CLOSE ENCOUNTERS WITH AVALANCHES DURING RAIN-ON-SNOW: 
LESSONS LEARNED
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ABSTRACT: Two close encounters with avalanches during rain-on-snow in the spring of 1996 were aha-moments for the Milford Road avalanche program; these defining events motivated changes in operational procedures and development of new instruments. Here we discuss the events, lessons learned, and instruments and procedures now in place. Key lessons learned include: (i) pay attention to weak signals and early warnings of instability; ongoing reassessment of stability is essential; (ii) reliable data and clear communication are essential for informed decision making; (iii) real-time measurements of key properties are needed to make quantitative estimates of the evolution of snow stability; theory alone is not yet sufficient; (iv) managing deep instabilities in the snowpack is critical; all pockets of instability that have not released naturally need to be dug out with explosives before opening the road.

1. INTRODUCTION
The Milford Road links TeAnau to Milford Sound on the SW coast of New Zealand through a tunnel. Fifty avalanche paths affect 17km of the road. Annual precipitation exceeds 7 m (w.e.) and winter storm cycles often deposit 2-3 m of new snow in the start zones. Most potentially hazardous avalanches are “direct-action” avalanches that release during or soon after storms. Mid-winter rain-on-snow is common.

Access to the start zones is limited; assessment of the hazard is based on data from remote weather stations and observations from the valley floor. There are few places to hide in the valley floor and the consequences of being caught in the open are serious.

Two close encounters with avalanches during rain-on-snow in the spring of 1996 were defining moments for both the avalanche program and the client (Transit NZ). The events highlighted the seriousness of the avalanche hazard on the road and emphasized the need for quantitative data and analytical forecasting procedures. Here we discuss conditions leading up to the events, lessons learned, and changes in operational procedures and new instruments that have been developed to help mitigate the hazard.

2. THE EVENTS
2.1 Murrells 1&2, September 18, 1996
A size 3.5 avalanche down Murrells (Fig. 1) blasted the highway at 0900 on September 18 (day 262), 1996 while the road was open. The blast just missed a vehicle; fortunately nobody was caught.

Figure 1: Crownwall of the Murrells avalanche that blasted the road at 0900 on September 18, 1996. The blast just missed a vehicle travelling down the road.

Avalanche control (using 25kg charges placed by helicopter) three weeks earlier (day 241) released 14 large (>3.0) avalanches. One of these down Murrells ploughed through trees and dusted the road, giving confidence that deep instabilities in the start zone had been cleaned out. Fig. 2 shows the evolution of conditions on the days following the control work.

The storm started on day 242 with low-density (80-100kgm⁻³) snow, followed by a period of mixed snow/rain in the start zones between days 245-250 (Figs. 2a&b). The road remained closed. Over the next four days, cooler temperatures and continued precipitation (total of 280mm w.e., resulted in three natural avalanches ≥ 3.0 on day 254. Control work during a brief weather window on day 255 released seven more avalanches that crossed or blasted the road; it was not possible to control Murrells at that time. Snowfall continued over the next three days and several small (≤ 2.0)
avalanches released; none of these affected the road. Precipitation eased and the road was opened on day 261 based on a forecast of 20-30mm precipitation for the next 12hrs.

It turned out that the forecast under-estimated precipitation; more than 65mm fell in 10 hrs overnight. On day 262, four large avalanches on uncontrolled slopes (Gates, McPherson, Crosscut and Barrier) released naturally early in the morning, and Murrells blasted the road at 0900. Other paths (East Homer, Raspberry, Cleddau, and Loop 1) that had been controlled seven days earlier on day 255, did not release naturally, but they did respond to control work the next day (day 263). Interestingly, results from the SNOSS model (Fig. 2c) indicate the stability was near critical (shear stress exceeds strength) on day 260 at 1700 and again on day 262 at 0100, about 7 hrs before Murrells released.

2.2 East Homer 2&3, October 7, 1996

A size 4.5 avalanche down East Homer 2&3 on October 7 (day 281) 1996 destroyed the east portal of the Homer tunnel (Fig. 3). The road was closed but one of the technicians who had been checking road conditions on the West side had a close encounter. He was just 20 sec from exiting the tunnel when the avalanche released; very fortuitous timing.

Most instabilities in the snowpack would have been eliminated during extensive control on day 263 after the Murrells event (section 2.1). However a large (100kg) charge set in East Homer 3 on day 263 failed to release an avalanche.

By the time East Homer released on day 281, a total of 705mm (w.e) had fallen since day 263. Notable was that 250mm had fallen in the 24 hrs prior to the avalanche (Fig. 5a). The snowline varied widely during the weeks leading up to the event (Fig. 4b); rain or mixed rain/snow fell in the start zones on days 274 and 275, and again on day 281. Three natural avalanches size 3.5 released on day 275 when precipitation changed to rain at the top of the start zones (Fig. 4b). From day 276 until 0600 on day 281, the snowline was generally below the bottom of the start zones (<1600m – Fig. 4b); precipitation in the start zones was snow. These conditions changed abruptly just before East Homer 2&3 released; the snowline increased rapidly above the top of the start zones (2100m) by 0800 (Fig. 4b).

Morning observations from road level reported eerie conditions in the valley floor. Two avalanches ≥ 3 (Raspberry 1 and Christina 1) released some time before 0600 on day 281 but other paths that threaten the road had not
released. It was raining at road level but waterfalls over the cliff bands were not active. Liquid water was not draining through the snowpack; the upper slopes were still loading.

The decision to keep the road closed to the public proved judicious when a large wet avalanche released down East Homer 2&3 paths at 0805 (NZST), destroying the reinforced concrete portal of the Homer tunnel (Fig. 3). Clearing weather in the afternoon allowed extensive control; a total of 25 avalanches size 2.5 and larger were released with explosives; nine of these crossed or blasted the road.

Figure 3: Close encounter with avalanche during rain-on-snow, October 7, 1996. The road was closed. (a) View seen by one of the road crew who was travelling in a vehicle and about to exit the tunnel. (b) Impact pressures destroyed the east portal; damage to such reinforced-concrete structures requires impact pressures of ~1000kPa (McClung and Schaerer, 1993). (c) Clearing the road to the tunnel. Estimated mass of the avalanche is ~70,000 tons.

Figure 4: Evolution of conditions leading up to the size 4.5 avalanche down East Homer 2&3 on October 7 (day 281) 1996. Avalanche events are marked with arrows (n=natural; x=controlled with explosives). The dashed vertical line marks the time that East Homer released (a) cumulative precipitation measured at the West Homer gage; (b) snowline at 1850m estimated using air temperature measurements at Belle (1600m), assuming a lapse rate of 6.5°C/km, and that precipitation falls as rain at elevation z when the temperature at elevation z, Tz ≥ 2. (c) evolution of shear stresses calculated for 40° slope using SNOSS with same assumptions used for the Murrells avalanche.
A fracture-line profile the next day indicated the 130cm slab was moist, average density 455kg/m³. Slope angle was 35°. Field observations indicated that a smaller avalanche from the summit snowfield of Mt Belle likely triggered the East Homer avalanche. Measurements extrapolated from the Belle weather station suggest that the avalanche released immediately after precipitation on the summit snowfield changed from snow to rain (Fig. 4b).

3. LESSONS LEARNED
The close encounters and the damage to the east portal (Fig. 3) was a wakeup call for both the avalanche program and the client (Transit NZ). The events highlighted the seriousness of the avalanche hazard on the Milford Road and emphasized the need for quantitative data and systematic forecasting procedures.

Key lessons learned include:
(1) Recognizing and paying attention to weak signals and early warnings of instability is critical. In these cases, warnings included: (i) high cumulative precipitation (567mm for Murrells; 705mm for East Homer), and high precipitation rates just prior to the events (65mm in 10hrs for Murrells and 255mm in 24hrs for East Homer); (ii) natural avalanche activity just prior to the events; (iii) the lack of waterfall activity during the morning road check on day 281 indicated that slopes were still loading.

(2) Keeping track of the deeper snowpack in the start zones is critical. A quantitative measure of both inflow and outflow of water from the snowpack are essential for evaluating the evolution of stresses during rain-on-snow. These events prompted the design and construction of snow temperature poles and lysimeters (Carran et al., 2000) and the expansion of the weather station network.

(3) It is often thought that “two heads are better than one”, but studies show that in perceptual decision-making tasks (such as avalanche forecasting), this is true only if the individuals are able to accurately communicate their level of confidence to each other (Mercier and Sperber, 2012; Bahrami, et al., 2010). Clear communication of confidence is especially important in situations where individuals have different levels of observational aptitude.

(4) Reliable data are essential for making informed decisions; “evidence” of unknown reliability can have catastrophic consequences. For example telemetry data from the East Homer rain gauge (a pressure gage at the bottom of a tube) indicated that precipitation stopped before 0600, but in fact it started to overflow at that time.

4. NEW INSTRUMENTS AND PROCEDURES
The events motivated the development and installation of new instruments and some procedural changes. Some of these have taken time to come to fruition. Some of the new instruments and procedures now in place include:

4.1 Systematic and transparent forecasting processes
The daily road observations and hazard forecast has been restructured in order to ensure consistency and transparency in the process. The duty forecaster fills out the hazard form daily (more frequently during changing conditions) that is discussed by other forecasters. The checklist includes documentation of avalanche activity, snowpack stability, snow and weather observations, and forecasted changes in conditions. Threshold values have been assigned to observations and forecasted changes in precipitation rate and type, freezing level, snow level, drainage through the snowpack, and road conditions. The threshold values are based on lessons learned from past storm cycles. In this way the procedure is standardized and transparent; the checklist provides confidence that the forecaster has considered and synthesized all available data into the hazard forecast.

We work closely and communicate regularly with the NZ met service who provide mesoscale forecasts for the region twice a day; more often when conditions are changing. They have open access to 10-min data from the network of weather stations.

4.2 Instrumentation
New instrumentation includes:
(1) Snow temperature poles to measure when the snowpack becomes isothermal, and lysimeters to measure outflow of water from the snowpack have been designed, and built in-house (Carran et al., 2000). Scales beneath the lysimeter trays provide a measure of the overburden stresses at each site. More recently, a spatial array of lysimeters has been installed to map east-west and altitudinal variations in outflow (Conway et al., 2009). Previous work has shown that stability generally increases when drainage through the snowpack has been fully established (Conway and Raymond, 1993). Operationally, during rain events we assume that drainage is fully established only
when the timing and rate of outflow matches the precipitation influx (Milford Team, 2004).

(2) The network of stations telemetering snow and weather data to TeAnau base has been expanded since 1996; there are now two stations at road level, four located near the start zones, and two mobile stations. A shelter, constructed in 2003 at 1900m between two start zones on Mt Crosscut, facilitates the collection of manual measurements of snow conditions during storms. Associated with the expansion of the network of snow and weather stations, the increased reliability and increased bandwidth of radio communications has also enabled transmission of images from selected sites in real time. Cameras have been installed to monitor road and traffic conditions and key avalanche paths.

4.3 Active avalanche control
Avalanche control procedures have also evolved since the event. We have worked closely with local helicopters to develop manuals and procedures for helicopter operations. We now take a more aggressive approach to remove deep instabilities in the snowpack using large charges (25kg of ammonium nitrate), detonated with fast and powerful (900g) boosters. Charges are placed at targeted locations by helicopter during weather windows. Night-vision goggles are used on missions when weather windows occur during the night. Bomb placement and avalanche activity is logged and archived for future reference.

The summit snowfield on Mt Belle is now one of the regular targets. Bomb placement and avalanche activity is logged and archived for future reference.

4.4 Managing road conditions
The hazard to travellers increases significantly when their vehicles are stationary or immobilized; this problem is mitigated by enforcing no-stopping zones, and by ensuring that all vehicles carry chains. In addition we strive for a snow-free road because traffic problems increase exponentially with snow on the road. Implementing the snow-free-road policy can be a challenge during fast moving storms with rapidly changing freezing levels.

5. CONCLUSIONS
The consequences of these two avalanche events could have been much worse; the two close encounters were sobering for both the avalanche program and the client (Transit NZ); the client has no tolerance for avalanches greater than size 2.5 when the road is open. To this end, the program developed new instruments and modified operational procedures to quantify and manage the deeper snowpack. Also key has been the development of a more systematic and transparent forecasting process.

6. ACKNOWLEDGEMENTS
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7. REFERENCES