The effect of additional snow load on Extended Column Test and Propagation Saw Test results

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ABSRTACT:
The number of skier triggered dry slab avalanches typically increases during or shortly after snow loading events. However, field observations and research suggest that a skier is less likely to trigger a weak layer fracture as the depth to that weak layer increases. This begs the question: Why does skier triggered avalanche activity increase when the likelihood of initiating fracture seemingly decreases? This paper presents preliminary evidence that new snow loading may decrease the chances for fracture arrest once initiated. During the winter of 08/09 in Colorado's continental snowpack we used Extended Column Tests (ECT) and Propagation Saw Tests (PST) to track changes in the snowpack's ability to propagate facture before and after loading events. In addition, we present two case studies from Southeast Alaska's maritime snowpack. We used Extended Column Tests to measure the amount of additional loading required for a fracture to cross the entire column (ECTP). We compared these measurements to the natural loading at the end of the loading event and a day after the precipitation stopped. We also compared our data to avalanche activity on the same slopes. Our results suggest that in some cases the snowpack's propensity for fracture arrest decreased with the additional loading, and that artificial loading of an extended column may be a useful tool to estimate loading thresholds for full fracture propagation.

1. INTRODUCTION:

Dry slab avalanches threaten people living, travelling, working and recreating in alpine environments. Dry slab avalanches arise from a fracture in a weak snowpack layer. When the fracture undercuts a large area of the snowpack either an avalanche or a whumpf occurs. In other cases the fracture arrests after a short distance and the snowpack remains intact. Most skier triggered avalanches occur during or shortly after snow load events

Camponovo and Schweizer (2001) collected data showing that the stress applied by a skier on the snowpack decreases with increasing depth, and a recent model of skier triggering also shows the effect of depth on the ease of triggering (Heierli et al., Under review). Thus, fractures are easier to initiate in areas where weak snowpack layers are shallow. Field observations of avalanches are largely consistent with these results. Schweizer and Jamieson (2000) found that out of 186 skier triggered avalanches from the Swiss Alps and Canada's Columbia Mountains, the weak layer depth exceeded 0.7 m only 17% of the time. However, field experience also shows that the probability of triggering an avalanche increases shortly after additional snow load events like new snowfall or wind transport (McClung and Schaerer, 2006, p. 95). Thus, we see that additional snow increases the probability of triggering an avalanche because of the additional stress placed on the snowpack, while at the same time decreasing the probability of triggering due to the increasing depth of the weak layer.

In Colorado during the winter of 2008/2009, we used the Extended Column Test (ECT) (Simenhois and Birkeland, 2006; 2009) and the Propagation Saw Test (PST) (Gauthier and Jamieson, 2008a) to evaluate changes in the snowpack's ability to sustain propagating fractures in weak snowpack layers before and after snow load events. We also report on preliminary results from 2009/2010 in Southeast Alaska where we used the ECT to quantify the loading threshold needed for fracture propagation in comparison to avalanche activity on the same slopes.

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2. METHODS AND DATA:

Colorado data

During the 2008/2009 winter, in Copper Bowl at Copper Mountain, Colorado, we collected ECT and PST results from before and after 11 different loading events. In three of the 11 loading events we returned to the slope on the same day the loading event ended. In four events we returned a day after the event ended, in two events we returned two days after the event ended and in one case we returned to test the slope three days after the loading event. We report on results from 50 pits on 45 different slopes; we specifically targeted slopes we felt were on the verge of instability before the loading event. Loading events consisted of both wind and new snow events. Our pit data included all the typical snowpit observations following the techniques described by Greene, et al. (2004). In addition, we collected two ECTs in each pit and two PSTs in 38 of the 50 pits before and after the loading event.

In 45 of the 50 pits, the buried weak layer was near surface facets. Facets ranged in size between 0.5 and 2.5 mm. In the remaining five pits, the weak layer was 0.4 – 0.7 mm surface hoar. Weak layer depth varied between 0.1 and 0.55 m with median of 0.25 m before the loading event and between 0.22 and 0.71 m with median of 0.43 m after the loading event. In five of the 50 pits the slab above the weak layer consisted of wind crust. In the other 45 pits, the slab was small rounded grains, 4F to P hardness.

Alaska data

During two loading events in the maritime snowpack of Southeast Alaska in the 2009/2010 winter, we tracked the changes of ECT results throughout and up to two days after two loading events. In addition, we measured the threshold loading amount needed for ECT results to transition from ECTN to ECTP. Finally we verified our measurements against field observations toward the end of the loading event by attempting to trigger avalanches on the same slopes. The first loading event occurred between 9 January and 11 January 2010. During that time we received 0.91 m of new snow and 41 mm of snow water equivalent (SWE) By the end of the event on the morning of 11 January the weak layer depth ranged between 0.31 m in wind exposed areas and 0.77 m in sheltered areas.

On 10 January, we dug six pits on six different slopes and used the ECT to asses if initiating fracture in the weak layer is possible. We also measured the loading thresholds required to change a test result from an ECTN to an ECTP in five of the six pits (ECT results were already ECTP in the sixth pit). We simulated the snow load increase by gradually loading the top of the extended column with snow blocks (Figure 1) before dynamically loading one end of the column as in an ECT (loaded ECT). We gradually increased block sizes until test results changed from ECTN to ECTP. In addition, on slopes where we didn't trigger avalanches, we investigated if we initiated fractures that came to arrest within a short distance with our skis, or if we were not initiating fractures at all. We did so by digging across our ski tracks to below the weak layer's depth and seeing if it remained intact under our skis. If the weak layer failed under our ski tracks we initiated a fracture, otherwise the weak layer remained intact and we didn't initiate a fracture in the weak layer (Gauthier and Jamieson, 2008b) (Figure 2). On the morning of 11 January, we triggered avalanches on five out of the six slopes we investigated the previous day. On 12 January, we returned to the slopes and did ECT tests in the one pit on the slope that didn't avalanche and on the crown walls of the five avalanches we triggered the day before.

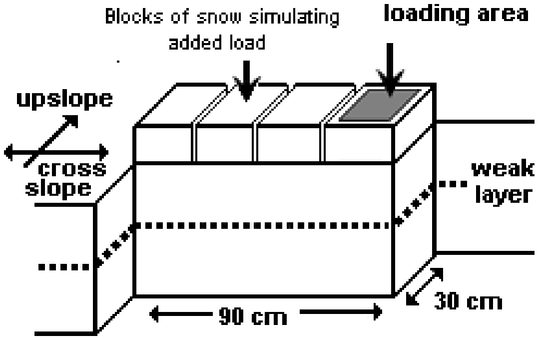

Figure 1: A loaded ECT involves creating additional load with snow blocks on top of ECT column to measure additional loading for fracture propagation.

The second loading event we investigated started on the morning of 5 March and ended on the morning of 6 March. This storm deposited about the same SWE (39 mm), but only half the amount of snow (0.45 m) as the January storm. During the morning of 5 March we did ECTs in four pits on four different slopes. In addition we measured the amount of additional load needed to change results from ECTN to ECTP. Finally, we looked at the potential for skiers to initiate fractures as described above. We returned to test the same slopes on the afternoon of 5 March and on 6 March. We compared our measured loading thresholds for fracture propagation to the natural loading amount that led to the skier triggered avalanche occurrences during the afternoon of 5 March. In all four pits the weak layer consisted of F hard precipitation particles. Weak layer depth ranged between 0.07 and 0.15 m in the morning of 5 March and between 0.15 and 0.43 m by the afternoon of 5 March.

Figure 2: Cutting across our ski cut to find out if fractures are initiated under our skis. In this case the fracture arrested after a short distance.

3. RESULTS:

Colorado data

Our Colorado dataset consists of data from 100 ECTs and 76 PSTs from 50 pits from before and after 11 loading events. The additional snow depth in our pits ranged from 0.03 to 0.55 m with a median of 0.16 m. We measured the density of the additional snow in 10 out of the 11 loading events. Additional SWE in our pits ranged from 5.4 to 99 mm of water with median of 24 mm. In 64 of 100 ECT tests from 32 (64 tests) out of 50 pits (100 tests), results changed from ECTN before the snow loading event to ECTP afterwards. In 12 of the 100 pits, ECT results were ECTP before and after the loading events and in remaining 12 pits (24 ECTs), results were ECTN before and after the loading event. Interestingly, all 12 pits where ECT results remained ECTN were on the same or on adjacent/similar slopes to slopes where ECT results changed from ECTN to ECTP. Further, the weak layer, bed surface and slab combination in areas where ECT results remained ECTN were similar to the adjacent locations where ECT results changed to ECTP in terms of layer hardness, grain type and size. The main trend we see in the data is that the loading in areas where the ECT remained ECTN was less than in places where ECT results changed to ECTP (Figures 3 and 4). The additional load in those pits where results remained ECTN was on average 65% of the snow load or 60% of the SWE of those pits where results changed from ECTN to ECTP. The average loading in those pits where results remained ECTN was 0.113 m of snow or 1.6 mm of water in comparison to the 0.21 m of snow or 3.4 mm of water in pits where results changed to ECTP. Also, the newly loaded slab in pits where ECT changed to ECTP was generally denser. The density in pits where results changed to ECTP was between 100 and 230 (average of 165) kg/m^3. In pits where ECT results remained ECTN, the newly loaded slab was between 100 and 190 (average of 135) kg/m^3. Still in two pits where ECT results remained ECTN the additional loading of snow, SWE and density were slightly higher than on similar slopes where ECT results changed to ECTP on the same day (Figure 4).

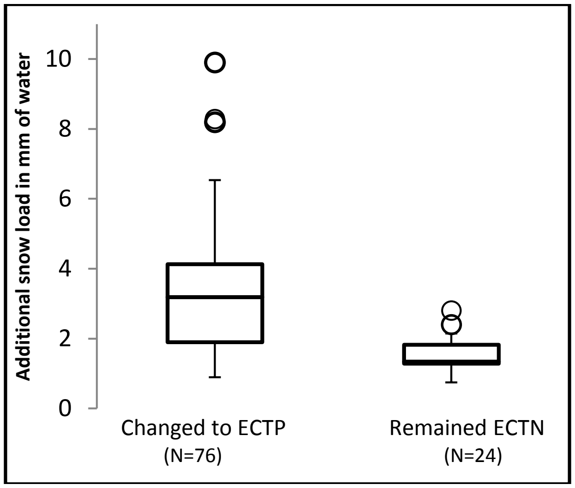

Figure 3: Comparison of additional snow load in mm of water (SWE) between pits where ECT results changed from ECTN to ECTP due to the loading event (N = 76) and pits where ECT results remained ECTN (N = 24). The line dividing the box represents the median value, the box is the values from 25% to 75% of the data, and the whiskers are the non-outlier range. We define outliers as more than outside 1½ times the interquartile range from the median.

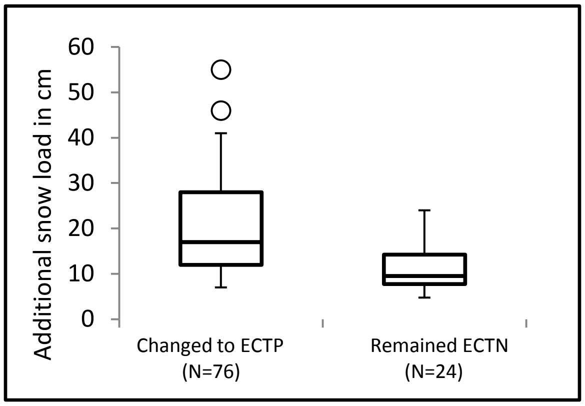

Figure 4: Comparison of additional snow load (cm) between pits where ECT results changed from ECTN to ECTP (left) due to the loading event and pits where ECT results remained ECTN (right).

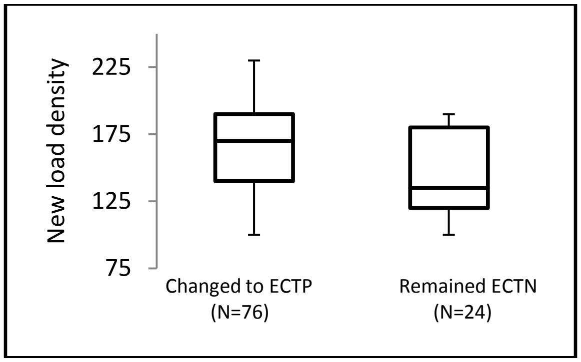

Figure 5: Comparison of slab densities between pits where ECT results changed from ECTN to ECTP (left) due to the loading event and pits where ECT results remained ECTN (right).

We also compared the number of taps to start a fracture in a weak layer before and after a loading event in the 38 pits where ECT results were ECTP after the loading events. Our data is fairly scattered. In general, it took about one more tap on average to start a fracture after the loading event. However in 25% of our pits the number of taps to initiate a fracture decreased after the loading event and in 17% it remained the same (Figure 6). This general trend was slightly less evident in the six pits where fractures propagated before the loading event. In those pits the number of taps needed to start a fracture increased in only 0.4 taps on average; there was a decrease in the number of taps in 33% and equal number of taps in 25% of the pits.

Our PST results showed a similar trend as our ECTs. In our dataset, the critical cut lengths decreased 0.05 to 0.52 m (average of 0.28 m) after loading events. All our loading events were accompanied by a decrease in critical cut length. On average, for every mm of additional snow water equivalent in loading, critical cut length decreased 11 mm. Like the ECT, there is a great deal of scatter in the data, but there is also a general trend that greater increases in load lead to larger decreases in the critical cut length (Figure 7).

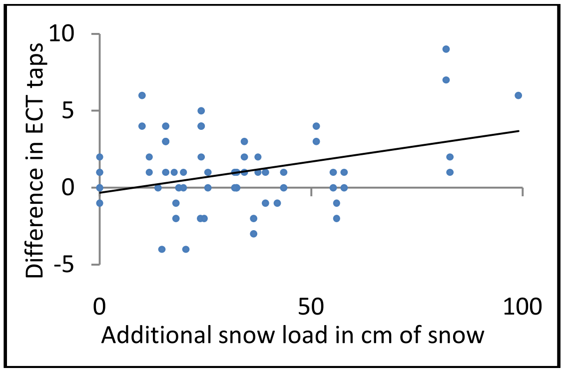

Figure 6: The difference in number of taps to initiate weak layer fracture from before and after loading event in relation to the amount of loading in water equivalent. Every point on the chart represents a data from a single pit.

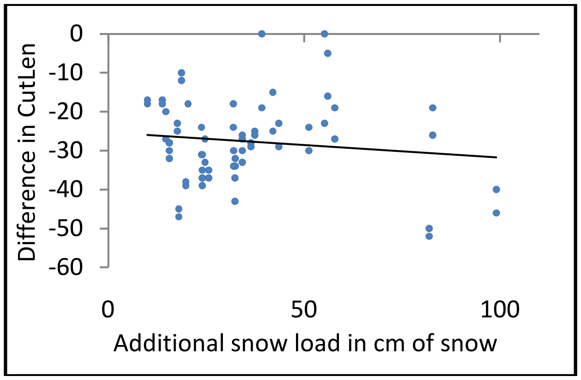

Figure 7: The difference in PST critical cut length in relation to additional load measured in mm of water.

<u>Alaska data</u>

In both case studies from Southeast Alaska we saw conditions change from ECTN to ECTP as the new snow load increased. Further in both case studies we initiated weak layer fractures under our skis that arrested within a short distance during the early stages of the loading events, and we subsequently triggered avalanches on the same slopes after they had been loaded. Both of these observations strongly suggest a decreased propensity for fracture arrest following loading events.

The first loading event occurred between 9 January and 11 January 2010. During the night of 9 January we received 0.13 m of snow and 6 mm of SWE. By the afternoon of 10 January there was an additional 0.65 m of snow and 28 mm of SWE on our snow stake. Another 0.26 m of new snow and 13 mm of SWE fell during the night of 11 January. Slab hardness above the weak layer was between 1F and 1F+ throughout the event. In all six pits, the weak layer's hardness was F+ and consisted of a mix of new snow and decomposed grains. On the morning of 10 January, weak layer depth ranged from 0.13 to 0.37 m in our pits. By the morning of 11 January the weak layer depth increased to between 0.31 m in wind exposed areas and 0.77 m in sheltered areas.

On 10 January, we had 0.13 m of new snow on our valley snow stake with continuing snow. On that day we dug six pits on six different slopes. Weak layer depths in five of the six pits ranged from 0.12 to 0.21 m, and results were ECTN in all five pits. Weak layer depth in the other pit was deeper (0.27 m) and the ECT was already propagating (ECTP 15). The lower (and steeper) part of this slope avalanched as we approached its steeper section, confirming that the propensity for fracture arrest on this slope was low. In one of the five pits, loading the top of the column with an additional 0.1 m of new snow changed our result from ECTN to ECTP. For the other four pits we had to artificially load columns with 0.2 m of additional new snow before our results changed from ECTN to ECTP. In addition to the ECTs, we also examined the weak layer under our ski tracks while traveling between pits. We found arrested weak layer fractures under our ski tracks around our pits on all six slopes.

An additional 0.65 m of new snow (28 mm of SWE) fell the next day, pushing the weak layer depth up to between 0.31 and 0.75 m on the same slopes where we dug our six pits the day before. Five of our six test slopes avalanched with ski cuts, and we did not conduct ECTs on those slopes since it was clear that the propensity for fracture arrest was low in on those slopes. Weak layer depth on the remaining slope was 0.31 m and ECT results were ECTN. By 12 January we received additional 0.26 m of new snow and 13 mm of SWE. However with the increasing wind speed and the direction change from easterly to westerly winds on ridge top, weak layer depth decreased by 0.016 m on average in five of the six pits. The sixth pit was on east facing slope, about 10 m off the ridge top, and weak layer depth increased from 0.31 to 0.59 m. ECT results on the crown walls from the day before were all ECTN and we didn't observe any new avalanches throughout the day. If the areas above the crown fractured when the avalanches released the day before, the snow may have strengthened considerably prior to our tests (Birkeland et al., 2006).

Our second case study is from March, 2010. On 5 March we dug four pits on four different slopes. Weak layer depth averaged 0.295 m and ECT results in three of four pits were ECTN. ECT results remained the same after loading the columns with 0.1 m thick snow blocks, but results in all three pits changed from ECTN to ECTP after we loaded the column with 0.2 m thick blocks. On the afternoon of 5 March, the weak layer depth on two of the slopes increased by more than 0.2 m. Those two slopes avalanched that afternoon with ski cuts. The weak layer depth on the other two slopes increased by less than 0.16 m by that afternoon, and they did not avalanche with ski cuts. Digging across our ski tracks on the slopes that didn't avalanche revealed weak layer fractures that arrested within a short distance, never exceeding 0.2 m in length. Later that day, new snowfall increased weak layer depths to 0.56 m on average. ECT results changed from ECTN to ECTP on the remaining two slopes, and they also avalanched that afternoon with ski cuts. On 6 March weak layer depth increased to between 0.34 and 0.68 m, and all four slopes avalanched with ski cuts (two of them remotely). Finally, on 7 March (about 30 hours after the loading event stopped) we attempted to trigger avalanches on slopes we could not access the day before. We used 18 kg charges with no results. That same day we returned to the slopes we monitored during the loading event and did ECTs on the avalanche's crown faces. All these test results were ECTN.

4. DISCUSSION AND CONCLUSIONS:

Our data from both the continental snowpack of Colorado and the maritime snowpack of southeast Alaska suggest that an increase in snow load can sometimes change ECT results from ECTN to ECTP. In fact, for 50 pairs of before and after tests in Colorado,

Table 1: Weak layer depth, ECT results and avalanches observed on our six test slopes for the loading event from 10 January to 12 January 2010.

	10 Jan, New snow 0.13m, 6 mm SWE					11 Jan, new snow: 0.65 m, 28 mm SWE			12 Jun, New snow: 0.26 m, 13 mm SWE		
Pit / slope #	WL depth	ECT	0.1 m loaded ECT	0.2 m load ECT	Avalanche observations on the same slopes	WL depth	ECT	Avalanche observations on the same slopes	WL depth	ECT	Avalanche observations on the same slopes
1	15	ECTN11	ECTN11	ECTP12		31	ECTN21		59	ECTN25	None
2	17	ECTN12	ECTN17	ECTP16		67		SS-AS-R4/D2-N	66	ECTN23	None
3	13	ECTN11	ECTN15	ECTP19		62		SS-AS-R4/D2-N	63	ECTN29	None
4	21	ECTN15	ECTP17	ECTP21		75		SS-AS-R4/D2-N	71	ECTN32	None
5	27	ECTP15			SS-AS-R3/D2-N	77		SS-AS-R4/D2-N	78	ECTN35	None
6	12	ECTN11	ECTN14	ECTP15		66		SS-AS-R4/D2-N	61	ECTN26	None

Table 2: Weak layer depth, ECT results and avalanches observed on our six test slopes for the loading event from 5 March to 7 March 2010.

5 Mar, 1100					5 Mar, 1530			6 Mar		7 Mar	
WL depth	ECT	0.1 m loaded ECT	0.2 m load ECT	Avalanche observations on the same slopes	WL depth	ECT	Avalanche observations on the same slopes	WL depth	Avalanche observations on the same slopes	Charge size	results
10	ECTN12	ECTN13	ECTP12		25	ECTN14		34	SS-ASr-D2/R3-N	18 kg	none
7	ECTN11	ECTN13	ECTP14		15	ECTN16		56	SS-ASr-D2/R3-N	18 kg	none
14	ECTN14	ECTN12	ECTP13		35	ECTP14	SS-AS-D1/R3-N	64	SS-AE-D2/R4-N	18 kg	none
15	ECTP14	ECTP14	ECTP12	SS-AS-D1/R2-N	43	ECTP15	SS-AS-D1.5/R4-N	68	SS-AE-D2.5/R4-N	18 kg	none

results changed from ECTN to ECTP 64 times (64%). An increase in load can also reduce the critical cut length for the PST. For our 38 pits in 11 Colorado loading events, the critical cut length decreased in every case. The changes in both ECT and PST results strongly suggest that the snowpack's propensity for fracture arrest decreases as new snow load is added. Clearly, additional snow load does not always decreases the potential for fracture arrest to the point of instability. Of the 50 pits we used to track changes in ECT results during loading events in Colorado, in 12 pits (24%) ECT results remained ECTN after the additional loading. In general, the loading amounts and the stiffness of the new load in pits where ECT results changed from ECTN to ECTP exceeded the loading in locations where results did not change to ECTP. Still in two pits, ECT results remained ECTN after the loading event although the loading amounts in those pits exceeded the loading on the same or on adjacent slopes where tests results changed to ECTP. Thus, we didn't find a common loading threshold for fracture propagation throughout our dataset. We also recognize that there are many other snowpack properties that may affect the snowpack's propensity for weak layer fracture on those slopes.

We attempted to measure threshold loads that would increase the propensity for slope scale weak layer fracture (and change ECT results from ECTN to ECTP) in two case studies in Southeast Alaska. Overall we did nine loaded ECTs measurements on nine different slopes. All our slopes avalanched with ski cuts after additional snow load that exceeded our measurements. However, we don't have data from loading amounts approaching our measured thresholds. Hence, more data and further evaluation is needed for the loaded ECT. We are encouraged by our preliminary results and the benefit in measuring additional loading thresholds for avalanche programs like ski areas, roads or guiding operations, but we also caution the reader that our data is very limited and more research is needed. In general, our data support what practitioners noticed a long time ago: the ability of the snowpack to sustain fracture propagation in weak layers depends heavily on the amount and the hardness of the new load.

Another thing we investigate is the effect of additional loading and weak layer depth on fracture initiation. Our data shows an overall increasing trend in the number of taps needed to initiate fractures as load (and therefore depth to the weak layer) increases. This trend mirrors previous studies (Schweizer and Camponovo 2001) showing an increase in difficulty for skiers to trigger avalanches as weak layer depth increases. However, our data is considerably scattered when comparing the changes in number of ECT taps with the additional weak layer depth.

Clearly not all loading events result in skier triggered avalanche activity. However, our data suggests that in those cases where skier triggered avalanche activity increases during or after new loading events, the snowpack's propensity for fracture arrest decreases faster than the increase in the difficulty of initiating a fracture.

5. ACKNOWLEDGMENT:

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