Snow stability on uniform slopes: implications for avalanche forecasting

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Abstract: This research investigated whether single snowpits can reliably represent snowpack stability on uniform slopes. The study utilized seven carefully selected slopes, three each in the Bridger and Madison Ranges of Southwest Montana, and one in the Columbia Mountains near Rogers Pass, British Columbia. Teams performed ten Quantified Loaded Column Tests in each of five snowpits within a 900 m^2 plot at a slope, measuring shear strength in a single weak layer. Collection of slab shear stress data enabled the calculation of a strength/stress stability ratio. Altogether, eleven stability-sampling trials were performed during 2000/2001 and 2001/2002, testing several weak layer types exhibiting a wide range of strengths. Of the 54 snowpits completed, 26 pits (48%) represented plot-wide stability and 28 pits (52%) did not. One plot collapsed prior to completion of a 55^{th} pit. Two of the eleven plots did contain full complements of five representative snowpits. The results of this study suggest the importance of improving our understanding of the processes affecting the variability of snowpack stability on any given day.

Keywords: stability, spatial variation, avalanche forecasting

1. Introduction

Avalanche forecasting has been described as "… the prediction of current and future snow instability in space and time relative to a given triggering (deformation energy) level …" (McClung, 2002). It follows, then, that among the many objectives of a forecaster is to "… minimize the uncertainty about instability introduced by the temporal and spatial variability of the snow cover (including terrain influences) … " (McClung, 2002).

As avalanche forecasters seek to minimize uncertainty regarding snowpack conditions, evidence of instability obtained from the observation of actual avalanches is customarily considered unambiguous, 'low entropy', 'scaled' information of the utmost relevance and, as such, is given the highest weighting (LaChapelle, 1980). In the absence of actual avalanche observations, or to corroborate the evidence they present, field measurements of snowpack stability obtained from in-situ stability tests are also generally considered relevant, low entropy, 'Class I' data (McClung and Schaerer, 1993). In-situ stability tests measure the critical triggering load, or deformation energy, required for snowpack rupture in a limited number of samples.

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However, it is often unsafe to conduct in-situ stability tests within avalanche starting zones, particularly when conditions approach the threshold of avalanching (Föhn, 1988; CAA/NRCC, 1995). Further, it is infeasible to obtain stability test data from every starting zone of interest, given the magnitude of terrain that most forecasters evaluate (Armstrong, 1991). For those reasons, avalanche forecasters routinely perform stability tests at carefully selected proxy sites presumed to be representative, to one degree or another, of snowpack conditions in nearby avalanche terrain but without the hazards associated with entering that terrain (McClung and Schaerer, 1993; Fredston and Fesler, 1994).

While actual avalanches present comparatively unambiguous stability information, stability test results may contain substantial informational ambiguity caused by unknown spatial variations in snowpack characteristics within the stability-sampling site itself. Several studies have documented spatial variation in snowpack stability within actual avalanche terrain, wherein terrain and snowpack characteristics were known to vary (Bradley, 1970; Conway and Abrahamson, 1984; Föhn, 1988; Birkeland, 2001; Kronholm et al., 2001).

Less attention has been given, however, to variation within study sites specifically selected to maximize the chances of sampling a snowpack that is homogeneous throughout a plot area. This study investigated spatial and temporal variations in snowpack strength and stability across stability-sampling sites selected to minimize the effects of spatial variations in terrain, aspect, substrate, vegetation and wind on snowpack processes. We asked, "Can a set of ten stability tests from a single snowpit reliably represent stability throughout a (nominally uniform) plot?"

In addition to varying across space, stability is also known to change over time, at a given location. This study also measured temporal variations in stability in a series of three side-by-side trials conducted at the same slope over a period of eighteen days. Those results, and their interpretation, are the subject of a companion article (Birkeland and Landry, 2002). The current article will focus on the *spatial* variations in snowpack strength and stability observed during this study.

2. Methods

2.1 Stability sampling design and site selection

We adopted a systematic sampling design for this study distributing five snowpits in a regular pattern across a 30m by 30m plot (Figure 1). Systematic sampling assured coverage throughout the plot. The 900 m^2 plot area was adopted to approximate a study plot large enough to accommodate most or all of an avalanche forecaster's routine snowpits for a season.

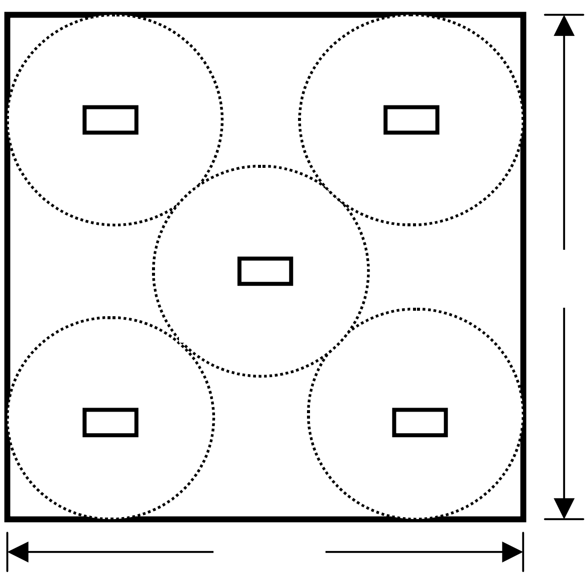

Figure 1: Showing the 900 m^2 stability-sampling plot pit layout. Five snowpits are represented as rectangles. (See Landry 2002 for exact pit locations and layout).

Seven 900 m^2 stability-sampling sites were selected based on several desired attributes: no prior disturbance by skiers, snowmobiles, etc; planar slope profile; no or minimal vegetation, besides grass; adequate distance from nearby trees to prevent shading; smooth substrate, without large scree or protruding bedrock; slope angle from 25-30°, for safety; protection from wind. Satisfying all of these conditions was difficult, and some sites suffered from more wind exposure than others.

Nonetheless, in the opinion of the observers, all of whom were experienced avalanche forecasters, the selected sites seemed to be nominally 'uniform' slopes capable of exhibiting consistent snowpack characteristics throughout the 900 m^2 stability-sampling plot. Three of the stability sampling sites were in the Bridger Range, northeast of Bozeman, Montana, three in the Madison Range, southwest of Bozeman, and the final site was at Rogers Pass, British Columbia, near Fidelity Station in Glacier National Park.

2.2 Measuring and calculating stability

Shear strength data for a single weak layer was collected at each plot using the quantified loaded column stability test (QLCT) method (Landry et al., 2001). Ten QLCT were performed in each of the five snowpits at a plot, using two rows of five, 50 cm wide test cells, with the front of the second row of five cells 1 meter uphill of the front of the first row. QLCT results were size-adjusted to a sample size of 'infinite' area, according to the area of the targeted weak layer actually tested. QLCT calculations, according to the QLCT mode employed, yielded shear strength τ_∞ in units of N/m^2. Slab water content (height in m, measured normal to slope) above the weak layer, was also measured once at each pit in order to calculate the shear stress τ_{Slab} (N/m^2) acting upon the weak layer at that pit location:

$$\tau_{Slab} = \rho g h \, Sin\Psi \qquad (1)$$

where h represents the snow-water-equivalence of the slab (meters of SWE), measured normal to the slope, ρ is the density of the slab (1,000 kg/m^3), g is gravity, and ψ is slope angle. A stability ratio was calculated:

$$S_{QLCT} = \tau_\infty / \tau_{Slab} \qquad (2)$$

Mean strength and mean stability values were calculated, pit-wise and plot-wise.

2.3 Measures of variability

Coefficients of variation (of the general form $CV = s/\bar{x}$, where s is the standard deviation of the sample mean strength $\bar{x}$) were calculated for strength, stress, and stability, both pit-wise and plot-wise. The coefficient of variation is preferred as a measure of variability in snow strength, over the standard deviation or variance, since the standard deviation of snow strength is known to increase as mean snow strength increases (Jamieson and Johnston, 2001).

2.4 Conservative *t*-test analyses of "no difference" in strength and stability

For each pit in a given plot, two-sample *t*-test analyses were adapted to conservatively evaluate the hypotheses of "no difference" between a single pit's mean strength $\overline{\tau}_{\infty}$ and its plot's mean strength $\overline{\tau}_{\infty(Plot)}$, and between a single pit's mean stability $\overline{S}_{QLCT}$ and its plot's mean stability $\overline{S}_{QLCT(Plot)}$. This adaptation of the two-sample *t*-test evaluated whether the mean strength $\overline{\tau}_{\infty}$ and/or mean stability $\overline{S}_{QLCT}$ in any single snowpit within a plot reliably represented mean plot strength $\overline{\tau}_{\infty(Plot)}$ and/or mean plot stability $\overline{S}_{QLCT(Plot)}$ and, therefore, whether that study plot represented a single "strength (or stability) population".

In our application of the two-sample *t*-test, the assumption that samples be drawn from two separate populations was relaxed. Instead, we pooled results from a single snowpit with the remaining four snowpits at a plot to obtain mean study plot stability $\overline{S}_{QLCT(Plot)}$ or mean plot shear strength $\overline{\tau}_{\infty(Plot)}$. If a particularly strong/weak or stable/unstable pit were not pooled with the remaining four pits, plot-wide variability in strength or stability would have been understated and made to appear more consistent than was actually measured.

3. Results

3.1 Summary of stability-sampling trials

Altogether, eleven 900 m^2 stability-sampling trials were performed over the course of the 2000/2001 and 2001/2002 winter seasons yielding data from 54 pits (Table 1). During the Round Hill trial the entire slope collapsed during the preparation of the final (5th) pit and no data was obtained, hence we logged data from 54 total pits rather than a full set of 55.

Weak layer types tested included depth hoar and/or basal facets (5 trials), near-surface facets (1 trial), surface hoar (4 trials), and new forms (1 trial). Weak layers ranged in age from 5 days (near-surface facets) to 75 days (depth hoar). In most trials, shear strength was more variable, sometimes by an order of magnitude, than shear stress. However, in three trials shear stress was somewhat more variable than shear strength (Table 1).

In the absence, during several trials, of a sufficient number of (or any) valid QLCT results from a plot's targeted weak layer, several pits were found empirically unrepresentative of their plot.

3.2 Variability in strength

Among the 51 individual snowpits in our study for which a valid coefficient of variation in shear strength could be calculated, $CV\overline{\tau}_{\infty}$ ranged from 0.057 (5.7%) to 0.369 (36.9%), with a mean of 0.174 (17.4%). During the first two of our three trials at Lionhead Mountain, testing buried surface hoar, we obtained $0.057 \le CV\overline{\tau}_{\infty} \le 0.062$ in six of the pits, at shear strengths 336-528 N/m^2.

3.3 Pit-to-plot differences in shear strength

Prior to evaluating pit-to-plot differences in stability we analyzed plot-wide patterns of weak layer shear strength. Of the 54 total pits performed, 5 pits were deemed unrepresentative of plot-mean strength based on conclusive empirical evidence. Such evidence included the absence of the targeted weak layer, observed in the majority of the plot, or the presence of other weaker weak layers.

At the remaining 49 pits our conservative two-sample *t*-test analyses yielded no statistically significant difference ($\alpha = 0.05$) between pit-mean and plot-mean strength in 30 pits. A statistically significant difference was found between pit-mean and plot-mean strength at the remaining 19 pits.

Only one trial, at Bradley Meadow on 3/17/01, produced a full complement of five pits statistically 'representative' of plot-mean strength, testing a layer of near-surface facets lying underneath a thin frozen-rain crust. Two other trials produced four 'representative' pits, the Middle Basin trial and the Lionhead Mountain trial of 1/9/02. At the other end of the spectrum, at Round Hill we found such dramatic differences in shear strength between the two 'sides' of the plot that all four of the completed pits were found statistically unrepresentative of the plot-mean shear strength.

3.4 Pit-to-plot differences in stability

When the variability of shear stress at a plot was very low (i.e., < 0.10), the spatial patterns of pit-to-plot differences in stability closely resembled pit-to-plot differences in shear strength. But, where shear stress showed larger variations across a given plot, patterns of

Table 1: Stability-sampling trials summary. Pits failing to yield a sufficient number of (or any) valid QLCT results in the plot's dominant weak layer were found empirically unrepresentative of plot stability. ('*CV'* indicates coefficient of variation. Weak layer types are: 'DH' = depth hoar; 'BF' = basal facets; 'NF' = new forms; 'SH' = surface hoar; 'NSF' = near-surface facets.)

Site (Weak Layer Type)	Trial Date	Plot Mean Stability Index	*CV* Plot Stability	Plot Mean Strength (N/m^2)	*CV* Plot Shear Strength	*CV* Plot Shear Stress	Weak Layer Age (days)	Pits Statistically Representative of Plot Stability	Pits Statistically Unrepresentative of Plot Stability	Pits Empirically Unrepresentative of Plot Stability
Bacon Rind (DH)	1/4/01	2.08	.313	533	.320	.036	≅60	2	3	0
Bradley Mdw. (NF)	1/27/01	5.74	.222	588	.228	.315	7	2	3	0
Round Hill (SH)	2/4/01	2.60	.437	831	.502	.102	7	0	4	0
Baldy Mtn. (DH/BF)	2/18/01	1.79 [a]	.201 [a]	1,125 [a]	.257 [a]	.278 [a]	≅75	0 [a]	0 [a]	5 [a]
Saddle Peak (DH/BF)	2/18/01	1.86	.261	1,482	.253	.159	≅75	2	3	0
Bradley Mdw. (DH/BF)	2/18/01	1.59 [b]	.204 [b]	1,657 [b]	.212 [b]	.479 [b]	≅75	0 [b]	0 [b]	5 [b]
Bradley Mdw. (NSF)	3/17/01	3.11	.266	433	.270	.019	≅5	5	0	0
Middle Basin (DH/BF)	12/7/01	2.03	.237	696	.230	.117	≅14	3 [c]	0 [c]	2 [c]
Lionhead Mtn. (SH)	1/9/02	2.53	.102	375	.104	.038	14	5	0	0
Lionhead Mtn. (SH)	1/15/02	3.08	.106	523	.105	.036	20	3	2	0
Lionhead Mtn. (SH)	1/26/02	2.43	.162	1,084	.175	.043	31	4	1	0
							Totals	26	16	12
							%	48.2%	29.6%	22.2%

[a] Five different weak layers were revealed; strength, stress and stability data are for 19 valid QLCT results obtained from the targeted weak layer

[b] Results are for 20 valid QLCT results in the targeted weak layer; 30 tests exceeded the range of the QLCT equipment

[c] 'Representative-ness' results (only) reflect estimation of the effect of including nine QLCT tests whose strength exceeded the range of the equipment

pit-to-plot differences in stability changed, as compared to pit-to-plot differences in strength.

Our conservative two-sample *t*-test analyses found no statistically significant pit-to-plot differences (α = 0.05) in stability in only 26 pits, while another 16 pits did
reveal a statistically significant difference, and the remaining 12 pits exhibited conclusive empirical evidence of 'un-representativeness' (Table 1). Only two of the eleven trials produced full complements of five pits exhibiting "no difference" in pit-to-plot stability (Bradley Meadow on 3/17/01 and Lionhead Mountain on 1/9/02) while three trials produced no 'representative' pits at all (Round Hill, Baldy Mountain, and Bradley Meadow on 2/18/01).

4. Discussion & conclusions

The central hypothesis of this research was that, "stability measured at a randomly selected snowpit location within a carefully selected study plot will demonstrate a significant probability of predicting the mean stability of the entire study plot." After eleven stability-sampling trials at seven different sites, we found that only roughly one-half of our pits had, in fact, shown no significant difference between pit-mean stability and plot-mean stability. Further, only two of the eleven trials had produced plots in which all five pits were representative of their plot-mean stability.

4.1 Potential sources of variability

In some trials, surprising variations in strength, rather than in shear stress, resulted in poor representation of plot-wide stability by individual pits. For instance, during our first trial at Bacon Rind the team was initially confident that the selected slope would exhibit a nominal, homogeneous snowpack. That first impression was supported by the results of the first pit and snow profile, showing an extremely simple snowpack consisting of a thick layer of depth hoar covered by an equally thick, single-layer slab, and the expected consistency in shear strength. Not until the third pit, at the center of the plot, did we discover what seemed to be 'anomalous' variations in strength, with the plot's strongest snow thus far. In the final analysis, neither the first, second, or the apparently 'anomalous' third pit proved to be representative of pooled plot stability.

No apparent spatial variations in the substrate, vegetation, aspect, wind effects, or slope shape was observed that might have explained that variability at Bacon Rind. Overall, we believe our site selection for these eleven stability-sampling trials was successful in minimizing those factors, at least to the extent that we understand the sensitivity of the snowpack to very small differences in those variables over space and time (Birkeland and Landry, 2002).

Instead, variations in the load produced by the overlying slab appeared to explain the variability in strength we observed during some trials, but not in others. Chalmers and Jamieson (2000) found evidence of increases in strength and stability in surface hoar associated with increases in slab load, and Johnson and Jamieson (2000) made a similar finding for faceted weak layers. Although those studies measured increases in strength and stability associated with increasing loads over time, the effect of spatial variations in the slab at a given moment in time could help explain spatial variations in weak layer strength and slope stability. However, large spatial variations in weak layer strength also occurred even when shear stress was effectively uniform across a plot. For instance, shear stress across the Bacon Rind plot varied only slightly, from 244 to 269 N/m^2, while plot-wide shear strength ranged from 301 to 1,141 N/m^2, and from 458 to 1,141 N/m^2 in the same (third) pit.

Variation in our observers' QLCT technique, or produced by the QLCT procedure itself, might have offered another explanation for the variability in strength we observed. We compared our QLCT results to a study of variability in shear frame test results. In their analysis of 114 sets of shear frame results, all of which were collected on slopes of similar steepness to our trial sites, Jamieson and Johnston (2001) found a mean coefficient of variation in shear strength of 0.178, and a range from 0.04 to 0.54. Those results bracket the variability we found in QLCT results, with a mean *CV* of 0.174 and a range from 0.057 to 0.369, providing evidence that the QLCT method may be no more prone to operator-induced variations in test results than the shear frame method. Further, with six pits producing coefficients of variation from 0.057 to 0.062 during the Lionhead trials of 1/9/02 and 1/15/02, at least some of which must be attributed to actual variations in snow strength, our results show that the QLCT is capable of detecting low levels of variability in comparatively weak layers. Therefore, like the shear frame, it seems that when performed by an expert, the QLCT method can be conducted without introducing problematic levels of 'background noise' to the test results.

Finally, we considered the relationship between the age of a particular weak layer and its variability in strength and stability. Clearly, the older a weak layer (on a 'uniform' slope) becomes, the more opportunity it has to experience and reflect spatially differing effects from variations in the overlying slab and from subtle variations in the underlying terrain and snowpack creep. However, although we have a limited amount of data for each weak layer type, our results show contradictory patterns relating weak-layer age and variability in strength. The hypothesis that a young surface hoar weak layer should be less likely to exhibit variability in strength than another older layer was belied by a comparison of our results from Round Hill, where buried surface hoar only 7 days old produced $CV\overline{\tau}_{\infty(Plot)} = 0.502$, versus the three Lionhead Mountain trials in older buried surface hoar, with values for $CV\overline{\tau}_{\infty(Plot)}$ of 0.104, 0.105, and 0.175 at ages 14, 20 and 31 days, respectively. On the other hand, our results in depth hoar/basal facet weak layers do show a more consistent relationship between weak layer age and variability of strength. We drew no conclusions regarding a relationship between a weak layer's age and spatial variation in its strength from this limited and contradictory data.

It should be noted that 'high' variability in strength within a particular pit did not preclude the possibility that the pit was representative of plot-wide strength or stability. For instance, shear strength at Bradley Meadow (on 3/17/01) exhibited $CV\overline{\tau}_{\infty(Plot)} = 0.270$, and individual pits ranged from $0.198 \le CV\overline{\tau}_{\infty} \le 0.319$, yet all five pits were statistically representative of plot-mean stability.

4.2 Pit representation of plot stability

In short, we found no physical factors or methodological problems capable of explaining or predicting the variability in shear strength and stability that we observed on apparently 'uniform' slopes. Therefore, with only 26 of 54 pits predicting plot-wide stability, and only two of eleven plots yielding five pits 'representative' of plot-wide stability, we concluded that a single pit on a uniform slope was not shown to be a reliable predictor of the slope's mean stability.

4.3 Implications for 'representative' slopes

The implications of our study for the concept of the 'representative slope' are apparent. While professional avalanche forecasters may now generally assume spatial variation in stability to be the norm in complex terrain, our study shows that problematic spatial variation in snowpack stability is also often present on apparently 'uniform' slopes. Systematically sampling stability on a carefully selected study plot slope does not necessarily produce results representative of (even) that slope. In fact, a single pit on an apparently uniform slope can be highly unrepresentative of the slope's stability. For example, a pit spacing difference of only 12 meters in our trials at Round Hill (one or two turns by a skier or snowboarder) revealed shear strengths differing by a factor approaching 3. Further, with stability indices of 3.6 and 3.7, neither of the two pits on one side of the Round Hill plot suggested that the entire plot and surrounding 30° slope was verging the collapse which occurred while preparing the final pit.

More importantly, perhaps, our results suggest that systematic and/or random sampling of a presumably representative study plot (or other uniform) slope, in pursuit of 'mean' slope stability information, may be less fruitful and less important than seeking worst-case, 'instability' data through 'targeted sampling' (McClung, 2002). The challenge remains, of course, to identify safe 'targeted sampling' sites that are likely to present the instability data desired.

4.4 Stability tests as Class I data

Our findings may also provide new information regarding the categorization of stability test results as Class I data, data that is easily interpreted and more revealing of current stability conditions than observations such as a snowpack profile (McClung and Schaerer, 1993). Our results show that stability tests results from a single pit often contained substantial informational ambiguity and were not reliable, even on a carefully selected 'uniform' slope.

To experienced avalanche forecasters, this may be 'old news'. Experienced avalanche forecasters may actually confer 'reliability' and 'representative-ness' upon very few field observations of stability. Diligent and objective application of their experience and theoretical knowledge of avalanche formation processes may enable skilled, professional forecasters to interpret stability tests, recognize their residual uncertainty, and give results the appropriate weighting. It may also be the case that the Class II (snowpack characteristics) information gleaned in the course of conducting stability tests, such as the snowpack stratigraphy, receives equal or greater weighting than the so-called Class I stability test results themselves.

If experience and knowledge are required to correctly interpret and appropriately apply stability test results, 'beginner' backcountry travelers, by definition, do not possess the requisite experience or knowledge. Nonetheless, the concept of the 'representative location' for snowpits and stability tests is described for (McClung and Schaerer 1993, Fredston and Fesler 1994, Tremper 2001), taught to, and commonly adopted by inexperienced 'amateur' backcountry travelers, as well as aspiring avalanche professionals and mountain guides. Our results highlight the difficulties associated with using stability tests to reduce uncertainty about spatial variations in (in)stability, the value of experience and objectivity in their interpretation and appropriate weighting, and the need for broader awareness of the shortcomings of representative sights and their stability test results.

4.5 Stability processes research

Additional research is clearly needed to explain why 'uniform' slopes sometimes do and sometimes do not exhibit uniform stability that may or may not be reliably sampled with a single set of stability tests. A deeper understanding of the complex processes leading to those conditions would contribute to reducing uncertainty regarding the spatial (and temporal) variability of snowpack stability (Birkeland and Landry, 2002).

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