

THE FIRST WETTING OF SNOW:
MICRO-STRUCTURAL HARDNESS MEASUREMENTS USING A SNOW MICRO PENETROMETER

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ABSTRACT: Wet snow avalanches are responsible for avalanche fatalities but more frequently they threaten infrastructure, as mountain pass roads, in spring. A weak snowpack base consisting of persistent grains is considered one of the causes for these avalanches. In three field experiments in the Grisons Mountains in eastern Switzerland the evolution of water flow and the loss of micro-structural hardness with first wetting were investigated focusing on layers of facets and depth-hoar crystals. The Snow Micro Pen (SMP) measures the micro-structural hardness (bond strength) of snow. Based on a total of 91 SMP measurements, snow hardness always decreased at water contents of about 3%. The loss in snow hardness was significant in a facet grain - depth hoar layer reaching 16% of initial dry snow hardness (water content < 6 %). The two other investigated layers also showed changes: hardness reduced by 36% to 21% (water content < 3%). These results indicate that the loss of strength with first introduction of water begins at very low water contents. Rapid hardness decrease may influence wet snow stability and be indeed one of the keys for deep wet slab avalanche release during spring snow melt.

KEYWORDS: wet snow, water flow, liquid water content, micro-structural hardness, mechanical properties

1. INTRODUCTION

In the Swiss Alps, wet snow avalanches repeatedly affect infrastructure, as road bridges or buildings (Figure 1). It is not uncommon that a large number of deep wet slab avalanches release within a very short time-span. T. Stucki/SLF, head of avalanche forecasting (personal communication March 7, 2006) states that the timing of these extreme wet snow avalanche activity peaks is very hard to forecast and often only included in the general description of wet snow avalanche cycles. While weather parameters play an important role in forecasting, they alone are insufficient to accurately predict wet snow avalanche activity. Additional information about previous avalanche activity and snowpack stability at onset of melting or during rain on dry snow events (Conway and Raymond, 1993) as well as information about a weak snowpack base or the existence of capillary barriers (Baggi and Schweizer, 2008) is crucial. Furthermore, knowledge of water flow advancement would be beneficial as preferential

flow channels may bypass measuring equipment undetected (e.g. snowpack temperature sensors at alpine weather stations). If water spreads laterally at layer interfaces snow stability may be reduced almost simultaneously over large areas (Conway and Raymond, 1993). Further complications, when assessing wet snow stability, arise due to the fact that mechanical properties of wet snow are poorly known (Schneebeli, 2004).

We assume that large wet snow avalanche cycles are often associated with first melt or first wetting of previously dry snowpacks with weak snowpack bases. This is our motivation to study this delicate process. In a first approach, we focused on the evolution of water flow and micro-structural snow hardness with first wetting. Primarily, we were interested in the behavior of initially dry, temperature gradient snow. Several research questions gained our attention:

- (i) Can the development of snow hardness with wetting be monitored using the Snow Micro Penetrometer (SMP)?
- (ii) Does the change in snow hardness (magnitude and speed) depend on snow class (Colbeck, et al., 1990)?
- (iii) What is the effect of different snow classes on water infiltration?

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In this text the following notation is used:

θ – liquid water content in % of volume

R – penetration resistance

U – wetting stage



Figure 1: Debris of a wet slab avalanche triggered during a rain-on-dry-snow event stopping just behind a building, November 2002, Pontresina, Switzerland.

1.1. Water flow in snow

Despite the fact that tracking water flow in snow using dye tracers is nearly as old as snow science itself (Schneebeli, 1995), water flow remains one of the least understood aspects of snow hydrology (Marsh, 1991; Williams et al., 1999). Conway and Benedict (1994) distinguish a *dry snow zone* where no liquid water flow occurs and the snow is subfreezing, an isothermal (near 0°C) *wet snow zone* and the *wetting front*, where liquid water comes into contact with subfreezing snow. Once the water content has reached a certain threshold (the *irreducible* limit) a continuous liquid water film begins to connect pore spaces in the wet zone and water becomes mobile. The irreducible water content depends on snow texture, grain shape and size (Colbeck et al., 1990). Three different flow regimes can be distinguished:

Matrix flow or *background wetting* is the zone where all snow is wet.

Preferential flow or *finger flow* is the most common component of water movement in snow. Small variations in seemingly homogenous snow lead to small differences in hydraulic conductivity, which may trigger finger flow (Marsh, 1991). Also, the formation of flow fingers at layer interfaces, regardless of snow properties above or below, has been noted (Marsh, 1991). In vertical flow channels, water penetrates the snowpack much deeper much faster resulting in isothermal conditions at lower depth than during

homogeneous wetting (Schneebeli, 1995; TNZ, 2004). Infiltration speeds may range between 0.01 to 0.1 m s⁻¹ (Schneebeli, 2004).

Lateral water flow may occur at almost any layer interface (Kattelman, 1985). If water pressure differences between layer interfaces exist, a capillary barrier impeding vertical water flux forms (Wankiewicz, 1979). Jordan (1994) and Waldner (et al., 2004) investigated the role of capillary barriers. Both authors noted temporarily increasing water contents at layer interfaces when fine-grained snow overlay coarser snow. Once pressure equilibrium across the interface is established, water flow may pass this barrier and (most often) finger flow forms (Wankiewicz, 1979; Waldner et al., 2004). Coarse over fine barriers, on the other hand, have no or little impedance on water flow (Jordan, 1994; Waldner et al., 2004).

1.2. Mechanical properties of wet snow

Knowledge concerning mechanical properties of wet snow is scarce (Schneebeli, 2004). Moist snow ($\theta < 3\%$) is often reasonably cohesive as grains are still well bonded. In the pendular regime ($3\% > \theta < 8\%$, wet snow) cohesion between grains begins to deteriorate, but grains are still tightly clustered and bonds relatively strong (Colbeck, 1982). The transition from low (pendular) to high (funicular) water content ($\theta > 8\%$, very wet snow) is expected to have a severe consequence on snow strength (Colbeck, 1982; Colbeck, 1997). In the funicular regime a film of water continuously surrounds snow grains and fills many pore spaces reducing strength further (Trautmann et al., 2006). Slush ($\theta > 15\%$) has the lowest strength due to the continuous liquid film between grains and hence the lack of inter-granular bonding (Colbeck, 1997).

Very few studies have investigated the effects of increasing water content on snow hardness. Ram hardness in wet snow has been used as one indicator for the critical loss of strength when forecasting wet snow avalanches (Armstrong, 1976). For a given dry snow density, hardness decreases exponentially with increasing liquid water content (Izumi and Akitaya, 1985) reaching a minimum snow hardness at saturation (Izumi, 1989). Comparing ram hardness and penetration strength in snow in the pendular regime Brun and Rey (1987) noted, "Liquid water content, even in very small quantity, seems to decrease penetration strength at high speed more than at low speed." At low water content ($\theta < 6\%$) neither a decrease in ram hardness nor penetration strength was recorded. Trautmann et

al. (2006) measured the evolution of micro-structural snow hardness of surface snow during the melt process using the SMP. They did not correlate the observations to moisture content but indicated a linear correlation between SMP snow hardness and shear strength. Brun and Rey's (1987) shear strength experiments in wet snow showed no significant strength decrease at low water content ($\theta < 6\%$) while Bhutiyani (1994) remarks shear strength decreasing rapidly by a factor of 2 once θ was higher. However, Yamanoi and Endo (2002) indicated shear strength decreasing as an exponential function of volumetric water content. Trautmann et al. (2006) monitored the weakening part of natural melt-freeze-cycles in the field. Shear strength decreased by as much as 50% in less than 20 minutes.

2. DATA AND METHODS

2.1. Data

On two days in March 2007, three field experiments close to the Weissfluhjoch at 2665 m a.s.l. in the eastern Swiss Alps were conducted. A southerly slope was chosen to benefit from warming through solar radiation. These experiments were aimed at the investigation of water flow behavior and the evolution of micro-structural snow hardness with increasing liquid water content. Layers with different properties (snow class, grain size, layer hardness) were chosen (Figure 2, Table 1).

2.2. Field methods

Snow profile observations followed international guidelines (Colbeck et al., 1990). The micro-structural hardness was measured using the SMP (Schneebeli and Johnson, 1998). It is the first application of the SMP in a study on changes in snow mechanical properties with first wetting of

snow under controlled water content. The relatively fast, high resolution and objective SMP measurements make it a suitable instrument for this study. The Denoth capacity meter (together with snow density sampling) allowed quantitative observations of the liquid water content (Denoth, 1994). Further, slope-parallel and vertical cuts of the snow allowed the qualitative monitoring of water flow patterns.

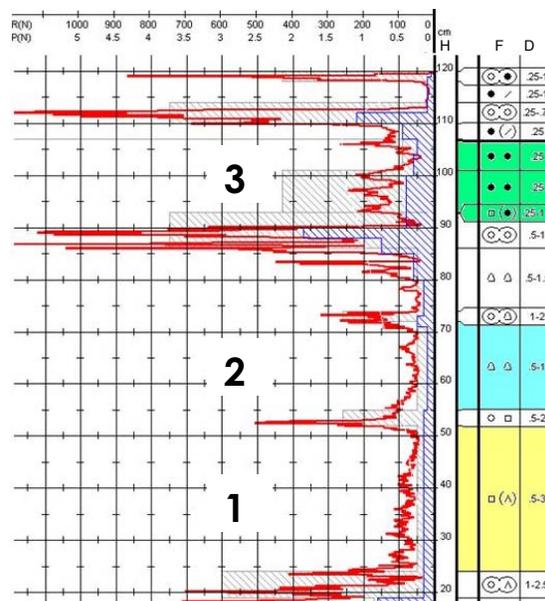


Figure 2: Snow profile observed 12 March 2007, Weissfluhjoch, Davos, elevation: 2665 m; aspect: S; slope incline: 27°.

Dark profile - ram hardness (R scale), light profile - hand hardness; red curve - SMP profile (P scale)

H - snow depth from ground (in cm), F - grain class, D - grain diameter (in mm).

Highlighted and numbered are the selected layers:

- 1: 24 thru 52 cm (yellow)
- 2: 56 thru 72 cm (blue)
- 3: 93 thru 107 cm (green)

Table 1: Description of the three layers including number of measurements taken, the total hourly wetting rate and the duration of the experiment. Snow classes: fa - facets, dh - depth hoar, mx - mixed forms (fa and sr), sr - small round grains

Layer (Experiment)	Grain Form	Grain size (mm)	Number of measurements (SMP / wetness / density)	Total wetting rate ($l m^{-2} h^{-1}$) / number of wetting stages	Duration between first and last measurement
1	fa (dh)	0.5 – 3.0	42 / 32 / 66	0.8 / 5	2.5 h (+ 2 h warming before-hand)
2	fa (mx)	0.5 - 1.0	21 / 14 / 28	3.0 / 4	1 h (+ 1 h warming before-hand)
3	sr/ sr/ fa	0.25 / 0.25/ 0.25 – 1.5	31 / 21 / 46	1.1 / 4	2 h (+ 3 h warming before-hand)

Upon the selection of a suitable snow layer (criteria were sufficient layer thickness, relative homogeneity of layer and grain shape), the layer was exposed and left to warm up by solar radiation until the whole layer was approximately 0.0 °C isothermal.

The snow surface was sprayed manually with cooled water – tracer mixture (temperature 0°C). The tracer applied was Brilliant Blue food coloring at a concentration of 0.4 g l⁻¹. Each wetting stage was followed by snow hardness, capacity and density measurements (Figure 3).

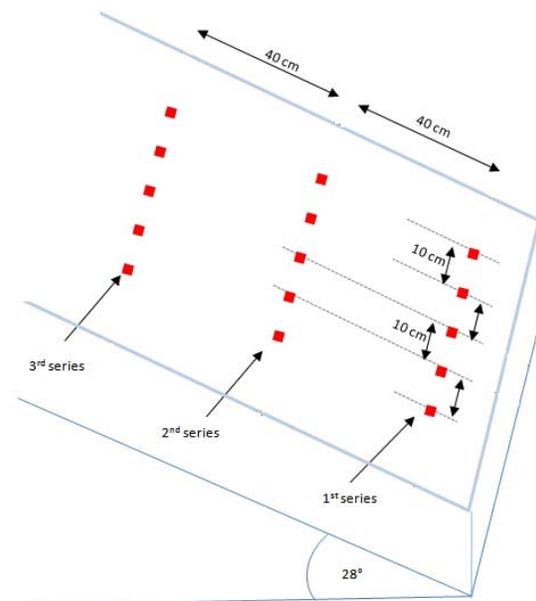


Figure 3: Experimental layout: Each series consisted of 5 SMP measurements spaced 10 cm apart (red squares). Each SMP measurement was complemented by a wetness measurement (6 cm below the snow surface) and two densities were sampled 4 and 8 cm below the snow surface. Consecutive measurement series were upslope at a distance of 40 cm.

Sequence of measurements

[A] Snow hardness: 5 SMP measurements. The SMP was mounted on a frame allowing steady slope-vertical measurements with a horizontal distance of 10 cm.

[B] Snow wetness: 5 Denoth probe measurements, taken down slope just below the SMP measurement. The capacity plate was inserted slope parallel (Fierz and Föhn, 1995), 6 cm below the snow surface or in the middle of the layer. One measurement took less than 15 s.

[C] Snow density: Density samples were taken with a 100 cm³ box-type density cutter (Hydro-

Tech) above and below each wetness measurement.

It took 20 min. for one set of spraying and the measurements (A to C) and approximately 35 min. if steps A to C were repeated before spraying again (experiments 1 and 3). Consecutive wetting stages were upslope at a distance of approximately 40 cm.

2.3. Calculation of parameters

Water content: Based on the obtained capacity and snow density measurements, the median water content θ (vol. %) was determined for each wetting series, using the formula

$$\theta = 4.69 * (k * \log \frac{S}{A} - 2 * \rho)$$

where k is a sensor – specific constant, S and A the measured values in snow or air respectively and ρ the snow density (in kg m⁻³)(Denoth probe instruction manual).

SMP snow hardness: Each defined layer was divided into four, 30.7 mm vertical subsections (15'000 SMP samples, layer 1 and 2) or into an upper and a lower half (layer 3). The median penetration resistance R was calculated for the complete layer and for each of the sub-layers. For better comparison of snow hardness decrease between experiments the relative SMP hardness is shown (relative to the median of the initial dry snow hardness R_0). To identify significant changes in R with increasing water content the non-parametric Mann-Whitney U-test (2-tailed, level of significance $\alpha < 0.05$) was used (Erickson and Harley, 1994).

3. RESULTS

3.1. Qualitative observations: water flow

Here we discuss the advance of the water-dye tracer mixture within the snow based on qualitative flow observations. All three flow regimes described earlier were observed (matrix wetting, preferential flow, layer-parallel water retention), but flow behavior differed largely between experiments.

Matrix flow (background wetting): Water spraying and solar radiation led in all three experiments to a surface layer being completely wet. The depths of the matrix wetting-front are shown in Table 2.

Preferential flow: Vertical flow fingers were well developed and advanced the wetting front in all three experiments. However, preferential flow

was more pronounced in experiments 1 and 2 (facets, depth hoar). Horizontal cuts revealed numerous small flow channels, and the number of flow fingers decreased with depth (Figure 4). Despite the small infiltration rates this was the case in experiment 3 when water passed from the finer round-grained layer through the coarser melt-freeze-crust and into the facets below forming isolated flow fingers (Figure 5 right).

Slope-parallel flow was noted at layer interfaces in experiment 3. Both, the interface representing a hardness increase (neither grain shape nor size differences could be recognized) as well as the

interface with significant grain shape and size differences led to slope-parallel water flow. The slope parallel cuts directly above the melt-freeze-crust highlight the lateral water flow and impeding of vertical water movement (Figure 5 left).

Table 2: Depth of matrix wetting-front based on visual observation.

Layer	Depth of back-ground wetting
1	approximately 10 to 12 cm
2	approximately 4 to 6 cm
3	not certain, due to extensive lateral flow at layer interfaces



Fig. 4: Water flow as observed in experiment 2, a facets-undergoing-rounding layer (dark [blue] areas are wet). Slope parallel cuts 8 cm (left) and 15 cm (right) below the layer surface highlight the predominantly vertical flow pattern [a]. A small surface layer, approximately 3 to 4 cm thick, was completely wet [b].

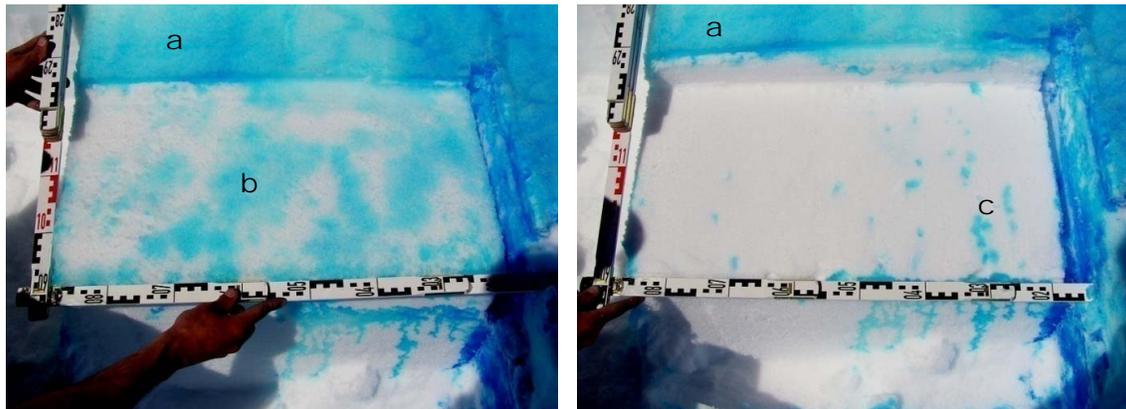


Fig. 5: Water flow in experiment 3, layers consisting of small round grains overlying a melt-freeze-crust (dark areas are wet). Slope-parallel cut above the melt-freeze layer (left) and below the melt-freeze layer (right). Surface layers were completely wet [a] with water ponding [b] above the melt-freeze layer (left). First isolated flow channels [c] developed below the crust (right).

3.2. *Water content measurements*

Following wetting and exposure to solar radiation wetness increased with time reaching median water contents between 2.0% and 5.6%

(Table 3). With one notable exception all measured water content values were within the pendular regime ($\theta < 8\%$). This one exception ($\theta =$

9.5%) was observed in experiment 3 with strong layer-parallel flow.

3.3. Changes in micro-structural hardness with first wetting of dry snow layers

All 91 SMP measurements were used for analysis. Snow hardness always decreased from dry snow (R_0) to the final measuring series (moist - wet snow, (R_3 or R_4 , Tab. 3). The temporal evolution of the relative SMP hardness is shown for all sub-layers which were considered (predominantly) wet (Table 2) after experimentation (Figure 6). The hardness decrease from dry snow to the first wetting stage was significant (Mann-Whitney U-test, level of significance $\alpha < 0.05$) for all sub-layers in experiment 1 and for surface subsections in layers 2 and 3. In layers 2 and 3 (lower sub-layers) a slight increase in hardness was noted before hardness decreased with further wetting. The hardness decrease in near-surface layers was greater than in layers below them.

Layer settlement with wetting was observed but not measured, therefore we cannot be completely certain as to which sub-layer has to be associated with the water content measurements at consistent depth. For this reason the data presented (Table 3, Figure 7) is based on the upper 120 mm section of the SMP resistance profile (layers 1 and 2) or the full layer depth (layer 3, which had clear layer boundaries).

Already at low water content ($\theta < 2\%$) a significant hardness decrease was observed in layer 1 (fa, dh). After initial hardness increase (layer 2 [fa, mx]), hardness also dropped at higher water contents (level of significance $\alpha = 0.076$). Hardness decrease was again significant in layer 3 (sr, layer sandwich) once θ reached close to 3%.

The hardness decreased to 16% of its initial value for layer 1. Snow wetness had not reached the values of the first experiment but hardness dropped to 79% of its initial value for layer 2 and 64% for layer 3.

Table 3: Median of initial (R_0) and final (R_3 / R_4) SMP snow hardness for each 120 mm snow layer (1, 2) or the full layer depth (3). Median water content measured in the middle of the layer (vol. %) at the end of experimentation (θ_3 / θ_4). In the square brackets, the 1st and 3rd quartiles are given.

Layer (Experiment)	Initial hardness R_0 (in N)	Final hardness R_3 or R_4 (in N)	Final liquid water content θ_3 or θ_4
1	0.31 [0.25, 0.44]	0.05 [0.04, 0.07]	5.6 % [4.9%, 6.6%]
2	0.34 [0.26, 0.39]	0.27 [0.22, 0.33]	2.0 % [1.5%, 2.3%]
3	0.58 [0.50, 0.64]	0.37 [0.29, 0.40]	3.2 % [2.7%, 3.5%]

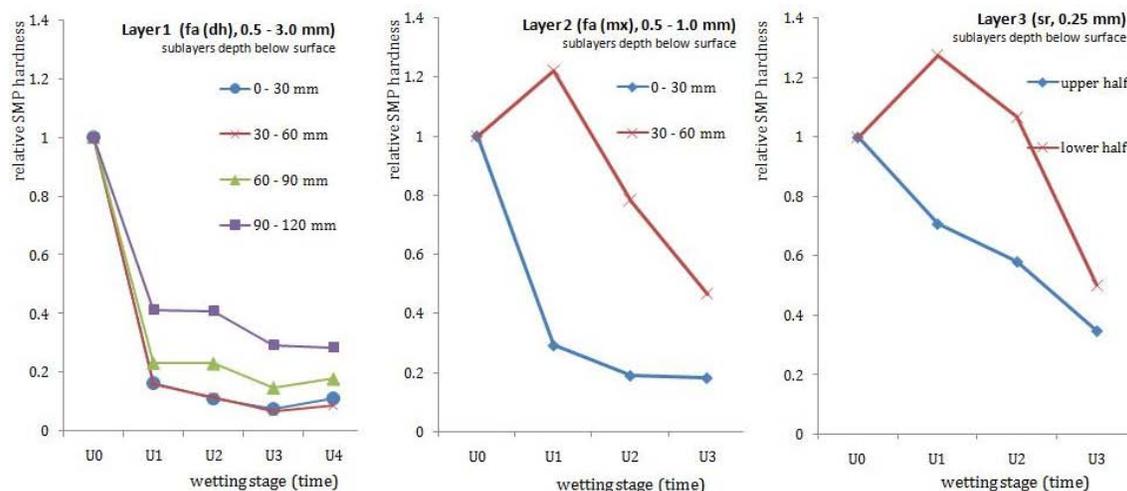


Figure 6: Temporal evolution of relative snow hardness during increased wetting. Shown are all sub-layers considered predominantly wet after experimentation (manual observations, Table 2). Dry snow (U_0) is taken as initial reference (relative SMP hardness is set to 1). Lines represent median hardness of 30 mm sub-layer sections (layer 1 and 2), upper and lower half of layer 3.

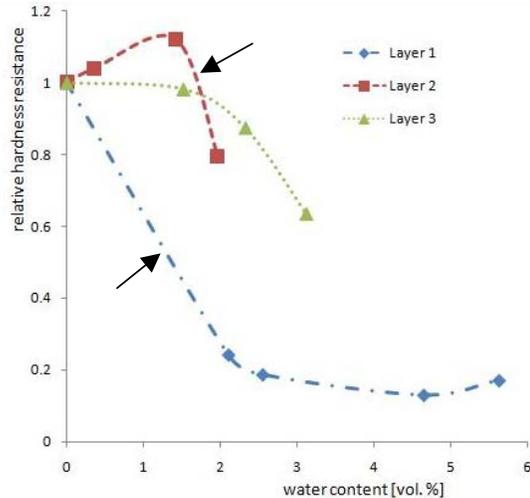


Figure 7: Liquid water content (in vol. %) and relative SMP snow hardness based on the upper 120 mm of layers 1 and 2 and the full layer 3. Arrows indicate significant hardness changes (Mann-Whitney U-test, $\alpha < 0.05$)

4. DISCUSSION

As noted in previous literature (i.e.: Wankiewicz, 1979; Marsh, 1991) water flow is complex: three-dimensional inhomogeneous wetting fronts, vertical flow channels and temporary ponding at layer interfaces were all observed. As the limited number of experiments doesn't allow conclusive comments, the observation of the decreasing number of preferential flow paths with increasing depth may be a singular observation. Only one model indicates the merging of water streams (Wankiewicz, 1979). However, the process is known from karst formation research. Water content observations were typical for field experiments and confirm that freely draining snow is generally within the pendular regime ($\theta < 8\%$).

In facet and depth hoar layers our results indicate a significant decrease in hardness with first wetting already at low water contents ($\theta < 3\%$) and well before the pendular-funicular transition. As we have not measured water contents above 6% we cannot confirm the rapid decrease in snow strength at the pendular-funicular transition (Colbeck, 1982). In two of the experiments, snow hardness increased (or changed slightly) at very low moisture content ($\theta < 1.5\%$), which is consistent with existing knowledge that moist snow is often rather cohesive. In all sub-layers considered completely or predominantly wet after experimentation, snow hardness decreased from

dry to moist/wet reaching values between 7% and 50% of the initial dry snow hardness (Figure 6). Our observations contradict earlier penetration resistance and shear strength observations proposing no significant decrease at water contents below 6% (Brun and Rey, 1987; Bhutiyani, 1994). However, our observations are consistent with recent wet snow shear strength studies (Yamanoi and Endo, 2002) if the SMP snow hardness signal and shear strength are linearly correlated as demonstrated by Trautmann et al. (2006).

5. CONCLUSION

In three delicate, time-critical experiments on the first wetting of dry snow we gained a first combined data set of SMP snow hardness and snow wetness measurements as well as traditional snow observations. We found evidence that a significant loss of snow hardness in depth hoar and faceted grains occurs at lower water contents than commonly expected. This has implications for avalanche forecasting. Avalanche failure planes, but also surface snow slabs, would experience a decrease in hardness (strength) well before high quantities of water are observed. In case a relatively weak faceted snowpack base is a widespread phenomenon over comparable slope aspects and elevations (which is often the case at the beginning of the spring melt-phase in the inner-mountain regions of the Swiss Alps), it is conceivable that this very first introduction of water is one of the causes of widespread deep wet slab avalanche activity.

Field experiments in wet snow are inherently difficult. The disturbance of water flow, irregular water infiltration patterns, settling of layers, unexpected water ponding at micro-interfaces and timing are just some of the challenges. It is unclear in how far these complications have influenced our measurements. Also, the presented study is certainly limited by the small number of experiments. Wetting was limited by the time available and the size of layer surface exposed beforehand. But in regards to these circumstances, we are convinced from our experiments that the evolution of micro-structural snow hardness during first wetting can be successfully documented by using the SMP.

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