POTENTIAL DRY SLAB AVALANCHE TRIGGER ZONES ON WIND-AFFECTED SLOPES

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ABSTRACT: Experience suggests that shallow, steep zones on slopes are likely spots for artificially triggering slab avalanches. However, a scientific understanding of this observation is not well quantified. We performed 108 point stability tests on a 30 x 30 m slope in central Svalbard. The slope has a rugged underlying topography and frequent wind influence both by top and cross loading. We found three persistent weak layers at different depths in the snowpack. Due to the rough nature of the study slope, snow surface does not resemble the ground topography. Weak layers forming early in the season follow the ground topography closely. As snow depth increases, the influence of ground topography diminishes. We further found a decrease in slab thickness with increasing slope and bed surface inclination. We therefore investigated the influence of slab thickness on slope stability. Our data shows that stability decreased significantly with decreasing slab thickness, which correlates to how deeply the weak layer is buried. Thus the weakest spots on the slope coincide with the shallowest and steepest spots, where the deeper buried weak layers are buried “less deep”. Such spots often occur around topographic heights such as large rocks, which are thus potential trigger zones.

1. INTRODUCTION

The limiting factor for weak layer fracture is the snow stratigraphy, where layers might not be continuous (Gauthier and Jamieson, 2010). Thus it is important to understand how snow layers spatially interact with the terrain. Schweizer et al. (2008) identified external and internal causes acting during snow layer formation. While wind is the most important external driver (Sturm and Benson, 2004), terrain topography is the most important internal driver (Schweizer et al., 2008). Furthermore slab avalanche release is prone to areas of less than average stability, called deficit zones (Kronholm and Schweizer, 2003). Such deficit zones are often found on rollovers around rock outcrops or topographic heights (Birkeland et al., 1995), and avalanche fracture lines often run along them.

We therefore chose to study a small, wind-affected slope in central Svalbard, where we expect snow stratigraphy and consequently weak layer formation to be highly influenced by wind loading, scouring and redistribution. Furthermore we expect the properties of persistent weak layers to be affected by the ground topography.

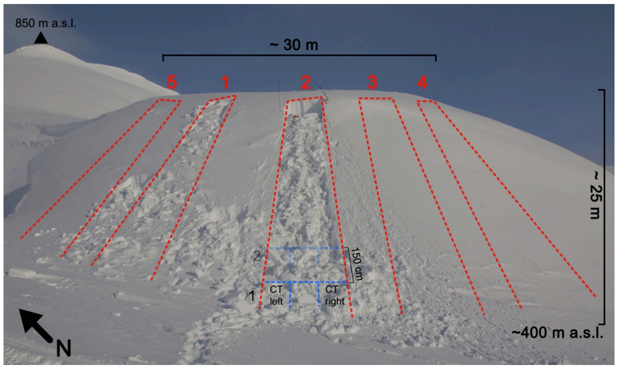

Figure 1: Study slope with the five trenches and the stability test setup.

2. STUDY SITE AND AREA

The study site is a small slope, approximately 30 m wide and 30 m high (Figure 1). The slope is located in the Fardalen valley, about 15 km south of Svalbard’s main settlement Longyearbyen. The site is situated on the lower part of a south-facing slope that rises up to 878 m a.s.l. It is generally wind exposed, both to top loading and cross loading. The slope, with a mean slope angle of 39 °, has a rollover exceeding 50° in its steepest middle section. It also has a small amount of convex cross slope curvature with aspect ranging from 27 to 45 °.

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The snowpack has continental characteristics, with a generally thin, highly stratified snow cover overlying a persistent depth hoar base. Extremely spatially variable snow depths stem from a rugged ground topography and constant winds in the barren landscape. Due to the vicinity of the sea, a significant maritime influence forms ice crusts and meltforms from mid-winter rain-on-snow events (Eckerstorfer and Christiansen, 2011).

3. METHODS

A total of 5 trenches from the bottom to top were dug, starting with the first trench on 18 March 2011 and finishing with the fifth one on 18 April 2011 (Figure 1). The trenches consisted of between 10 and 13 pits, with 150 cm between them. Each trench was about 2.5 m cross slope from another. In each pit, we performed two compression tests (CT tests (Jamieson, 1999)) next to each other (Figure 1). Following Jamieson (1999), we freed the columns only to a depth of 150 cm, if the total snow depth in the pit was deeper. In each pit, we recorded snow depth and slope inclination of each CT column. Slab thickness of each fractured weak layer and the bed surface angle were measured. The weak layer's structural properties were recorded according to industry standards. Each weak layer was assigned a letter and consequently traced from pit to pit. In trench 5, we traced three persistent weak layers by recording their slab thickness every 50 cm upslope on the snow surface.

4. RESULTS

4.1 Slope scale

Snow depths in the pits varied between 57 cm and 600 cm (Table 1). In all 5 trenches, the deepest snowpack was found at the foot of the slope, gradually decreasing to its shallowest spots in the steep, middle section. Towards the top of the slope, snow depths rose again. The steep middle section exceeded 50°, and slope angles decreased towards the top of the slope. Average snow depths varied, with the deepest in trench 4 (222 cm) and the shallowest in trench 1 (142 cm) (Table 1). These snow depth patterns suggest top loading, accumulating snow in the upper and lower part of the slope and erosion in the middle part. They also suggest cross loading from left to right, or NNW to SSE respectively, as the mean snow depths of each trench suggest. Amounts of precipitation were too small between the excavation of trench 1 and 5 to cause these differences.

Fractures occurred in five weak layers and one new-old snow interface. We selected three weak layers for further analysis, since they fractured in all 5 trenches over a month period, showing both spatial extent and temporal persistence.

Weak layer A was a layer of facets on top of hard meltforms, up to 2 cm thick, that formed during a rain on snow event 21 February 2011. This weak layer was the most shallowly buried weak layer, with a slab thickness between 11 and 48 cm.

Weak layer B was a layer of surface hoar only 0.5 cm thick. It was buried deeper than WL A, between 37 and 109 cm deep.

Weak layer C was depth hoar with a thickness that varied largely (5-30 cm), and with crystal sizes up to 4 mm. It was found at depths between 49 and 120 cm. All three weak layers did not change considerably over the one-month test period. Small changes did occur locally in layer hardness and grain size. The weak layer thickness remained constant.

Table 1: Topographical and snowpack characteristics on the test slope, divided into the 5 trenches dug.

Trench	**Date**	**Pits**	**Aspect**	**Min**	**Mean**	**Max**	**Min**	**Mean**	**Max**
N	**2011**	**N**	**(°)**	**Snow depth (cm)**			**Surface slope angle (°)**		
1	3.18	13	40	68	142	400	26	36	45
2	3.23	11	34	80	156	380	25	39	46
3	4.7	10	30	124	196	450	27	39	50
4	4.13	10	27	190	222	405	30	40	44
5	4.18	10	45	57	161	600	23	35	50

Table 2: Weak layer characteristics divided into the five trenches.

WL	Trench	Fractures	Min	Max	Stdev	Min	Max	Stdev	Min	Max	Stdev	Correlation	Correlation
		N	**Bed surface angle (°)**			**Slab thickness (cm)**			**CT scores**			**BS vs. ST**	**ST vs. CT**
WL A	1	9	31	43	4.4	25	133	40.8	2	29	7.4	**-0.881**	**0.479**
	2	7	33	42	3.6	23	73	19.9	10	22	5	**-0.920**	**0.743**
	3	4	31	40	4.7	48	99	28.3	21	27	3	**-0.988**	**0.600**
	4	7	36	45	2.9	47	110	26	15	27	4.6	**-0.538**	**0.597**
	5	5	50	55	2	11	57	21.3	2	22	7.5	**-0.133**	**0.896**
WL B	1	3	37	43	3.2	109	144	18.2	13	19	3.2	**-0.801**	**0.801**
	2	5	39	42	1.5	55	120	27.4	11	25	5.9	**-0.928**	**0.758**
	3	6	38	45	2.7	53	113	21.6	13	27	5.8	-0.043	**0.147**
	4	3	42	46	2.1	62	80	10.4	15	26	5.6	**-0.970**	**0.933**
	5	3	39	51	6.7	37	110	41.3	16	23	3.6	**-0.999**	**0.950**
WL C	1	20	28	45	5.4	65	120	17.5	1	15	3.7	**-0.753**	**0.364**
	2	18	30	46	4.3	75	200	37.2	2	28	6.6	**-0.460**	**0.706**
	3	11	37	45	2.4	59	150	24.7	14	29	6.2	**-0.257**	0.025
	4	15	39	46	2.6	120	176	17.0	6	30	6.3	**0.111**	**0.628**
	5	15	26	55	9.3	49	78	9.3	5	23	4.2	0.042	**0.211**

Overall, we induced 172 fractures in 108 CT tests, where WL A fractured 32 times, WL B 20 and WL C 79 times. WL A fractured in 18 %, WL B in 11 % and WL C in 45 % of the total CTs carried out in the five trenches. The standard deviation of the CT scores is high in all weak layers, being the lowest in WL C. Also the standard deviation of the depth of the fracture plane or the slab thickness is high in all weak layers, suggesting a relationship between CT score and fracture depth.

4.2 Trench scale

We collected the most comprehensive dataset in trench 5. In Figure 2 we present the depth of the fracture plane (bed surface) versus the differences between surface slope angle and fracture plane angle. The data shows that when WL A and C are buried more deeply, the difference between the bed surface angle and the surface slope angle becomes larger, with the bed surface angle becoming larger as well. It also shows that the bed surface angles of WL C at great depths follow more closely the ground surface inclination. For weak layer B an insignificant relationships was found, where a greater burial depth did not necessarily result in a difference between surface slope angle and bed surface angle.
As snow surface and ground topography thus do not resemble each other on a wind-affected slope, we tested the correlation between bed surface angle and slab thickness for each weak layer and each trench separately. For weak layer A and B we found strong negative correlations, implying that steeper bed surfaces coincide with thinner slab depths (Table 2). In three out of five trenches, this is also true for WL C (Table 2). We then further tested the relationship between slab thickness and CT scores and found good positive correlations (Table 2), indicating lower CT scores

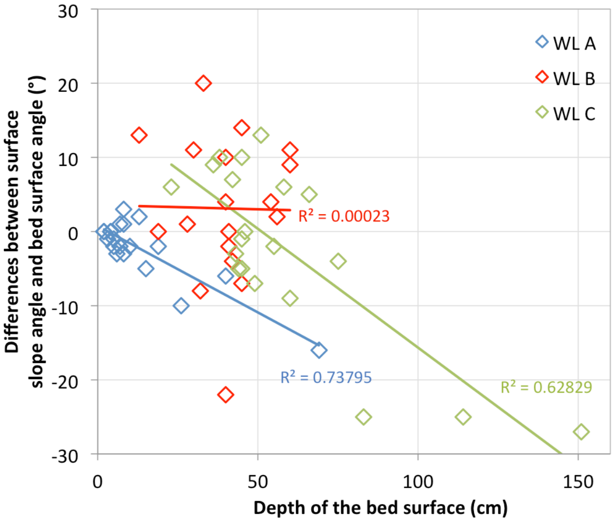

Figure 2: Differences between surface slope angle and bed surface angle versus depth of the bed surface.

in areas with thinner slabs. To test for correlation, we used a Spearman's rank correlation test.

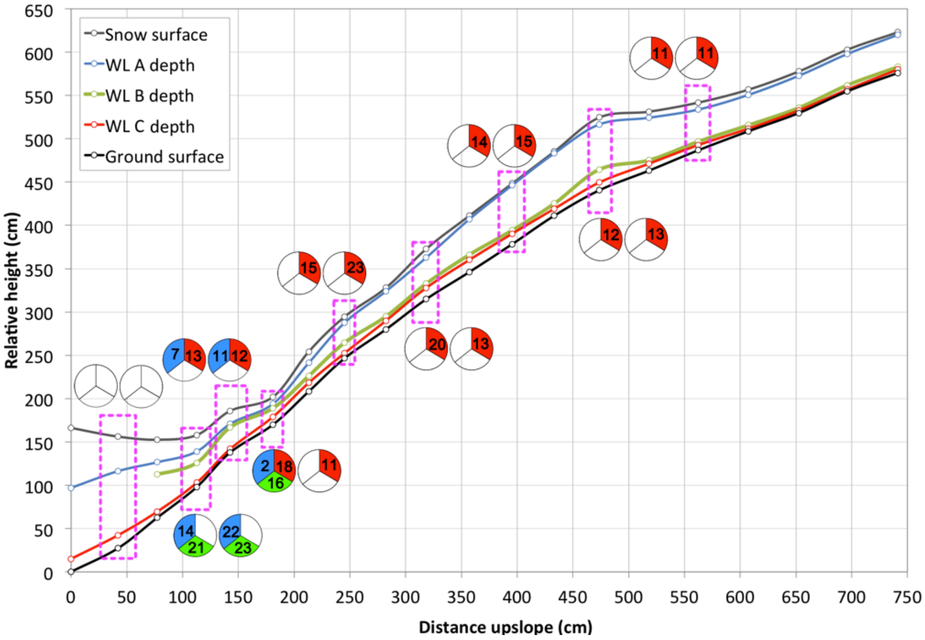

Figure 3: Layer trace of the three persistent weak layers WL A, B and C in trench 5. Total snow depth and slab thickness for each weak layer were recorded every 50 cm upslope. The pie charts show the CT scores, two in each pit, colored according to which weak layer failed.

The most unstable spot in trench 5 also coincided with the shallowest and steepest spot on the slope (Figure 3). At 200 cm upslope, the slope angle was 50° and the snow depth 57 cm. The snow surface inclination though was only 40°, clearly underrepresenting the slope angle. At this spot, all three weak layers were pressed together, and all of them failed in the left CT (Figure 3). As snow depth increased upslope, fractures could be only induced in WL C, depth hoar.

Figure 3 also clearly shows the wind effect on the snow sedimentation process, with wind accumulation both near the top (450 – 500 cm) and at the bottom of the slope.

5. DISCUSSION AND CONCLUSION

We found strong correlations between slab thickness and CT scores, as well as between slab thickness and slope angle. Our results suggest that slab thickness is one control of stability on our wind affected test slope. With decreasing snow depth, slab thicknesses above each of the three persistent weak layers decreased as well. Further, slab thickness positively correlated with stability. With decreasing snow depth, it became more likely to induce a fracture, especially in the lower buried weak layers like WL C, depth hoar. Our results are consistent with some studies that show that the force reaching the weak layer increases dramatically when the distance to the weak layer is less (Schweizer and Camponovo, 2001). Our results showing easier test results in steeper areas is in contrast to Heierli et al. (2011), but their tests were done on a slope with only minor slab thickness deviation. Thus, previous research suggests that the changes we are seeing in CT results are more likely due to changes in slab thickness than changes in slope angle.

Our results show that shallow spots on the slope have the steepest inclination. We thus tested for correlations between slab thickness and bed surface inclination for each weak layer, as these bed surface inclinations did not resemble the snow surface inclination. Deeper buried weak layer bed surfaces followed the ground topography more closely; so knowing the terrain is crucial for a complete understanding of the variability of the slope.

During snow onset, snow layers follow closely the ground topography. As the snowpack accumulates further, topographic highs and lows are being leveled out. Significantly changing ground topography due to large boulders on the slope, for example, is not visible anymore on the snow surface. However, these are the spots where the snowpack is thin, and weak layers, normally buried deep in the snowpack, emerge closer to the surface, thus making it more likely to induce a fracture. Since cracks are more likely to propagate from thinner areas to thicker areas (Simenhois and Birkeland, 2008) propagation from these thinner areas is also more likely.

Based on our results, we were able to better quantify a piece of common knowledge. Slab avalanches are highly likely to fracture around shallow, steep zones, rock outcrops and large boulders. Our results are consistent with past observations (Logan, 1992) his must be especially true for wind affected slopes, which comprise the majority of slopes in the high alpine. On such slopes, the snow surface does not resemble the ground topography, thus hiding its real steepness as well as any topographic heights. Therefore, knowledge of the underlying terrain can be critically important for understanding likely areas to trigger avalanches.

6. ACKNOWLEDGEMENTS

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