Wet snow diurnal evolution and stability assessment

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ABSTRACT: Wet snow avalanches pose a threat to snow recreationists and to infrastructure such as mountain roads. The timing of wet snow avalanche formation is difficult to predict. The loss of strength is more important than stress imposed by additional loads. Processes leading to weakening, such as water infiltration can be gradual or sudden. Therefore, the time scale of observations is essential. A questionnaire among 40 international avalanche professionals aimed at determining common practice in assessing wet snow stability during first and repeated wetting events. It turns out that only few respondents use different stability tests for dry and wet snow. 14 respondents consider tests in wet snow useful. In view of the responses, we sampled 35 locations during first and repeated wetting cycles in the Swiss Alps. We compare the results of one rutschblock test (RB), four extended column tests (ECT) and two shovel shear tests from the morning and the afternoon. Additionally, vertical liquid water content profiles and snow profiles are analyzed. Moist and very soft persistent weak layers most often produce unstable test results, where the failure character is a collapse. Observed ponding horizons did not produce failures in the tests. As in dry snow, the RB is comparable to the ECT in wet and moist snow. The influence of surface melt-freeze crust is investigated by comparing ECT fracture propagation with a modified version of the ECT, where the surface melt-freeze crust is removed. A procedure to assess deep, wet snow instabilities is suggested.

KEYWORDS: Wet snow, snow stability, water content, rutschblock test, extended column test, shovel shear test, persistent weak layer

1. INTRODUCTION

Information on snow stability is important for avalanche forecasting. The key problem when assessing wet snow stability are the rapid temporal changes of the snowpack following wetting. The snowpack conditions may change within minutes or hours (Trautmann, 2006; Tremper, 2001). Hence, wet snow stability information must be temporally interpreted. Further complications arise due to the fact that often the advancement of water infiltration in the snowpack is not known and very heterogeneous, and its impact on snow stability is not sufficiently understood. Standard stability tests provide valuable information in dry snow conditions. Their performance in wet snow is unclear.

In this study, the focus has been on the assessment of wet snow stability with the help of shear and snow stability tests (Rutschblock RB, extended - column test ECT and shovel shear test ST). In a first step, the common practice among avalanche professionals was evaluated by approaching experienced avalanche forecasters in the European Alps, Norway, North America and New Zealand with a questionnaire. Based on the results of this survey and previous research, field tests were conducted to investigate the diurnal change in wet snow stability using shear and stability tests. Test results, snowpack characteristics like water content (LWC) or snowpack structure, were compared to signs of instability (avalanche activity, cracking, collapsing of snowpack).

2. DATA AND METHODS

2.1. Survey

A survey consisting of 15 questions was distributed in English, German and French to 40 selected avalanche professionals. Forecasters were contacted following recommendations by national avalanche organizations or through personal contacts of the authors. The survey focused on the type of the avalanche organization, snow climate, avalanche situation, assessment of wet snow stability using shear

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and stability tests as well as wet snow avalanche forecasting in general.

The respondents from Switzerland, the United States, New Zealand, Canada, Norway and Austria are generally involved in several avalanche operations: from national- or regional–scale, to ski area, highway or mining operations, from recreational use to mountain guiding, research, rescue, avalanche education or military.

2.2. *Field experiments*

To investigate diurnal changes in snow stability, suitable slopes were selected allowing sufficient space for afternoon tests in the immediate vicinity of morning observations. Depending on expected warming, criteria for site selection were slope aspect, elevation and slope angle, as well as snow depth. The intention was to select sites which became unstable during the day. Beside standard snow profile observations (SLF, 2009), LWC was measured using the Snow Fork (Sihvola and Tiuri, 1986). Based on preliminary results in dry snow, LWC was corrected assuming a snow density of 250 kg/m^3. Stability tests were performed adjacent to the snow profile (Figure 1). These included one RB (SLF, 2009), two ECTs (Simenhois and Birkeland, 2006) and two STs (Greene et al., 2004). During morning observations, two ECTs with the surface melt-freeze crust removed (ECTmod) were performed to approximate the expected loss in diurnal surface strength due to melting of the surface crust. Shear and stability tests were repeated in the afternoon, generally only two or three meters away from the morning observations.

2.3. *Statistical methods*

Failure planes, detected by the tests, had to be a minimum 15 cm below the surface to be considered relevant. If a test failed at several depths, the weakest score and the best release type/fracture potential were considered for further analysis. Stability test scores, structural weaknesses and LWC were compared using the Mann Whitney U-test or the Wilcoxon rank sum test (Ross, 2006). Contingency tables, release type, fracture potential, persistent weak layer (wL) and capillary barrier index (CBI) were tested for significance using Fishers Exact test for count data (Agresti, 2007). The level of significance was α≤0.05.

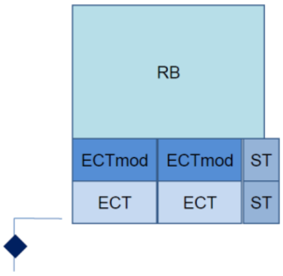

Figure 1: Layout for field experiments. One Rutschblock (RB), two extended column tests (ECT), and two shovel shear tests (ST) were carried out. Additionally, two ECT with the surface melt-freeze-crust removed were undertaken in the morning (ECTmod). The diamond represents the snow profile location.

Tab. 1: Investigated variables.

Variable	Description
RB score	1 to 7
RB release type	whole block wB, partial break pB, edge E
ECT score	mean of two tests; 1 to 30, no failure - 35
ECT fracture potential	two tests; fp – full propagation (both tests fp), pp – partial propagation (once fp), np - no propagation or no failure.
ST score	mean of two tests; 0 - 5 for collapse, very easy, easy, moderate, hard, no failure,
ECTmod	ECT with melt-freeze surface crust removed, score and fracture potential as for ECT
Structural weakness (lemons)	0 to 6 lemons, Schweizer et al., 2008
Persistent weak layer wL	hand hardness < 4F and persistent grain form (including mixed forms)
Capillary barrier index CBI	Baggi and Schweizer, 2009
LWC	Liquid water content in vol. %, mean; tool: Snow Fork (Sihvola and Tiuri, 1986)
LWC sf	LWC of snow surface (upper 15 cm), mean (N = 12)
LWC wL	LWC of persistent weak layer, mean (N > 3)

2.4. *Stability classification of wet snow profiles*

For this analysis, profiles are classified as *stable* or *unstable* based on signs of instability in the same slope as the profile and at the time of profile observation (Brown (2008) used a similar approach). This approach was chosen as wet snow stability is very much depending on slope angle, aspect and elevation and as wet snow stability is known to change rapidly. Considered signs of instability are triggering of avalanches, collapsing of snowpack, whoompf-sounds or crack formation. Five of the seven as *unstable* classified profiles were recorded during the intense wet snow avalanche period with avalanches reaching the valley floor (Davos region, between 2 April and 4 April 2009).

3. RESULTS

3.1. *Assessing wet snow stability - avalanche professional's experience*

Direct signs of instability, in particular natural avalanche observations from indicator slopes, are considered the most important information when assessing wet snow stability. Of these direct instability observations, natural avalanche observations ranked higher than results from artificial slope testing (explosives, ski-cutting) and stability tests.

Most popular stability tests in wet snow include the compression test (CT), RB and ST. None of the respondents specifically indicated using a different test in dry or wet snow. All tests are used less frequently in wet snow than in dry snow. Four respondents do not use any standard test in wet snow. Common practices include ski-cutting and explosives-testing of suspect slopes. Non-standardized tests, like the hand shear test are also used. When asked if tests are useful for wet snow stability assessment, the majority of the respondents mentioned some limitations. In particular, the moment of observation is of critical importance as rapid changes in snowpack stability occur. Therefore, one approach taken is the increase in observation frequency. Snowpack parameters observed by practitioners are the advance of the wetting front, hardness, penetration resistance and snow temperatures.

Release type (RB) and fracture propagation (ECT) were ranked higher than test score, shear quality or fracture quality (CT). The ST is positively correlated to the "usefulness of the test in wet snow". The ST is applied more frequently in snow climates where winter rain is common. The RB is most frequently used in Switzerland.

The survey indicates further that if faceting occurs frequently, deep failures (in basal layers) are considered a bigger concern than surface avalanches.

Major forecasting problems concern the timing of avalanche release, in particular the onset of avalanching. The estimation of avalanche size and the failure of deep, persistent instabilities resulting in slab avalanches cause difficulties. Glide avalanches were often mentioned by Swiss respondents. Meteorological factors causing problems include rain-on-snow, despite it being relatively rare in most snow climates. Surface processes, like surface warming or refreezing of a wet snow surface have also been linked to the triggering of wet snow avalanches.

3.2. *Assessing diurnal changes in wet snow stability with stability tests*

Based on our wet snow stability classification scheme, 7 unstable and 28 stable profiles were analyzed. No meteorological forcing variables were considered in this approach. The measured surficial LWC is used to determine melt-water flux in the afternoon (Fig. 2). In all unstable profiles a moist wL existed (Tab. 2). The LWC in these wL was generally less than 3 vol. %, but significantly higher than on stable slopes (Fig. 2). Further significant differences ($p \leq 0.05$) between stable and unstable profiles are RB score and release type in the afternoon and structural parameters (lemons, Schweizer et al., 2008).

Both, morning ECT score and afternoon ST score may also provide some valuable information ($p \leq 0.1$). Interestingly, afternoon RB (stable profiles) and ECT (stable and unstable) scores tend to be higher than morning scores (Fig. 3). Unstable RB and ST scores show a slight diurnal decrease. RB (am) observations, ECT score (pm) and ECT fracture propagation (am, pm) do not sufficiently discriminate between stable and unstable slopes (Fig. 4). Removing the morning surface melt-freeze crust (ECTmod) considerably reduced the ECT fracture propagation (Fig. 5). For the same sites, the ECT had eight full propagations, while the ECTmod had only four. No propagation results increased in frequency.

Thin water-saturated layers were sometimes observed. However, these layer interfaces did not serve as the failure plane for shear or stability tests.

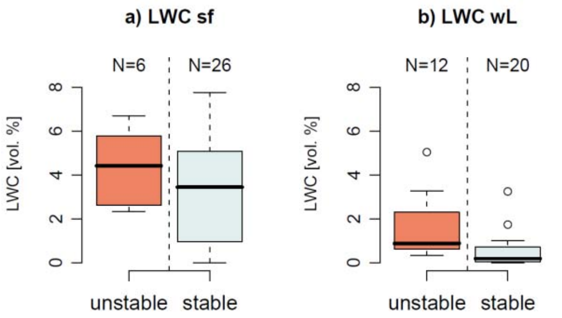

Fig. 2: Afternoon LWC measurements of the snow surface (a) and within persistent weak layers (b). The snow surface of unstable profiles had a minimum mean LWC of 2.3 vol. %, while LWC of persistent weak layers is significantly higher in unstable than in stable slopes.

Tab. 2: Investigated snowpack properties and shear and stability test results for 7 unstable and 28 stable profiles. Significant differences between stable and unstable parameters are highlighted by asterisk (** p≤0.01, * p≤0.05, (*) p≤0.1).

Parameter		unstable	stable	p
Lemons	median	5	4	*
wL	yes/no	7 / 0	14 / 14	*
CBI	mode	1	0.1	
LWCsf (vol. %)	mean/min	4.4 / 2.3	3.5 / 0	
LWCwL (vol. %)	mean	1.6	0.5	**
RB score am	median	4	4	
RB score pm	median	3	5	**
RB release type am	mode	wB	pB	
RB release type pm	mode	pB	nf/E	*
ECT score am	median	12	18.5	(*)
ECTmod score am	median	18.75	24	
ECT score pm	median	17	20.5	
ECT propagation am	mode	fp	np	
ECTmod propagation am	mode	np	np	
ECT propagation pm	mode	fp	np	
ST score am	median	1.75	2	
ST score pm	median	1.5	2	(*)

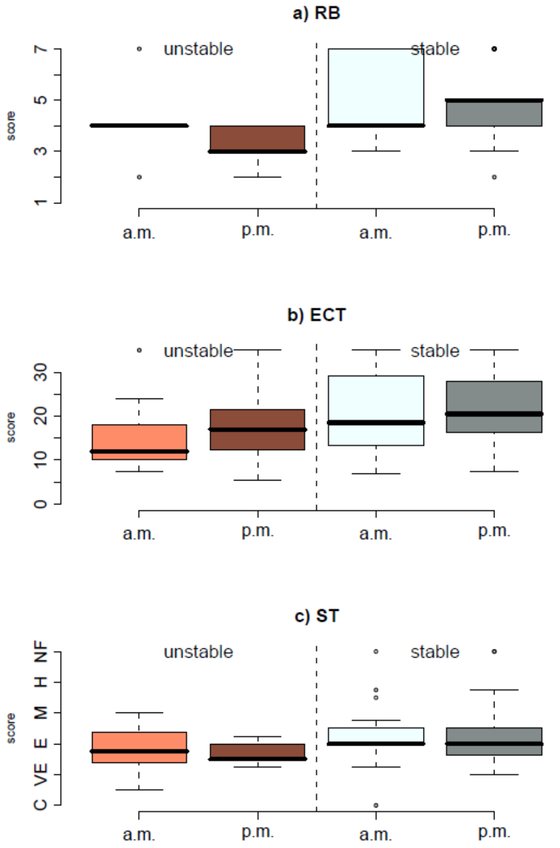

Fig. 3: Morning (am) and afternoon (pm) RB (a), ECT (b) and ST (c) scores. Unstable (N = 7) and stable (N = 28) profiles. Afternoon unstable RB scores and morning unstable ECT scores are lower than their respective stable tests medians. Afternoon ECT scores (stable and unstable) and RB scores (stable) tend to be slightly higher than morning observations. Unstable RB and ST scores show a slight diurnal decrease.

4. DISCUSSION

Wet snow instability is often a rather short-lived phenomenon, thus timing of observations is of critical importance. Even though we aimed for unstable days and slopes, still only one fifth of the profiles were unstable. It was particularly difficult to estimate in the morning which slope was not only going to warm sufficiently to produce a melt-water flux, but was also becoming unstable.

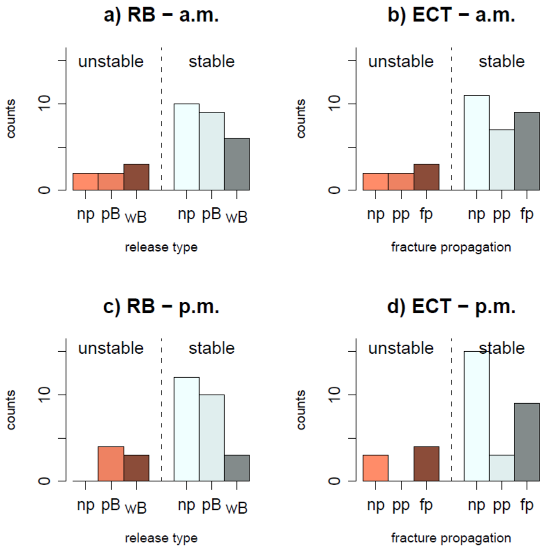

Fig. 4: Release type and fracture propagation for morning (am) and afternoon (pm) RB (a,c) and ECT (b,d). RB: wB – whole Block, pB – below Ski, np – edge or no failure. ECT (two tests): fp – full propagation (twice fp), pp – partial propagation (once fp), np - no propagation or no failure. Unstable (N = 7), stable (N = 28) profiles.

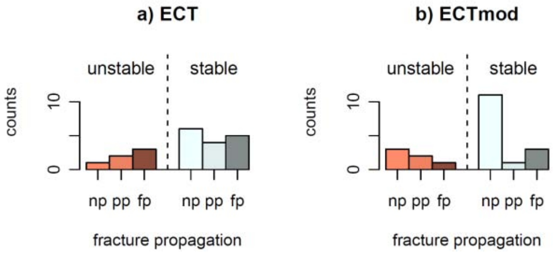

Fig. 5: Fracture propagation for a) ECT and b) ECTmod. Two tests: fp – full propagation (twice fp), pp – partial propagation (once fp), np no propagation or no failure. Unstable (N = 6), stable (N = 15) profiles. Removing the melt-freeze surface crust reduced the fracture propagation.

After only one season, the data set is small and unbalanced between stable (N = 28) and unstable cases (N = 7). Considering these limitations, all profiles classified unstable had moist or wet snow surface layers (LWC > 2.3 vol. %) and a persistent weakness existed. The presence of significant wL was discussed as one important factor in the formation of climax wet slab avalanches (Reardon and Lundy, 2004). LWC in wL was low (generally < 3 vol. %) in unstable profiles, but significantly higher than in stable profiles highlighting the major influence of small introductions of liquid water in wL. This supports findings from an earlier study, where micro-structural hardness of persistent wL decreased at low LWC (Techel et al., 2008).

For deep instabilities, stability tests have the potential to provide additional information. In these slopes, the RB score (pm) was significantly lower and the release easier. ECT (am) and ST scores (pm) were lower, however these results were not significant. The slight increase in ECT (stable, unstable) and RB (stable) scores from morning to afternoon is surprising, though not significant, and may possibly be attributed to spatial variability. None of the tests truly performed better, including the ST. The latter contradicts the feedback from the survey.

The effect of surface melt-freeze crusts has been observed in stability tests (ECTmod): if the crust was removed, fracture propagation was less than if the crust was not removed. Using this approach aimed at approximating stability with afternoon surface conditions (a melted, soft crust). However, so far this approach did not produce conclusive results.

Thin water-saturated layers above layer interfaces were observed, but standard tests did not fail on these layers. This indicates that standard tests are either not suitable for this type of failure or saturated layers are not relevant failure planes.

5. CONCLUSION

The survey showed that no established procedure exists to assess wet snow stability. The observation of signs of instability is often too late for wet snow avalanche forecasting. Hence, instability indicators are necessary in advance. Based on a small data set, we propose a first approach to indicators that assist in the estimation of afternoon wet snow instability for deep instabilities:

- presence of moist, persistent weak layers
- presence of structural weaknesses (> 4 lemons)
- AND sufficient increase in surficial melt-water.

LWC at the snow surface and in the wL are important factors in the diurnal evolution of wet snow stability. The collapse of moist, persistent weaknesses may be one of the trigger mechanisms involved in wet slab avalanche release. Stability tests may provide additional information, yet there is still much uncertainty in interpreting the test results in wet snow. The data set should be expanded primarily with unstable profiles. Furthermore, research is necessary to improve the understanding of the infiltration process and wet snow mechanics.

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