STORM LEWIS: A RAIN-ON-SNOW EVENT ON THE MILFORD ROAD, NEW ZEALAND

Transit New Zealand Milford Road Avalanche Program*

ABSTRACT: We report and discuss observations and measurements during Storm Lewis, a 160mm rain-on-snow event on the Milford Road, New Zealand from 21-23 October 2003. Data include: a suite of snow pack (creep, temperature profiles and out-flow of liquid water) and meteorological measurements that were telemetered from several remote sites; observations from snow pits excavated at ~1900 m throughout the storm; observations of avalanche activity; results of control work following the storm; fracture-line profiles from avalanches that had been artificially released.

Keywords: rain-on-snow, avalanches

1. INTRODUCTION

The Milford Highway (SH-94) links TeAnau to Milford Sound on the southwest coast of New Zealand. The climate is strongly maritime; annual precipitation exceeds 7m (water equivalent) – cumulative snow depth in the start zones is ~3 to 5m; up to 2m of snow may be deposited in during a winter storm. Melt and mid-winter rain often causes avalanches that threaten the highway. Here we report and discuss observations and measurements during storm Lewis, a 160mm rain-on-snow event during 21-23 October 2003.

2. OBSERVATIONS AND MEASUREMENTS

Knowledge of snow stability prior to onset of rain is key for predicting the response of a snow pack to rain; widespread avalanche activity is common at the onset of rain if the snowpack is close to critical, but avalanching may be delayed several hours if the snowpack is stable (Conway and Raymond, 1993). Valuable clues about the avalanche potential of these delayed avalanches during continued rain can be obtained from road-level observations of activity on avalanche-indicator paths, weather, waterfall and river flow.

This year for the first time, a new hut located at 1900m between two start zones on Mt Crosscut (Fig. 1) enabled monitoring of snow and weather conditions near the start zones during storms. Additional information comes from real-time measurements of weather (including winds, air temperature, precipitation) and snow conditions (including snow depth, temperature profiles, creep, and water outflow) telemetered from a network of remote stations to a base station in TeAnau (Carran et al., 2000). Some of the instrument packages are illustrated in Figure 2.

Figure 3 shows weather and snowpack conditions prior to Storm Lewis. We estimate air temperature T_z at elevation z from T_{1600} measured at the Mt Belle weather station (1600m asl) and the moist adiabatic lapse rate (6.5^{o}Ckm^{-1}).

Figure 1: Night photo of snow pit outside the new hut located at 1900m between two start zones on Mt Crosscut enables continual monitoring of snow conditions near starting zones during storms.

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Observations from the hut during storms indicate that precipitation falls as rain when air temperatures are warmer than +0.5 to $+1^{o}$C; here we assume that precipitation falls as rain when the air temperature is >+0.5 and snow otherwise. We have found that the East Homer gauge at road level (900m asl) yields a reliable estimate of precipitation in the start zones.

2.1 Snow stability prior to Storm Lewis

Extensive control work with explosives dropped by helicopter following snowfall on 8-9 October (days 281-282) produced avalanches down most paths that affect the highway with East and South aspects. Snow profiles subsequent to the storm showed the lower snowpack was generally high density (>390kg/m^3), well bonded and stable. The snowpack at Cleddau (1780m) became isothermal (at 0^{o}C) when warm air temperatures caused precipitation to fall as rain in the start zones on 17 October (day 290); the snowpack at Mt Belle (1600m) was also isothermal, but the lack of outflow measured by the lysimeter indicates that drain channels were not yet fully established (Fig. 3).

2.2 Onset of rain and avalanche activity

Measurements indicate that precipitation in the start zones started as snow early in the morning of October 21 (day 294), but changed to rain by mid afternoon (fig. 4). Rain, heavy at times, continued for the next 40 hours. However, even though 160mm (more than 6”) of rain fell in the start zones during the 42 hour period, relatively few avalanches released; no activity was observed when rain first started, and only two released naturally during the storm: the first on Talbot occurred 20 hours after rain started, and the second released about 10 hours later in Monkey Creek. Because neither path affects the highway they are not usually controlled with explosives.

Control work, done by dropping charges from a helicopter soon after the storm ended, was successful on just three paths (a total of 13 charges were placed). A charge dropped near the top of Loop 1 triggered a size-2 avalanche, which then released a large (size 4) avalanche that reached the road. In addition, a sympathetic release (size 3) occurred on a SE aspect slope of McPherson. Later during the control mission two size 3.5 avalanches were released on Students and Cleddau. By next day (day 297) cooling and drying (Fig. 3) had allowed the snowpack to strengthen and active control (4 charges) produced only a few size 1 avalanches.

Figure 2: Rover (a) is a mobile station that can be moved to sites of special interest during the season. A down-looking sonic ranger measures changes in snow depth. Snow temperature profiles are measured using thermocouples mounted at 12cm intervals along a pole (b) and multiplexed to a data logger. Rover is anchored to rock, and creep is measured by running a cord around a rotary potentiometer downslope to a glide shoe buried in the near-surface snow. A lysimeter at 1600m (c) measures water outflow from the snowpack. Summer photo shows the 2mx2m catchment tray; typically 3-5m of snow accumulates on top of the tray in winter. A tipping-bucket gauge measures outflow. Antifreeze is pumped into the outflow-orifice to prevent freezing; antifreeze contributes 0.031mm every 3 hours to the outflow.

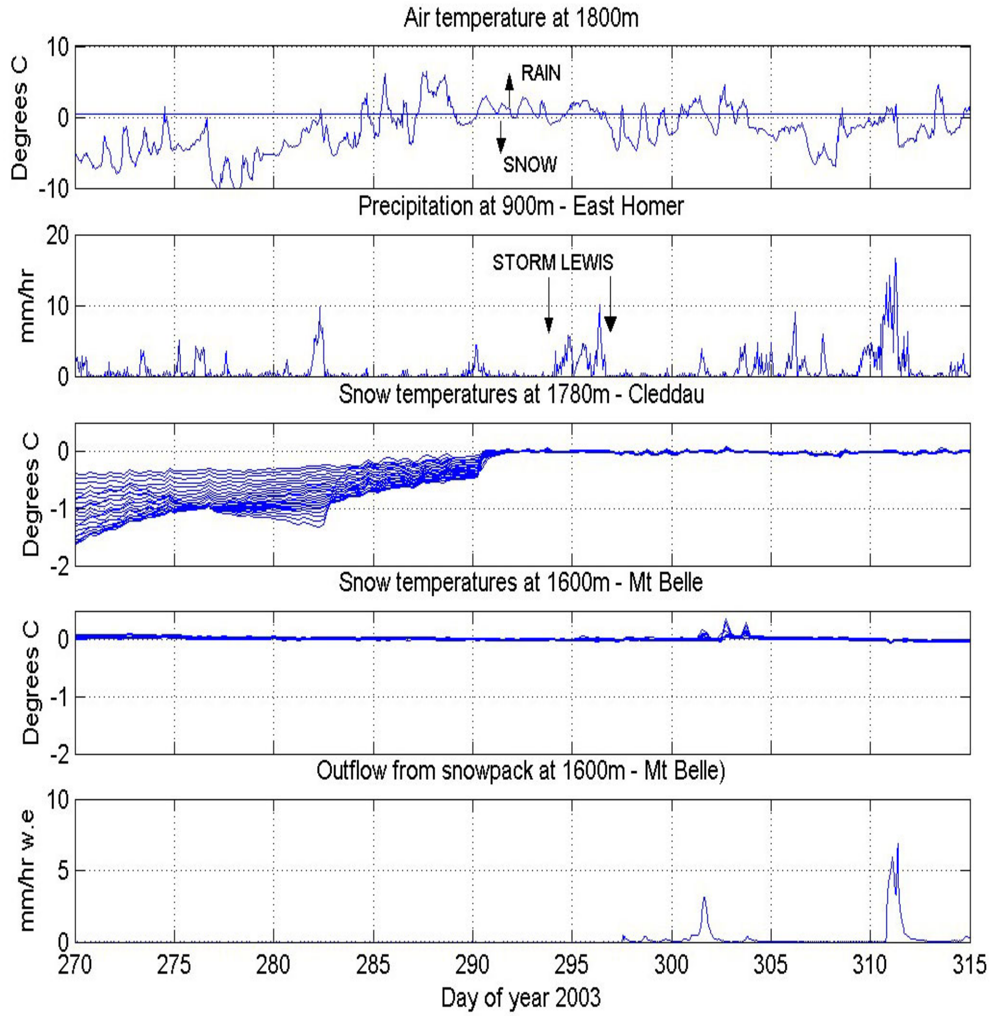

Figure 3: Time-series measurements of air temperature at 1800m, water equivalent precipitation at 900m, snow temperatures at 1780m and 1600m, and outflow from the snowpack at 1600m. The time series starts September 27 (day 270) and ends November 11 (day 315) 2003. Line at +0.5°C in the air-temperature series is the rain/snow discriminator. Heavy rain fell in all start zones during Storm Lewis (between days 294-297). The snowpack at Cleddau (1780m) had already become isothermal (at 0°C) during rain on day 290; the snowpack at Belle (1600m) was also isothermal before Storm Lewis. Snow depth at Belle was 330cm and the lysimeter measurements indicate that drainage channels were not fully established until additional rainfall on day 301 (October 28), almost a week after Storm Lewis.

2.3 Snow pit observations

Profiles before Storm Lewis indicated that the snowpack was generally stable, consisting of dense (340-450kg/m^3) well-bonded snow. A profile on a S. facing study slope of ~28° soon after precipitation changed to rain (profile 03-19) showed that the snow above a 5cm-thick ice crust at 58cm was wet, but below it was moist down to a transition in hardness (from pencil to pencil+) at 110cm (Fig. 4). Infiltration past this interface was impeded for more than 16 hours; profile 03-20 shows that although the wet/dry snow boundary had penetrated the ice crust, snow beneath the deeper interface (then at 90cm) was still dry. Drain channels were first observed on the study slope about 26 hours after rain started (Fig. 4 - profiles 03-22&24). However results from probing indicate that the drain channels did not extend all the way through the snowpack, even after 160mm of rain (Fig. 4 - profile 03-25). This observation is consistent with measurements from the lysimeter at Mt Belle (1600m) that indicate that water did not drain from the snowpack during

Storm Lewis (Fig. 3). Hence on average, the 160mm of rainfall during Storm Lewis would add about 700Pa to the down-slope stress imposed by the overburden (calculated for a 30^{o} slope) as well as lubricating and weakening grain boundaries. However comparison with profiles on low-angle slopes (not shown) indicate that infiltration occurs faster than on steeper slopes; water flows down-slope as well as vertically into the snowpack (Colbeck, 1979). Liquid water (and stresses) is expected to concentrate on low-angle slopes but with time, these regions will be the first to establish drain channels to the ground.

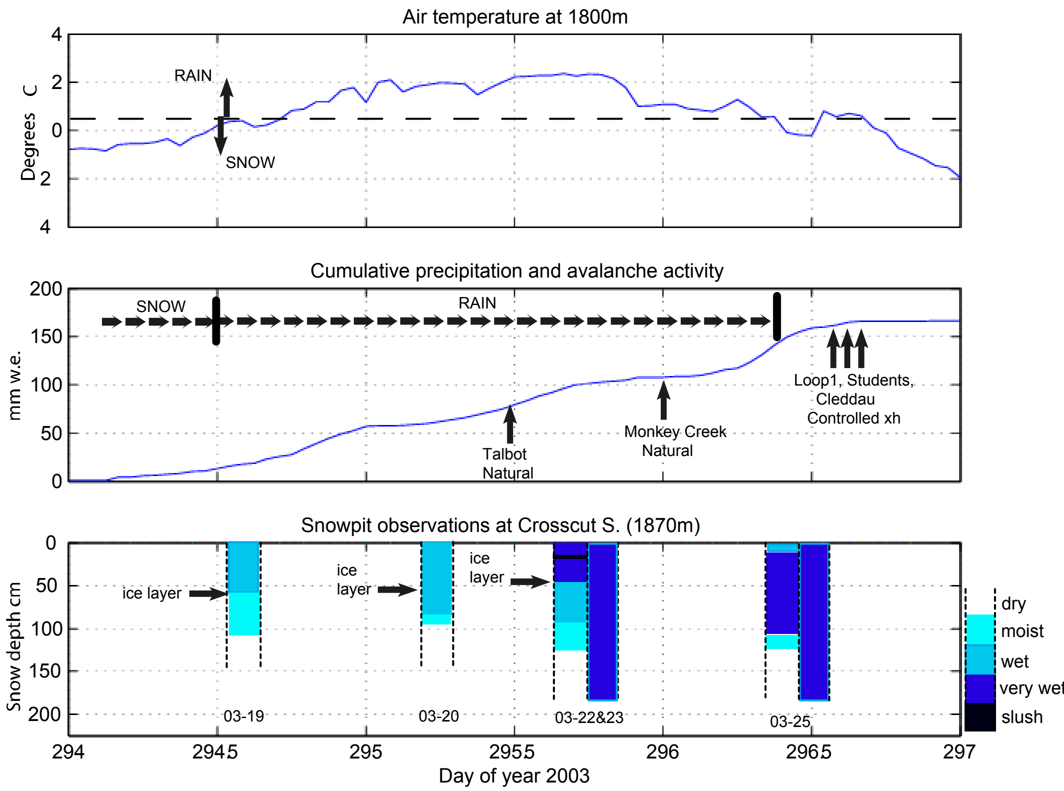

Figure 4: Evolution of conditions during Storm Lewis: when precipitation first started at 3am on 21 October (day 294) it fell as snow in the start zones, but early in the afternoon of the same day it changed to rain. Total accumulation was 160mm over 42 hours. Also shown is the timing of natural avalanches on Talbot (11:30am on day 295) and Monkey Creek (estimated ~12 midnight of day 295), and three avalanches (Loop1, Students and Cleddau) that were controlled by dropping charges from a helicopter (xh). Lower plot shows the evolution of water infiltration on a S. facing slope of ~28^{o} near the hut, where total snow depth exceeded 5m. Profile 03-23 is within a drain channel beside profile 03-22; results from probing suggest that the drain channel extended about 3.5m into the snow pack. The ice crust observed in other profiles at about 50cm had disintegrated by midday on day 296 (profile 03-25) and probing in the drain channel suggests that moisture had penetrated at least 450cm.

2.4 Fracture-line profiles

Fracture-line profiles (Figs. 5 and 6) were taken about 24 hours after control work and after rain had stopped (Fig. 4). Observations during the storm showed that the liquid water content of snow often decreases rapidly after rain stops; we do not expect the fracture-line profiles to be fully representative of conditions during rain. Nevertheless, the profiles show interesting results. Figure 5 shows depth-profiles of local down-slope stress (calculated from $\sigma_{xy} = g\sin\theta\sum\rho_i\Delta h_i$ where g is the gravitational constant, θ is the slope angle, ρ_i is the density and Δh_i is the thickness of layer *i*) and the strength (calculated from $\sigma_f = 1.95 \times 10^4 \left(\rho_i / \rho_{ice}\right)^2$) of layer *i*. From these calculations, the consistently high-density (400 to 550 kg/m^3) snow pack implies very high stresses and strengths (about 10x higher than typical values for new, dry snow with density 150 kg/m^3). Probability of failure is expected to increase when the down-slope stresses approach the strength of a layer. Our estimate of layer strength from density is subject to much uncertainty; gray shaded regions in the plots represent uncertainty of $\pm 0.61\sigma_f$. One reason for such large variability is that wet snow with lubricated grain boundaries is likely to be weaker than snow of the same density that is cold with frozen grain boundaries; we expect moist or wet snow to be weaker than the average, with wet snow to be in the lowest range.

In all cases the avalanches released within moist or wet snow layers. Analysis of stresses (Fig. 5) shows that failure always occurred at locations where the stress was lower than the mean estimated strength, but within the lower limit of the uncertainty. However results from the stress analysis are equivocal. For example in the case of Students Peak (Fig. 5c) stress first approaches the envelope of strength 100cm below the surface and yet the failure surface was at 200cm depth. The analysis does not always clearly delineate the avalanche-sliding layer. Similarly, shovel shear tests did not always clearly identify the sliding layer; in the case of Loop 1 (Fig. 5a) for example, tests gave an easy failure above the ice crust at 120cm, and yet the sliding layer for the avalanche was below the crust.

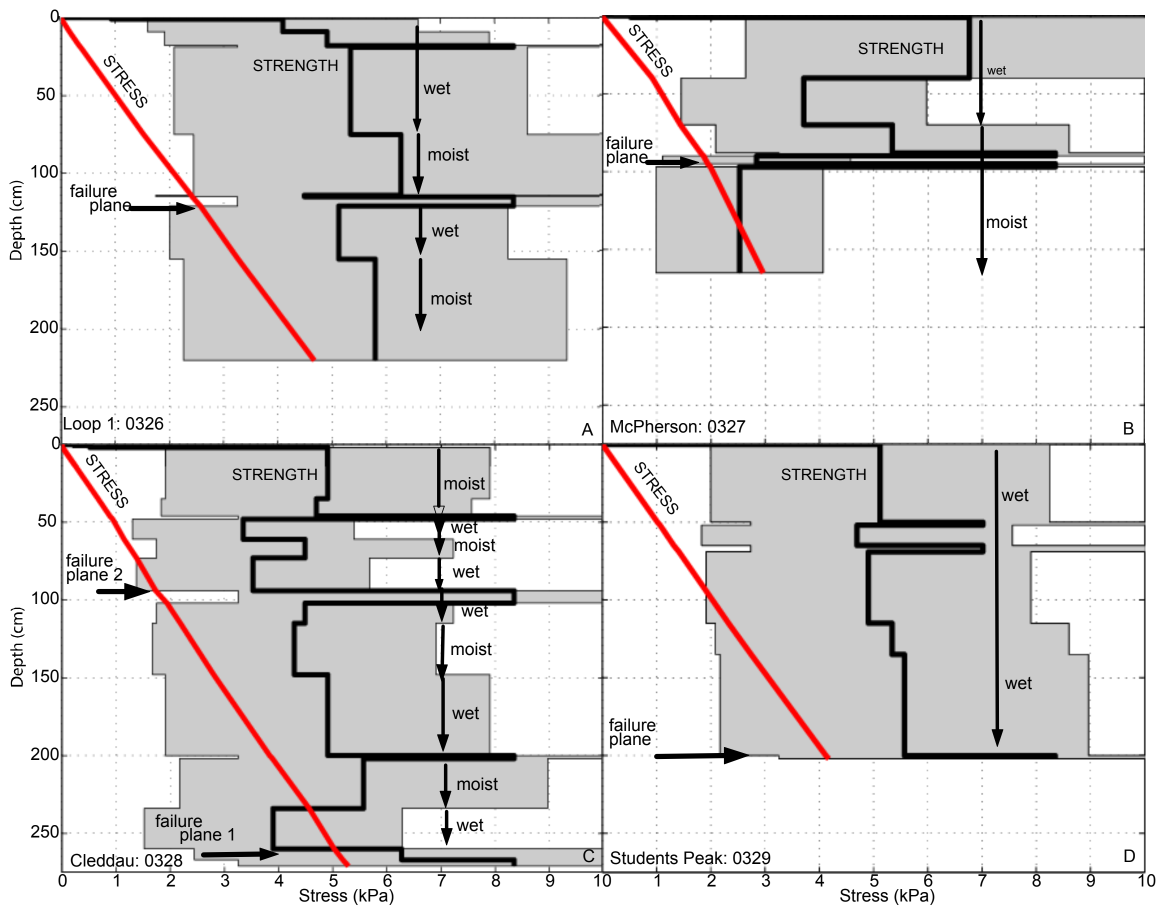

Figure 5: Depth-profiles of local down-slope stress, strength and water content estimated from fracture-line profiles taken after control work on 23 October (day 296). Rain had stopped more than 24 hours prior to observations; liquid water had already started to drain from the snow pack. Mean strength of a layer is estimated from its density; gray shaded region represents the uncertainty. Probability of failure is expected to increase when the down-slope stresses approach the strength. Profile A from Loop 1 (slope=31°) shows the avalanche slid within wet snow immediately below an ice crust 120cm below the surface. The sympathetic avalanche on McPherson (Profile B, slope=28°) slid in moist snow between two ice crusts 95cm below the surface. Cleddau (profile C, slope=30°) failed first on top of an ice layer 265cm below the surface and then stepped up to slide within wet snow on top of a crust 85cm below the surface. The Students Peak (profile D, slope=27°) avalanche failed in wet snow on top of an ice crust 200cm below the surface.

Figure 6: Crown walls of controlled (25kg charge) avalanche on upper Loop 1 (left), and sympathetic avalanche on McPherson (right). Two people are visible just above the McPherson crown.

Numerous possibilities might contribute to complicate interpretation of snow profiles: (i) excavation of a snow pit alters the hydraulic gradients and hence distribution of liquid water - the profile might not be representative; (ii) drainage of liquid water subsequent to avalanching might have altered the distribution of stresses and strength in the snowpack; (iii) we have not considered the dynamic effects of the explosives used to trigger the avalanches. We note that most failures occur just above or below ice crusts. It is possible that an ice crust acts as a guide to concentrate stresses. Alternatively, changes in hydraulic gradient across such an interface might cause accumulation of liquid water and weakening of grain boundaries in those regions.

2.5 Observations during active control

It is often difficult to trigger wet snow avalanches; bomb placement is critical and we used charges up to 75kg (on Students Peak) for effective control. Timing of control is critical; control just 20 hours after rain stopped control was ineffective; apparently cooling and drying had allowed the snowpack to drain and strengthen. However bad weather and marginal flying conditions often prevents control missions at optimal times. Further care is needed to keep explosives dry when doing missions in rain (Fig. 7). Wet snow avalanches typically start slowly; Students Peak was particularly slow but once started, it entrained and scoured much of the snow in the track. The charge dropped near the top of Loop 1 triggered a size-2 avalanche, which then released a large (size 4) avalanche that reached the road (Fig. 8).

Figure 7: An umbrella, essential equipment when loading explosives and doing control during rain, 23 October 2003.

2.6 Observations during road clearing

The Loop1 avalanche covered 80-100m of the road to an average depth of 5m (Fig.9). Average density of the deposit (calculated from 10 measurements taken 24 hours after the avalanche) was 615kg/m^3. The road was open for traffic 24 hours after the control work.

Figure 8: Controlled (75kg charge) wet snow avalanche flowing over cliff bands on Loop1, 23 October 2003.

Figure 9: Snow clearing on Loop1, 24 October 2003.

3. SYNOPSIS

For the first time in the history of the Milford Road Avalanche Program, the new Crosscut hut provided the opportunity for observers to track evolving conditions near the start zones during a significant rain-on-snow event. It is well known that avalanche activity often increases immediately (within a few minutes) after the onset of rain (Conway and Raymond, 1993). However observations and theory (Conway, 1997) indicate that immediate avalanching occurs only if slope stability prior to rain is close to critical. Avalanche activity may be delayed when rain falls on more stable snow.

The snow pack prior to Storm Lewis was generally stable; immediate avalanche activity at the onset of rain was not observed. In this case stability is controlled by the evolution of stresses as the rainwater penetrates the snow pack; predicting the time of avalanching is problematic because it is difficult to accurately define the spatial and temporal distribution of liquid water in the snow (Colbeck, 1979).

Observations during the storm highlight some problems that hamper accurate predictions:

- Loading patterns depend on whether precipitation falls as rain or snow. During Storm Lewis, the transition from snow to rain occurred when the local air temperature was warmer than +0.5 to +1^{o}C.
- The generally high densities (400 to 550 kg/m^3) prior to rain imply relatively high stresses and strengths (stress about 3x higher and strength about 10x higher than typical values for new, dry snow with density 150 kg/m^3). Although down-slope stresses increased with the weight of the rain, but we suspect that the primary control on slope stability during Storm Lewis was the weakening effects of infiltrating liquid water.
- Liquid water becomes mobile only after the water content has increased sufficiently to form a continuous film through the pore spaces (Colbeck, 1979). This critical or "irreducible"

moisture content depends on the size and texture of grains (Wankiewicz, 1979). Build-up of water above the irreducible moisture content occurs when the rate of rainfall exceeds the rate of drainage; the local moisture content also depends on the rate of precipitation.

- Hence water infiltration is not uniform; hydraulic conductivity is affected by the snow stratigraphy. Local penetration of water through channels may be much faster than average rates (Marsh and Woo, 1985; Conway and Benedict, 1994; Kattelmann and Dozier, 1999). Infiltration is often impeded at stratigraphic boundaries such as between fine- and coarse-grained snow (Wankiewicz, 1979), or at ice crusts (Langham, 1975).
- Build-up of liquid water at such stratigraphic boundaries affects the strength locally (Kattelmann, 1984; Heywood, 1988; Conway et al., 1988), and slope stability will become critical when the water (and associated weakening at depth) is distributed spatially over distances of several meters.
- The build-up of liquid water depends on slope angle as well as the rainfall rate and internal stratigraphy. On slopes there is a down-slope component of flow; liquid water tends to pond in areas of low angle.

4. ACKNOWLEDGEMENTS

The U.S. National Science Foundation and Transit New Zealand supported this work. We also thank all the people who have worked on the Milford highway. Contributors to this particular study include: Russell Blair, Karl Burt, Ann Carran, Wayne Carran, Mike Costello, Noel Eade, Mark Faulkener, Stewart Hall, Richard Hayes, Jordi Hendrikx, Chris Kendall, Don Lyon, Mike O'Cain, Alistair Pearce, George Robbi, Bill Rodgers, Jeff Shanks, Frank Techel and Ian Wilkins.

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