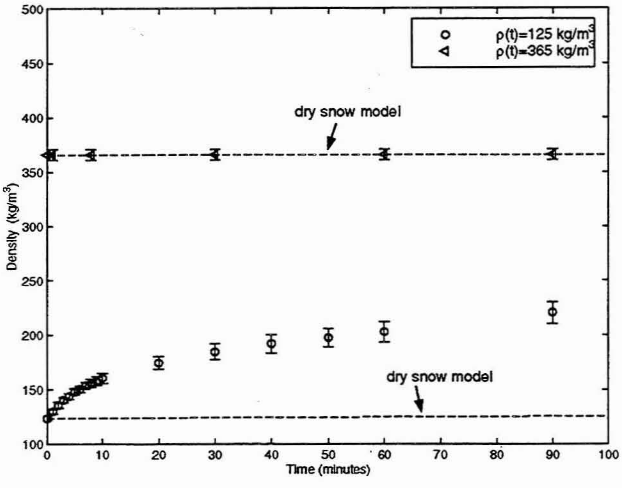

Figure 4. Evolution of snow density $\rho(t)$ calculated from measurements of $\rho(0)$ and $h(t)$ for $\rho(0) = 120 kg\,m^{-3}$, and $\rho(0) = 360 kg\,m^{-3}$. In both cases 14% (by volume) of water was added at $t = 0$. The densities plotted are *dry* density - that is without the liquid water. The dashed lines show the dry snow model for comparison.

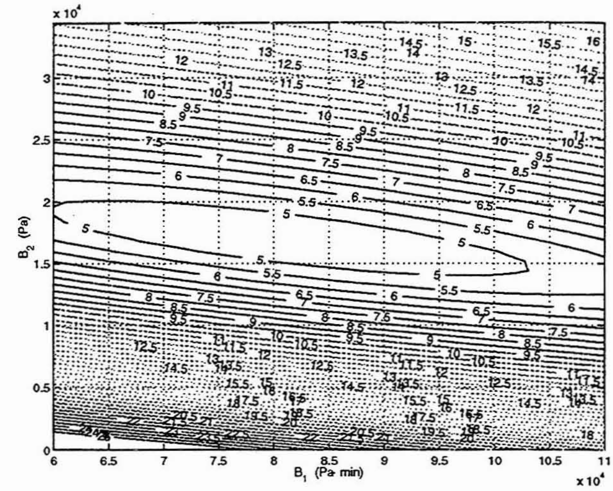

Figure 5. Optimization of model parameters B_1 and B_2. The optimum values ($B_1 = 8.0 \times 10^4 Pa\,min$, $B_2 = 1.65 \times 10^4 Pa$) gave $\overline{S} < 4.6\ kgm^{-3}$.

introduced to low density snow, and at higher densities we expect the presence of liquid water would lubricate grain boundaries and enhance densification [*Colbeck et al.*, 1978].

3.1 Model development

We use a similar formulation to that used for dry snow (Eqns. 1 and 2) but with different values for the model parameters. For a first approximation we assume $\eta_{zz(wet)} = A_1 \times \eta_{zz(dry)}$. $T = 273°K$ for wet snow and σ_{zz} is small (ranging from 0 at the surface to $\sim 140\ Pa$ at the bottom of the container) compared with other effects during wet snow compaction and here we ignore it. For the experimental conditions we rewrite Eqn.1:

$$\frac{1}{\rho(t)}\frac{d\rho}{dt} = \frac{1}{A_1\,\eta_{zz(dry)}}(\sigma_m(t) + 0) \qquad (4)$$

Eqn.4 is not easily integrated and instead we solve for $\rho_z(t)$ iteratively using 1 minute time steps. A constant value for $\sigma_m(t)/A_1$ does not capture the rapid densification when water is first added to dry snow and we use a time dependent function:

$$\frac{\sigma_m(t)}{A_1} = \frac{B_1}{t} + B_2 \qquad (5)$$

The term B_1/t captures the rapid initial change. $B_1/t \to 0$ as $t \to \infty$, and so B_2 models the long term impact of wetting.

The root mean square error S_k for each experiment is calculated from:

$$S_k = \sqrt{\frac{1}{N_k}\sum[\rho_k(t) - \rho^*(t)]^2} \qquad (6)$$

where $\rho_k(t)$ is the measured density at time t, $\rho^*(t)$ is the modeled density (from Eqn. 4), and N_k is the number of measurements.

We choose B_1 and B_2 to minimize the average root mean square error $\overline{S}$ for all 20 experiments:

$$\overline{S} = \sqrt{\frac{1}{20}\sum(S_k)^2} \qquad (7)$$

Fig. 5 shows results of the optimization which indicate (for t in minutes) $B_1 = 8.0 \times 10^4\ Pa\,min$, $B_2 = 1.65 \times 10^4\ Pa$. The average rms ($4.59\ kgm^{-3}$) is small considering that the density of a natural snow layer can vary by up to 10%. Fig. 6 shows measured and modeled results for five experiments. For most experiments, the model was within the measurement error. In the few places where the model did not match the measurements it is possible that densification was affected by a change in conditions. For example in the experiment shown with $\rho(0) = 100\,kgm^{-3}$ the rate of densification slowed between 50 and 125 minutes, probably because the air temperature decreased during that time.

4. Discussion

The model developed for wet snow densification from the experiments fits the measurements made in the natural snowpack during rain on January 24,

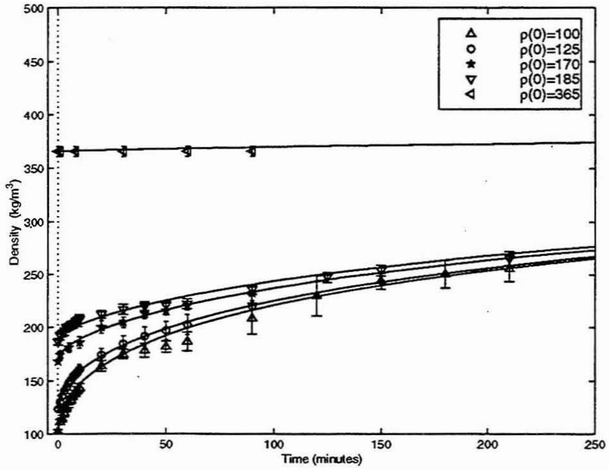

Figure 6. Measurements and model results during first wetting of low density snow. The plot shows five experiments with snow of different initial densities. The rate of densification increased with introduction of liquid water, and decreased as the density increased. The increase was especially fast during the first 10 minutes.

1993 (solid line in Fig. 2B) remarkably well. Precipitation rates at Snoqualmie Pass are typically $\sim 10\, mm\, hr^{-1}$. Observations indicate liquid water is usually contained within the upper 7–10 cm of the snowpack during the first hour, which implies a water content of 10 to 15% (by volume) after one hour. In our experiments the snow samples reached a similar water content much more quickly, and this difference in application rate is most likely the reason the measurement immediately after the onset of rain deviates slightly from the model (Fig. 2B).

We expect both the viscosity and the metamorphic components will change when liquid water is introduced to dry snow. We are unable to resolve the separate contributions from our data (Eqn. 5) but we can compare the increase in compaction rate during wetting (no load conditions) from the ratio $\dot{\varepsilon}_{zz(wet)} : \dot{\varepsilon}_{zz(dry)}$ which reduces to $\frac{1}{75}(B_1/t + B_2)$. Hence the addition of water increases the compaction rate more than $1000\times$ in the first minute, and even as $t \rightarrow \infty$ (>100 minutes) the rate is still $\sim 200\times$ faster than for dry snow. We note that in our experiments the amount of liquid water ($\sim 14\%$ by volume) was not varied. We suspect the model parameters depend strongly on both the water content [*Yamazaki et al.*, 1993] and the application rate. It would be useful to do more experiments to determine the dependence of the model parameters on both the rate of application and the liquid water content.

We note that our results suggest the rate of densification in wet snow is much faster than that commonly used in the literature [e.g. *Anderson*, 1976; *Jordan*, 1991]. Even the long-term rate is about two orders of magnitude faster than the more commonly used value. It is possible that the difference arises because the liquid water content in a natural snowpack consisting of well rounded grains is likely to be somewhat less than 14% and the viscosity is strongly dependent on water content [*Yamazaki et al.*, 1993].

It is dangerous to extrapolate (because the model was formulated using measurements over less than a day) but the model predicts the snow density will be 550 $kg\, m^{-3}$ (the density of equal-sized, close-packed spheres of ice) after about 35 days and about 600 $kg\, m^{-3}$ after 90 days. We are not certain whether our model is applicable over this time scale but it is interesting to note that end of season measurements at Blue Glacier in the Olympic mountains (typically after about 90 days of melt) indicate the residual snow density is similar ($\sim$ 580 $kg\, m^{-3}$).

It is likely that the burst in densification at the onset of rain is a result of grain rearrangement and structural changes. It has been suggested that this rapid alteration in mechanical properties at the surface has a controlling influence on snow slope stability at the onset of rain [*Conway*, 1998]. It would be useful to investigate this further, and in particular, measure the evolution of the vertical distribution of liquid water together with densification rates through natural snowpacks after the onset of rain.

5. Conclusions

The simple model for compaction of wet snow fits our measurements very well but more experiments are needed to determine the dependence of model parameters on liquid water content. The model captures the essential features observed on first wetting of dry snow. These are:

- on first wetting the densification rate increases by three orders of magnitude. We suspect this initial burst of densification is caused by rapid structural changes and grain rearrangement when liquid water is first introduced.

- the rate decreases rapidly with time although it remains about two orders of magnitude higher than for dry snow of the same density. We suspect the presence of liquid water reduces friction at grain boundaries which would increase the rate of densification.

- as with dry snow, the rate of densification decreases as density increases.

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