SNOW TEMPERATURE AND WATER OUTFLOW DURING RAIN AND MELT; MILFORD HIGHWAY, NEW ZEALAND

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ABSTRACT: Avalanches often release within a few minutes after the onset of rain on new snow. The avalanche potential remains high until drainage through the snow pack has been established; tracking infiltration and outflow of water is key to improving predictions of snow stability during rain and melt. Measurements of snow temperature near the start zones of avalanches that threaten the Milford Highway are used to track infiltration; liquid water is assumed to be present when the temperature is 0°C. A lysimeter is used to measure the time of water outflow from the base of the snow. Results show that the time between the onset of rain and first outflow depends on the rate of input as well as the stratigraphy of the snow pack. A large flux of water infiltrates through homogeneous snow faster than a small flux through a layered snow pack.

KEYWORDS: Snow, rain, avalanches

1. INTRODUCTION

The Milford Highway (SH-94) links TeAnau to Milford Sound on the southwest coast of New Zealand. The potential avalanche hazard along the highway is well known (Smith, 1947; LaChapelle, 1979; Fitzharris and Owens, 1980). The climate is strongly maritime; annual precipitation exceeds 7m (water equivalent) and winter storms often deposit 2-3m of snow in the start zones. Access to the start zones is not possible during storms and avalanche forecasters rely heavily on information telemetered from a network of remote weather stations. Melt and mid-winter rain often results in avalanches that threaten the highway and as an aid to operational forecasting, we have installed instruments to measure infiltration of liquid water through snow.

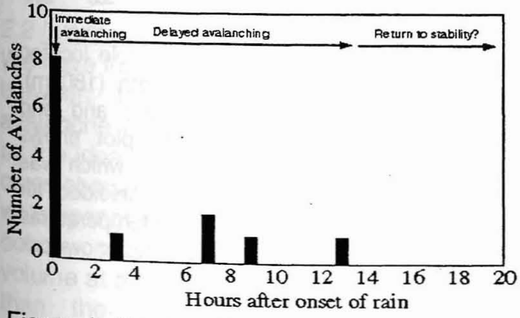

Figure 1: Number of avalanches in relation to the time that rain started. Data are from eight rain-on-snow events in the Washington Cascades, USA. (Adapted from Conway and Raymond, 1993).

Three evolutionary stages of snow stability have been identified following the onset of rain on new snow (Conway and Raymond, 1993). Avalanche activity often increases immediately (within a few minutes) after the onset of rain (Fig.1). With continued rain it is thought that the potential for avalanching remains high until liquid water drains out of the snow pack, which may take 20 hours or more. Few avalanches have been observed after drainage has been established.

Fig. 2 shows a conceptual picture of conditions during infiltration: (1) during the first hour, liquid water is usually retained within the upper few centimeters of the snow pack. Redistribution of stresses caused by alteration of the rheology of the near-surface snow can cause failures at depth (Conway, 1997); (2) before drainage has been fully established, additional rain or melt-water is retained in the snow pack. Slopes are potentially unstable because stresses from the overburden are increasing; (3) full-depth avalanches might release after drainage has been established if the water weakens the basal interface. However stresses from the overburden will decrease as water drains out of the snow and even during continued rainfall, the snow pack may be relatively stable.

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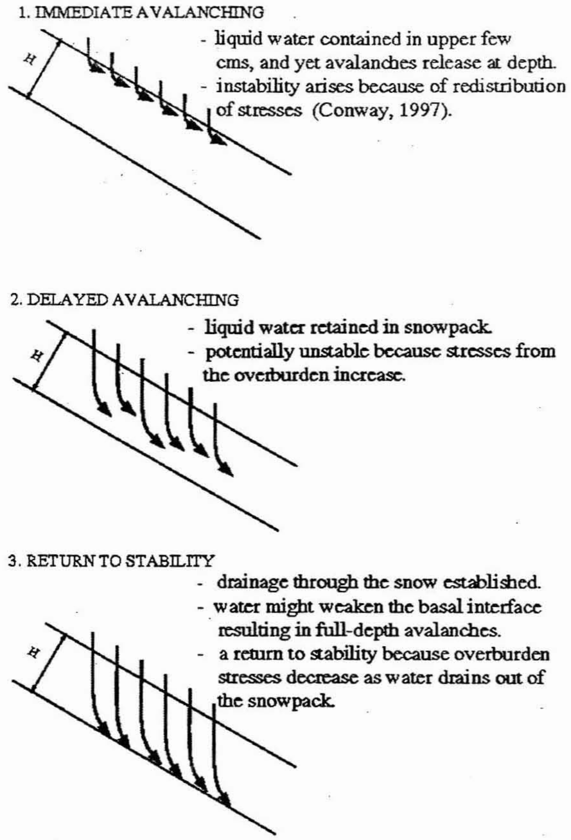

- liquid water contained in upper few cms, and yet avalanches release at depth.
- instability arises because of redistribution of stresses (Conway, 1997).

- liquid water retained in snowpack.
- potentially unstable because stresses from the overburden increase.

- drainage through the snow established.
- water might weaken the basal interface resulting in full-depth avalanches.
- a return to stability because overburden stresses decrease as water drains out of the snowpack.

Figure 2: Conceptual picture of the evolution of stability during infiltration.

2. INSTRUMENTATION

In an effort to gain information about conditions in the snow pack during infiltration, and in particular the time of outflow, we have installed poles to measure snow temperature profiles and a lysimeter to measure water outflow from the snow pack.

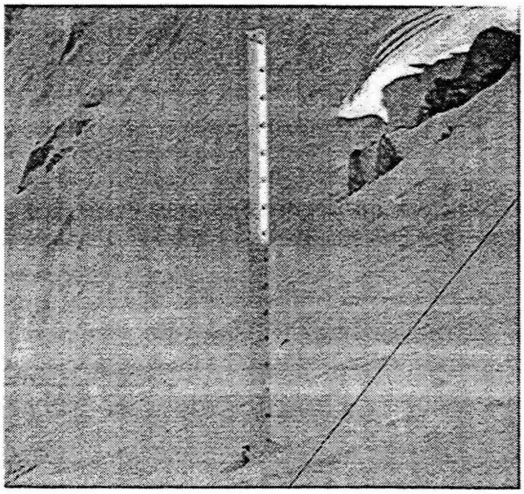

Figure 3: A snow temperature pole.

2.1 *Temperature poles*

Temperature poles, constructed from three hollow fiberglass poles that have been fibreglassed together for extra strength, are 3m long. Thermocouples mounted in nylon bolts spaced at 12cm intervals up the pole are used to measure the vertical temperature profile. Measurements are recorded on a data logger and transmitted via radio to the base station at TeAnau.

We use the temperature profiles to track infiltration; liquid water is assumed to be present when the temperature is 0°C. Some caution is needed when interpreting infiltration from such a one-dimensional temperature profile because it is well known that infiltration is not homogeneous (Conway and Benedict, 1994).

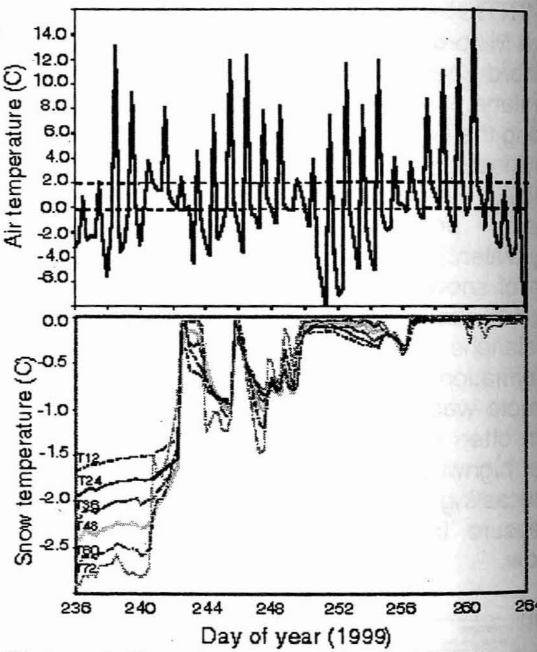

Figure 4: Snow temperature from a pole located near the start zone of the Gates path (1805m). Measurements start August 24 (236) and end September 21 (264), 1999. Upper plot shows temperature near the top of the pole, which was snow-free (taken here to be the unshielded air temperature). Lower plot shows snow temperatures 12, 24, 36, 48, 60 and 72cm above the snow/rock interface.

Fig. 4 shows that the snow temperature in the start zone of the Gates path (1805m) increased rapidly to near 0°C at all depths at about midday on August 30 (242.5). Although precipitation was not measured at this site, we suspect that the rapid warming occurred during a rain event. Some precipitation was recorded at the East Homer gauge (900m) during this period, and the air temperature at the site (+2.5°C) suggests that any precipitation would have fallen as rain (we assume that precipitation falls as rain when $T_{air}>2^{\circ}C$).

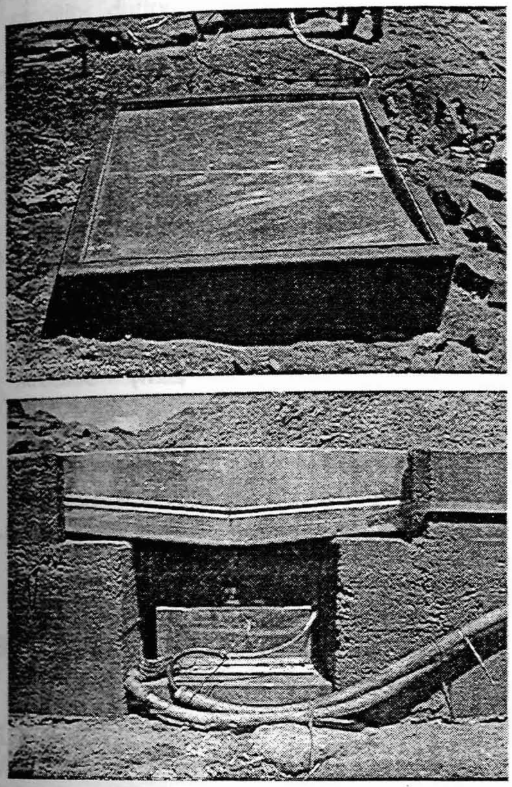

Figure 5: Summer pictures of the lysimeter at Mt Belle (1600m). Upper picture shows the catchment tray. Lower picture shows the housing for the tipping bucket gauge. During winter the lysimeter is typically covered by 2-3m of snow.

2.2 Lysimeter

We have installed a lysimeter (Fig.5) at 1600m between the start zones of two major avalanche paths. Construction was motivated by the idea that the time of outflow might offer clues about snow stability. It is well known that water penetrates snow through channels that occupy only a fraction of the total snow volume at a local rate that is often much faster than the average rate (Colbeck, 1979; Kattelmann and Dozier, 1999). The spacing between drain channels is typically 2m or less, and in an effort to capture flow from at least one channel, the catchment tray has dimensions 2m x 2m. Flow through an orifice in the tray is measured using a tipping bucket gauge. A small amount of antifreeze is pumped into the orifice to prevent freezing; the antifreeze contributes 0.031mm every 3 hours to the outflow.

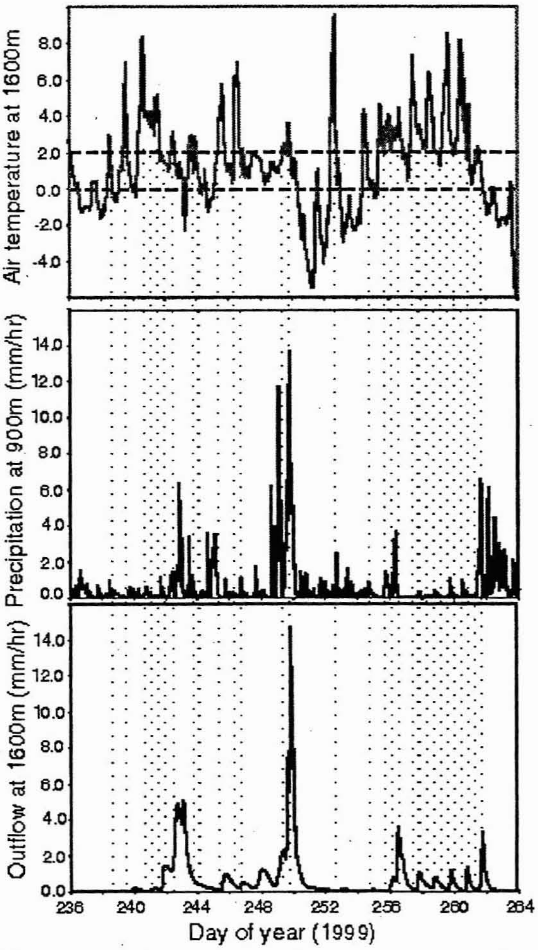

Figure 6: Air temperature at 1600m, precipitation at 900m, and outflow from the snow pack at 1600m. Measurements start August 24 (236) and end September 21 (264), 1999. Shaded regions indicate times when the air temperature at 1600m was greater that 2°C; we assume that precipitation falls as rain when $T_{air}>2^{\circ}C$.

Fig. 6 shows measurements of air temperature at 1600m, precipitation at 900m, and outflow at 1600m. Quantitative analyses of relationships between water inflow and outflow are hampered for several reasons:

1. The relationship between precipitation measured by the gauge at 900m and that at 1600m is not known.
2. Although changes in snow depth are measured using a sonic ranger, uncertainties in the snow density

profile complicate estimates of the influx from surface melt.

3. The flux of water at the surface is likely to be concentrated into channels within the snow pack that may or may not be captured by the lysimeter.

Nevertheless, measurements from the lysimeter clearly define the time of outflow; the first major outflow (more than 115mm) peaked at 0200 on August 31 (243.08). Total snow depth decreased from 2 to 1.9m during this period; the measured outflow was probably a combination of melt and rain water (less than 40mm precipitation was recorded at East Homer, and air temperatures suggest that at least some of this would have fallen as snow at 1600m). Field observations indicate that the snow pack was relatively stable during the entire period; the avalanche hazard to the highway was low.

One week later the snow depth had decreased to 1.7m. The peak outflow (14.6mm/hr on day 249.79) lagged the peak rainfall by only one hour; otherwise the characteristics of the outflow were remarkably similar to those of the rainfall (Fig.7). We suspect that the drainage system was well established; again, observations indicate stable conditions and the avalanche hazard to the highway was low.

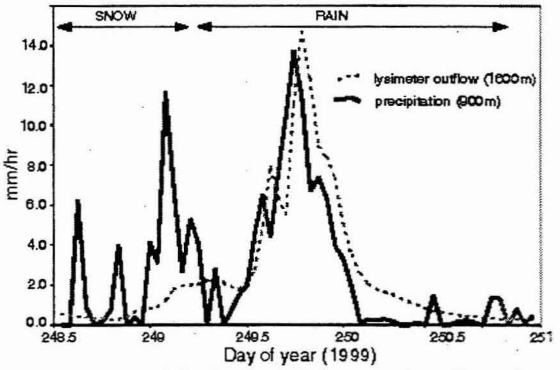

Figure 7: Precipitation at 900m, and outflow from the snow pack at 1600m. Measurements start at 1200 September 5 (248.5) and end September 8 (251), 1999. Snow depth at the start of the period was 1.7m.

Outflow between September 14-16 (days 257-259) exhibits a strong diurnal cycle (Fig.8). Precipitation during this period was typically less than 0.1mm/hr (at 900m) and it is likely that most of the outflow was derived from melt. In contrast with the rain event discussed previously, the peak outflow lagged the peak influx (at midday when both T_{air} and the radiative flux were maxima) by about 6 hours (Fig.8). Snow depth at the start of the period was 2.1m.

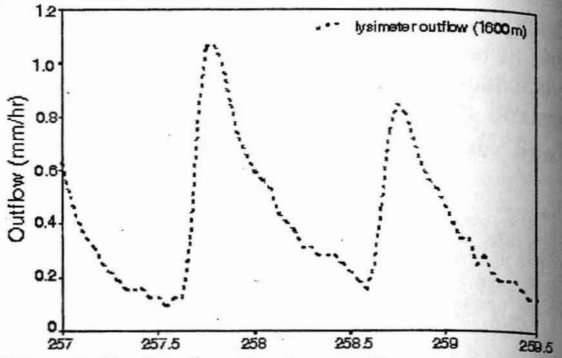

Figure 8: Outflow from the base of the snow pack at 1600m. Measurements start on September 14 (257) and end midday September 16 (259.5), 1999. Snow depth at the start of the period was 2.1m.

The flux of water through porous media such as snow has a power-law dependence on the saturation (Darcy's Law). Colbeck (1972, 1979) pointed out that this relationship implies that a large flux of water should infiltrate faster than a small flux. It is likely that this effect contributed to the different lag-times measured in Fig. 7 (a large flux and rapid infiltration) and Fig. 8 (a small flux and slower infiltration). Pressure gradients associated with stratigraphic boundaries in heterogeneous snow packs are also expected to impede infiltration (Colbeck, 1974,1977).

3. SUMMARY

Preliminary results illustrate the potential use of snow temperature profiles and measurements of outflow for tracking infiltration of water through snow. The rate of infiltration depends on the snow stratigraphy as well as the volume and rate of water influx. Other things being equal, infiltration will be slower in cases of small surface fluxes through new, layered snow packs that have not been previously wetted (heterogeneous snow). Infiltration is expected to be faster through homogeneous snow during high intensity rainfall. More measurements during rain and melt events are needed to establish a relationship between infiltration and the evolution of snow stability.

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5. ACKNOWLEDGEMENTS

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