Uncut Column Stability Tests For Hard Slab Snow Conditions

Wesley R. Farnsworth[1,2] and Markus Eckerstorfer[3]

[1] Arctic Geology Department, University Centre in Svalbard, Norway
[2] Department of Geosciences, University of Oslo, Norway
[3] Earth Observations, Northern Research Institute (NORUT), Forskningsparken, Pb. 6434, 9294 Tromsø, Norway

ABSTRACT: This study aims to better understand a slabs influence on the mechanics of artificial avalanches. It seems that stability tests do not represent stability in hard slab conditions well. We believe this is caused by the complete isolation of the stability column unnaturally "fixing the race" between weak layer propagation and the fracture down through the thickness of the slab. This study is based on two small data sets comparing normal Propagation Saw Test (PST) to a variation where the up-slope end of the column is not cut, thus an un-isolated beam or an uncut column (u-PST). Initial results suggest that cut lengths for the u-PST are greater than the PST. Although results are significant, the temporary lack of a robust dataset inhibits concrete conclusions. Still it seems the data sets provide important insight regarding fracture mechanics and suggest the importance of incorporating slab properties into stability test, especially when dealing with hard slab avalanche conditions.

KEYWORDS: Slab Properties, Propagation Saw Test, Hard Slab, Uncut Columns

1 INTRODUCTION

It is understood that a slab's structural properties (thickness and hardness) not only control weak layer reactivity, but propagation propensity. The slab directly governs the range of the stress bulb through the snowpack (Föhn, 1987; Schweizer and Camponovo, 2001), and additionally affects whether the subsequent fracture will surpass a critical distance or arrest prior to a full propagation (Gauthier and Jamieson, 2010; Simenhois and Birkeland, 2008).

Most stability tests used today concentrate on weak layer reactivity but the majority neglect slab properties. Both the Extended Column Test (ECT; Simenhois and Birkeland, 2006) and the Propagation Saw Test (PST; Gauthier and Jamieson, 2006; Sigrist and Schweizer, 2007) have gained popularity in recent years due to their focus on propagation propensity. Thus, not only focusing on weak layer reactivity but the slabs ability to articulate the propagation through the weak layer. One of the fundamental requirements of avalanche formation is that a fracture must run down through the slab. This is most likely to occur at weak spots in the slab that are unable to transfer the energy. Common weak spots include: shallower zones, trees, boulders or bedrock outcrops (Eckerstorfer et al., submitted). Depending on slab strength and topography it is possible that failure and propagation can occur in a weak layer, yet the slab does not fracture. This results in just the settling of the snow in a whumpf.

Although validations prove stability tests effectively address propagation propensity (Simenhois and Birkeland, 2009; Gauthier and Jamieson, 2008; Ross and Jamieson, 2012) there is some discussion as to how accurately the tests represent snow conditions (McClung, 2009) especially in hard slab environments.

With regards to the PST, arguments based on modeling show the maximum tensile force in the slab to be around one slab depth's length ahead of the disturbing saw cut (Ross and Jamieson, 2012). Additionally it has been suggested that the cut length, as an unnatural weakness, could "attract" a propagating crack due to the low resistance to rotational and tensile forces that form as a result of the saw cut (Gauthier and Jamieson, 2010; McClung, 2009; Ross and Jamieson, 2012).

We hypothesis that completely isolating a PST column with a slab hardness exceeding one-finger (1F+ or harder) is not representative of the full propagation process, or "the race" with regards to artificial avalanches (Van

Corresponding author: Wesley R. Farnsworth, Dept. of Arctic Geology, University Centre in Svalbard, Norway;
wesmoveseast2004@yahoo.com

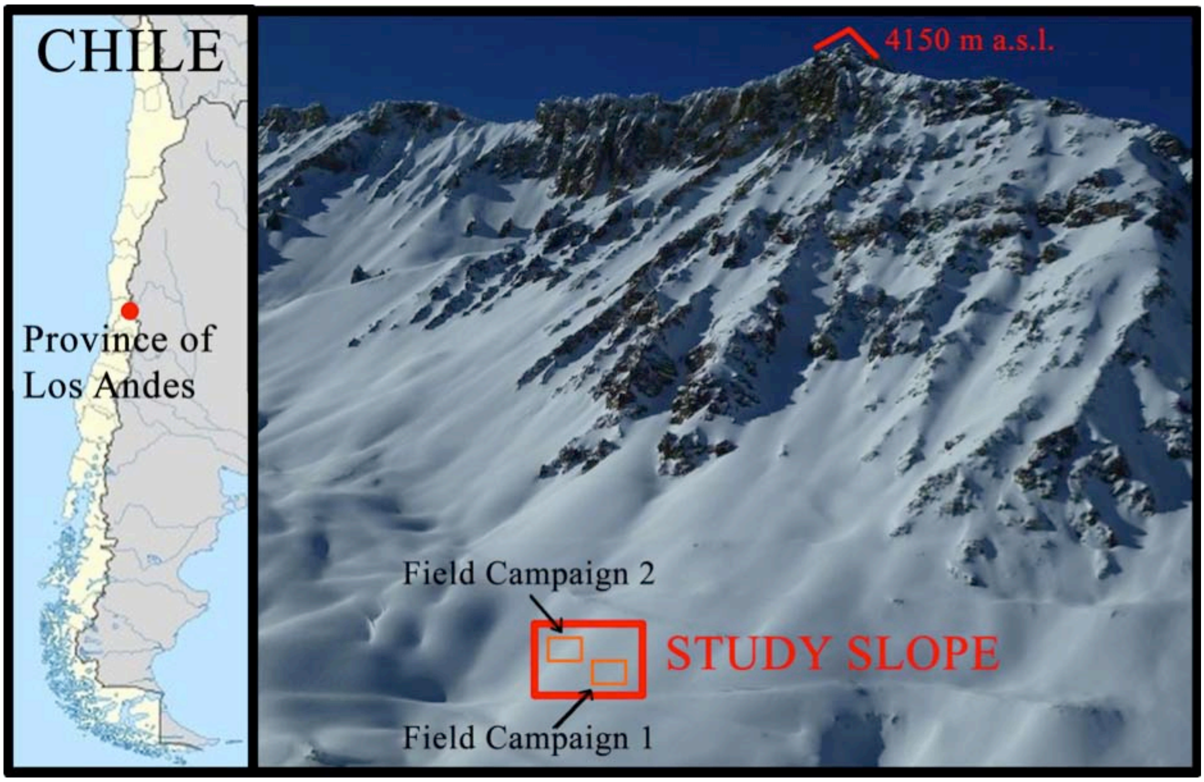

Figure 1. Regional location of the field site in Chile and image of study slope with surrounding

Herwijnen, 2005; Gauthier and Jamieson, 2010). In the PST it is important to note that propagation occurs by artificially disturbing weak layer resulting in the bending of the overlaying slab (Birkeland and Van Herwijnen, 2013). This however does not present the slab's willingness to fracture itself. We anticipate a PST that is not completely isolated from the slope can better display how the slab articulates stress on the weak layer as well as the weak layers willingness to fracture. As a means of more accurately testing stability of hard slab conditions, a variation of the PST have been developed similar to those of McClung (2009) and assumed to be comparable to Ross and Jamieson (2012). Thus, the u-PST was adapted by leaving the upper extent of the column uncut.

2 STUDY SITE

Two small data sets comparing normal PSTs with uncut PSTs (u-PSTs) were collected in the high Alpine Andes of central Chile during July 2013. The site is located in the central Chilean cordillera in the province of Los Andes (Figure 1). The study slope is in the southern end of the Pimenton Valley roughly 5 km from the Argentine border at approximately 3450 meters above sea level (S 32' W 70'). The elevations of local summits range from ca. 3800 to 4400 m with the valley floor located at ca. 3000 m.

The study slope is roughly 60 m by 45 m and is located between two road cuts (Figure 1). The face exhibits minor cross-slope curvature with a general aspect to the South-southwest. Additionally the face is slightly concave with gentle inclinations of 15° – 20° at the base gradually increasing to roughly 40° - 45° below the upper road cut. The slope is covered in poorly sorted talus without major depressions or outcrops.

3 METHODS

During July 2013 two separate field campaigns (FC-1 and FC-2) were conducted allowing for the collection of two data sets each containing 22 stability tests. Each field campaign lasted no more than 26 hours from start to finish.

Half of the tests were conducted as standardized Propagation Saw Tests (PSTs), were a .3 m wide by 1 m up-slope column was completely isolated from the snowpack by cutting the back (Gauthier and Jamieson, 2006; Sigrist and Schweizer, 2007). The second half of the tests were performed with the same dimensions and orientation, but the upper .3 m of the column was not cut. In previous literature this type of variation has been referred to as isolated / un-isolated columns (Ross and Jamieson, 2012). This test from here on will be described as an uncut column (hence, u-PST).

Prior to performing each test, basic data was collected for both cut and uncut columns; snow depth (front and back), snow surface inclination, and slab thickness (front). Following the completion of the test, the weak layer cut length was recorded. In addition if the test resulted in a slab fracture (SF), slab length was measured on the top and bottom, on both left and right flanks of the test column. If the test resulted in propagation to the end of the column it was considered that all slab lengths would be equal to 1 meter. All results were recorded according to America Avalanche Association standards (Greene et al., 2010).

In both field campaigns a full snow profile was conducted according to standard with stratigraphy, manual hardness, crystal form and size (Greene et al., 2010). Snow temperature and density measurements were also performed through the snowpack. In addition to the snow profile, several compressional stability tests (ECT and CT) were performed to gain an understanding of weak layer reactivity to increasing steps of loading. (Simenhois and Birkeland, 2006; Jamieson, 1999)

During the first field campaign (July 17-18th) slab density measurements were performed following the test with a Wasatch Touring 100 snow density kit (Conger and McClung, 2009). During the second field campaign (July 27-28th) density measurements were conducted solely in the center of the study slope (snow profile) and at both left and right flanks.

Instead of conducting density measurements in each slab during the second field campaign, the Thin Blade Test (TBT) was used at a .02 m resolution stratigraphicaly through the slab and weak layer (Borstad and McClung, 2011). The TBT measures penetrative resistance and snow strength, by recording the Newton strength of force required to break snow crystal bonds. In order to test the most representative slab and weak layer conditions test columns were originally formed with .4 m wide by 1 m dimensions allowing for the thin blade to test the slab without effecting the column or test results. The test columns were then trimmed down to standard dimension. During the first field campaign the TBT was not conducted on each individual column, but just once as part of the full snow profile.

It is believed that by running the tests in a paired grid-formation there would be less variability of snowpack processes between cut and uncut tests (Birkeland et al., 2010).

The Wilcoxon signed-rank test was used to statistically analyze the PST and the u-PST results by comparing critical cut length percentages in match pairs. It is a non-parametrical statistical hypothesis test with a directional analysis.

4 RESULTS

A total of 44 Propagation Saw Tests were conducted during to field campaigns resulting in 22 matched pairs with 11 in each data set (Table 1). During FC-2 a test column (u-PST 13) was substantially disturbed by a large rock protruding through the weak layer. This result was disregarded and resulted in only 10 matched pairs possible to analyze for FC-2 (Table 1).

4.1 Snowpack Characteristics

Snow depths during FC-1 ranged from 82 - 117 cm and averaged roughly 103 cm (Table 1). Snow depths at both the front and the back of the column averaged slightly over 1 m. Slab thicknesses ranged from 44 – 52 cm and averaged just over 49 cm. The highest densities recorded in each slab displayed minor deviation ranging form 29.5 % to 30.5 % (Table 1). These values were recorded at the hardest, lower most part of the slab and displayed no cross slope variability. Tests from both field campaigns were consistently conducted on slope angles between 26° - 30° and averaged roughly 28° (Table 1).

The snowpack characteristics of the FC-2 data set like FC-1 only displayed minor variation between the cut and uncut tests (Table 1). Snow depths during FC-2 ranged from 105 - 150 cm and averaged roughly 138 cm (Table 1). Snow depths recorded at the front and the backs of the test columns averaged just under 130 cm. Slab thicknesses during FC-2 were nearly 15 cm thicker than FC-1, averaged just over 73 cm.

Density measurements were not conducted in all the FC-2 slabs. Instead, the TBT was performed on each test through the slab and weak layer. Results displayed a slight increase in crystal bond strength from lookers left to right across slope. Additionally, this also corresponds with a slight increase in slab thickness. Thus a harder slab was present to the right of the face where the snow depths were greater. This is believed to be a function of cross loading through wind drift. Densities measurements were conducted at either flank of the test site towards the base of the slab. These values were roughly 30 – 35 % snow water equivalent from left to right.

Table 1. Snowpack characteristics for cut/uncut PSTs for FC-1 and 2. Slab values (cm). Inclinations (Deg.). Densities (percent snow water equivalent). Test 13 from FC-2 was excluded due to a rock interupting the column. Lines intersecting data sets and test numbers indicate the two rows of tests.

FIELD CAMPAIGN 1

PST - CUT COLUMN								u-PST - UNCUT COLUMN							
TEST #	Incl.	Slab	Density	Cut Length	Fracture Length (cm) Avg. Top	Fracture Length (cm) Avg. Bot.	% Cut	TEST #	Incl.	Slab	Density	Cut Length	Fracture Length (cm) Avg. Top	Fracture Length (cm) Avg. Bot.	% Cut
2	28	50	30.5	40	100	100	40	1	28	51	30	47	70	87	54
4	28	51	30	45	100	100	45	3	27	51	30	49	55,5	77	64
6	26	51	29.5	43	100	100	43	5	26	52	30	45	68	89	51
8	27	52	30.5	39	100	100	39	7	27	50	30	44	70,5	89,5	49
10	28	50	30.5	40	100	100	40	9	27	51	30	53	69,5	88,5	60
11	29	46	30	39	100	100	39	12	28	44	29.5	56	76,5	84	67
13	28	46	30	42	100	100	42	14	27	48	30.5	48	92,5	99,5	48
15	26	48	30	41	100	100	41	16	28	50	30	49	99,5	111,5	44
17	27	51	29.5	42	100	100	42	18	28	50	30	46	96	105	44
19	27	48	30.5	40	100	100	40	20	27	49	30	44	88	98	45
21	26	50	31	39	100	100	39	22	28	51	30	46	74,5	94,5	49
AVG	27,3	49,4	30,2	**40,9**	100,0	100,0	**40,9**	AVG	27,4	49,7	30,0	**47,9**	78,2	93,0	**56,0**
MAX	29,0	52,0	31,0	45,0	100,0	100,0	45,0	MAX	28,0	52,0	30,0	56,0	99,5	111,5	74,0
MIN	26,0	46,0	30,0	39,0	100,0	100,0	39,0	MIN	26,0	44,0	30,0	44,0	55,5	77,0	46,0
STDEV	1,0	2,1	0,4	1,9	0,0	0,0	1,9	STDEV	0,7	2,2	0,0	3,8	14,0	9,9	10,0

FIELD CAMPAIGN 2

PST - CUT COLUMN								u-PST - UNCUT COLUMN							
TEST #	Incl.	Slab	Density	Cut Length	Fracture Length (cm) Avg. Top	Fracture Length (cm) Avg. Bot.	% Cut	TEST #	Incl.	Slab	Density	Cut Length	Fracture Length (cm) Avg. Top	Fracture Length (cm) Avg. Bot.	% Cut
1	29	72	x	46	100	100	46	2	28	71	x	53	50	74	72
3	28	70	x	45	100	100	45	4	27	68	x	59	29,5	68	87
5	28	70	x	49	100	100	49	6	26	70	x	52	40,5	69,5	75
7	29	70	x	50	100	100	50	8	27	77	x	66	69,5	96,5	68
9	30	76	x	48	100	100	48	10	27	78	x	69	71	103,5	67
11	28	80	x	39	100	100	39	12	28	81	x	74	99,5	124	60
14	27	68	x	41	100	100	41	13	x	x	x	x	x	x	x
16	27	67	x	41	100	100	41	15	28	68	x	54	49,5	82	66
18	28	75	x	38	100	100	38	17	28	71	x	51	52,5	84	61
20	26	78	x	42	100	100	42	19	27	75	x	56	95,5	115,5	48
22	28	79	x	41	100	100	41	21	28	76	x	52	95,5	107,5	48
AVG	28,0	73,2	x	**43,6**	100,0	100,0	**43,6**	AVG	27,4	72,9	x	**56,5**	63,6	91,2	**63,2**
MAX	30,0	80,0	x	50,0	100,0	100,0	50,0	MAX	28,0	81,0	x	74,0	99,5	124,0	86,8
MIN	26,0	67,0	x	38,0	100,0	100,0	38,0	MIN	26,0	67,0	x	35,0	29,5	68,0	44,3
STDEV	1,1	4,6	x	4,2	0,0	0,0	4,2	STDEV	0,7	4,7	x	10,5	24,3	19,3	12,7

The tested weak layer was a bed of 2.5 mm facets roughly 2 cm thick. Hand hardness ranged from fist to fist plus (F to F+) and corresponded with crystal bond strengths of ca. 1.00 N ($\pm$ .10 N). In profiles from both field campaigns this instability was found close to 50 cm from the base. These facets are believed to have formed between the 22nd and 25th of June. In some places the facets were found below a minor melt-freeze weathering crust. The weak layer overlay a bed surface of rounding facets with a hardness of four-finger-plus to 1-finger.

In addition the weak layer of facets displayed relatively high stability scores for both the compress (CT) and extended column tests (ECT). The ECTs performed for both data sets all failed with propagation between 27 and 29 compressional strikes. The additional 8 CTs that were conducted ranged from 23 to 30 compressional strikes with sudden collapse.

4.2 Cut Vs. Uncut

Results from the two small data sets suggested that cut lengths for the normal PSTs are lower than the u-PST (FC-1 averaged 41 cm and 48 cm; FC-2 averaged 44 cm and 57 cm; Table 1). In addition the cut column tests all exhibited smaller standard deviations (2 – 4) compared to the greater range in values from the u-PST data (4-10). In each PST propagation proceeded until the end of the column once a critical length was reached, whereas u-PSTs displayed a range in slab fractures (as there was no column “end”). Slab lengths varied for the u-PSTs, but the fractures lengths measured at the base of the slab always exceeded lengths at the top due to the harder snow in the lower slab (Table 1).

The data was analyzed by dividing the cut-

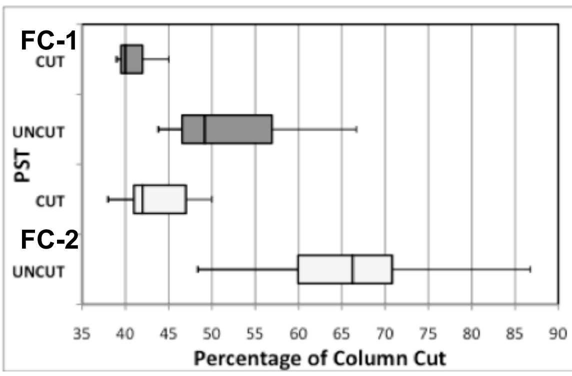

Figure 2. Box and whisker plot comparing percentage of column cut required to initiate propagation for both cut and uncut tests from FC-1 (grey) and FC-2 (white). N=11 for all except FC-2 uncut, n=10.

length values by the fracture lengths recorded at the slab bottom. Thus normalizing the cut and uncut tests as well as calculating what percentage of the column was disturbed in order to initiate propagation.

The percentage cut values for the PST were again smaller than the u-PST values, but exhibited a smaller range (Figure 2). Additionally results display that the relationship between cut and uncut increase between FC-1 and FC-2. Where mean values for FC-1 were 41 % and 56 %, cut and uncut values for FC-2 were 44% and 63% (Table 1, Figure 2)

The cut column percentages were analyzed with the Wilcoxon signed-rank test for matched pairs. Based on the difference in percentages between matched pairs, the distributions were significantly different for directional tests. The FC-1 data set had a significance level of $P > 0.005$ and FC-2 had a significance level of $P > 0.008$. Calculated z values equaled 2.85 and 2.67 respectively. Additionally a T-test for the significance between means was calculated and indicated that FC-1 had a significance level greater than 0.05 (df = 20) while FC-2 was significant up to 0.001 (df = 18).

5 DISCUSSION AND CONCLUSION

The major difference between the cut and uncut PST is the unnatural disturbance that isolating the column creates. This separation at the rear of the test column changes the mechanical properties of the slab and weakens the beam. Thus it is reasonable that cut PSTs in hard slab conditions propagate at a shorter cut length than u-PSTs.

With an uncut test column the slab must articulate the propagation as well as fracture from the slope. As the weak layer is cut by the blunt end of the saw, the lower end of the slab begins to hang and put stress on to the weak layer. If a dense slab is freed from a hard snowpack it is possible that some rotational strain will act in a hinge fashion around the location of the saw. Thus the unnatural weakness will attract the propagation (Gauthier and Jamieson, 2010; McClung, 2009; Ross and Jamieson, 2012). But if the test column is uncut the beam will have to be forced to fracture from the top down (Johnson, 2001). This is the actual process that is naturally occurring in skier-triggered avalanches.

So in combination of the added effort to fracture the slab in a u-PST and the induced weakness of a completely cut PST column, it is reasonable that PSTs present shorter critical lengths and lower cut column percentages.

Additionally the cut columns present much more consistent data values exhibiting standard deviations of at least half of those from the u-PSTs (Table 1). Initially this confirms the relatively low variability of snowpack properties across the slope, especially of the weak layer reactivity. In addition, the uncut data should display a greater range in values, as it is a natural failure. The slab will fracture at the weakest point in the beam based on microstructure as long as topography or other external factors are not at play. This is not necessarily true for the cut column. The cut column can thus be compared to an unnatural outcrop, tree line or disturbance in the snowpack that doesn’t allow the transfer of stress and attracts fracture crown lines.

Interesting differences exist between the FC-1 and the FC-2 data sets. The FC-1 had consistent slab thickness and hardness, while the FC-2 data displayed slight variation in both slab thickness and hardness. A slightly thicker slab as well as a range in slab hardness seems to have resulted not only in greater cut column percentages, but greater variability in results (Figure 2). Despite the small data set, results suggested an increase in column cut length as well as slab length as the snow conditions increased in hardness across the slope. This supports the understanding that harder slabs pull back further than soft slabs. The harder slab conditions tested in FC-2 also seem to present a greater deviation between cut and uncut results.

This suggests that a softer slab will have less of a deviation between cut and uncut tests. Under such circumstances an uncut column only results in a more difficult interpretation of the test. It seems possible that Ross and Jamieson (2012) although analyzing a larger data set, were unable to record significant results due to grouping of different slab conditions. The authors do highlight several interesting points; excavation takes longer without the use of a cord, uncut test displays no improvements in slope scale accuracy and results are more difficult to interpret.

It is true that preparation takes a longer time, but its possible to use a cord on the flanks of the test. This also allows for setting up two tests and comparing results from a cut and an uncut PST. Depending on how hard slab conditions are, it maybe more or less effective in enhancing slope scale accuracy. Finally Ross and Jamieson (2012) are correct in stating the results are more difficult to interpret. This is true, but isolated PSTs in a hard slab climate can also be difficult. It is possible that “stable” conditions can appear “unstable” due to the unnatural weakening of the slab during the isolation. Although it is better that the tools we use to analyze snow conditions are conservative.

Trends from the two small data sets suggest that PST columns that are completely isolated have shorter critical lengths than u-PSTs. Thus slab conditions and how the fracture is articulated through the beam are important aspects to address especially where conditions exceed 1-finger hardness.

It seems that the u-PST could provide interesting prospects for fracture mechanics in hard slab conditions. Foremost it would be important to expand upon the data set and test a greater range in slab hardnesses as well as stable and unstable snow conditions. It would also be interesting to test different beam geometries. In addition to slab strength, it is important to also address the influence of slab temperature, as the brittle to semi-ductile conditions will have large implications for critical length values. Finally it would also be valuable to develop a compressional stability test focused on hard slab conditions for example a longer ECT.

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