COMPARING FRACTURE PROPAGATION TESTS AND RELATING TEST RESULTS TO SNOWPACK CHARACTERISTICS

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ABSTRACT: The Propagation Saw Test (PST) and the Extended Column Test (ECT) are two recently and independently developed field tests that indicate the propensity for a slab and weak layer combination to propagate a fracture. University of Calgary researchers performed the PST and ECT throughout the 2008 winter season along with other standard stability tests to establish their strengths and limitations. The PST and ECT were compared side-by-side in over 80 test pits with close to 600 individual test results throughout the 2008 winter in the Columbia Mountains of British Columbia, Canada. We tested numerous slab and weak layer combinations including tracking four persistent weak layers from initial burial to depths of over two meters. Field observations and initial analysis indicate correlations between slab hardness, weak layer depth, and propagation propensity, and hint at how these snowpack characteristics influence the observed results of each test. We discuss the specific slab and weak layer combinations that appear to have high, low, or no propagation propensity, and suggest particular conditions under which one test is more appropriate than the other for aiding forecasters in assessing propagation propensity.

KEYWORDS: fracture propagation, snowpack stability test, extended column test, propagation saw test, avalanche forecasting, snowpack properties.

1. INTRODUCTION

Weak layer failure leading to dry slab avalanche release is known to require both fracture initiation *and* propagation within the weak layer. Although fracture initiation is required prior to the onset of propagation, the propensity for propagation is independent of the ease of initiation (Schweizer et al., 2003). In some cases, initiating failure may be difficult but the propensity for large scale propagation could be high, particularly for thick, stiff slabs (van Herwijnen and Jamieson, 2007). Conversely, fracture initiation may occur easily, for instance, at shallow storm snow interfaces, without the onset of propagation (van Herwijnen and Jamieson, 2007). Standard stability tests such as the compression test indicate snowpack stability based primarily on the ease at which weak layer fracture initiates, which may overestimate instability at times when propagation propensity is low, and may also fail to initiate fracture in deeper layers with high propagation propensity.

Recent efforts to better understand and predict propagation propensity within a slab and weak layer combination has lead to the development of two distinct and independently conceived snowpack tests specifically for indicating propagation propensity: the Propagation Saw Test (PST) and Extended Column Test (ECT).

The PST has been in development at the University of Calgary since 2005 by Gauthier and Jamieson (2006, 2007, 2008; Gauthier, 2007) and independently in Switzerland by Sigrist and Schweizer (2007). Discussion of the PST in terms of fracture mechanics (FM) (e.g. McClung, 1981; Bazant et al., 2003) and weak layer collapse (WLC) theory (e.g. Heierli and Zaiser, 2006; Sigrist, 2006) was presented by Gauthier (2007, pg 159-163) and Gauthier and Jamieson (2007, 2008); while initial empirical validation based on comparing results with independent observations of propagation in the field was more recently presented by Gauthier and Jamieson (2008).

The Extended Column Test (ECT) is an alternative field test indicating propagation propensity that was developed by Simenhois and Birkeland (2006, 2007) and initially tested in Colorado and New Zealand in 2005-06.

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In the winter of 2008, ASARC field staff from the University of Calgary performed the PST and ECT side-by-side in over eighty snow-pits in the Columbia Mountains of British Columbia (B.C.), Canada, amassing close to 600 test results. In this paper, we report on our findings from 2008, assessing the strengths and limitations of each test method individually and in comparison with each other, particularly in relation to characteristics of slab and weak layer combinations with varying degrees of propagation propensity.

We seek correlations between slab hardness, weak layer depth, and propagation propensity, and assess the influence of these snowpack characteristics on the observed results of the PST and ECT. Particular slab and weak layer combinations with high, low, or no propagation propensity are discussed in relation to test results and some suggestions are presented as to when one test might be more appropriate under certain conditions to aid forecasters in predicting propagation propensity.

2. METHODS

The PST (figure 1) involves a 30 cm cross-slope by 100 cm+ upslope column isolated to below the weak layer of interest on two sides by shovel and usually on the other two sides by cord cut. The upslope length is the greater of 100 cm or the equivalent depth of the weak layer being tested. Fracture initiation is simulated by drawing the blunt edge of a 2 mm thick saw upwards within the weak layer until the onset of propagation, or until the entire column has been cut.

Three different results can be observed in the PST: one is when the fracture propagates suddenly from the end of the saw cut to the end of the column; while the other two involve the fracture propagating but stopping within the column either at a slope-normal fracture through the overlaying slab, or at an indiscernible point of self-arrest along the layer. To interpret the PST results, propagation within the weak layer is said to be *likely* when fracture propagation initiates with a saw cut of less than or equal to 50% of the column length and continues uninterrupted to the end (Gauthier, 2007, pg 156).

PST results were recorded as: x/y (arr/sf/end) down w on yymmdd (or alternative layer ID), where x is the cut length; y is the column length; 'arr' indicates the propagating fracture self-arrested in the column before reaching the end; 'sf' indicates the propagating fracture was interrupted by a slab fracture; 'end' indicates the propagating fracture ran to the end of the column; w is the weak layer depth (measured vertically) in the snowpack; and yymmdd refers to the date of burial (date ID) for the weak layer being tested.

Fig. 1: Propagation Saw Test (PST) in process. The operator is drawing the blunt edge of a 2 mm thick saw upwards through the weak layer, stopping and marking the spot where the fracture propagates suddenly forward from the end of the saw cut.

The ECT (figure 2) utilizes a 90 cm cross-slope by 30 cm upslope 'extended' column isolated on all four sides. The same loading steps as a standard compression test (e.g. CAA, 2007; Greene et al., 2004) are applied to one end of the column until fracture initiates in a weak layer and potentially propagates across the remainder of the column.

The ECT is therefore also an indicator of the ease of fracture initiation. Simenhois and Birkeland (2006) determined that propagation propensity can be said to be *likely* when propagation to the end of the column occurs on the same or one extra tap as initiation, provided propagation occurs in one layer and is not broken.

ECT results were recorded as ECTP n, ECTN n, or ECTNR after Simenhois and Birkeland (2007), where ECTP indicates propagation to the column end on the *n*th or *n*th + 1 tap; ECTN indicates initiation on the *n*th tap with limited or no propagation, and ECTNR indicates no initiation or propagation (no result). The variable 'n' refers to the number of taps required for initiation. The depths and date ID's of the layers that fractured were also recorded, as were measures of damping snow between the weak layer and shovel blade when initiation occurred, and a measure of propagation extending only part way across the column in instances of ECTN.

Fig. 2: Extended Column Test (ECT) in process. The operator is applying the same loading steps as for the standard compression test to one end of the column, noting when fractures initiate in a weak layer under the shovel and when they propagate across the column.

The daily field method for comparing PST's and ECT's involved a minimum of two compression tests (CT), two PST's, two ECT's and a comprehensive snow profile. Site selection required sufficient space to conduct the minimum number of tests, and often a third and fourth PST or ECT was performed if initial results were inconclusive or operator error was a factor. In addition, a Rutschblock (RB) test was often performed. A typical pit layout for comparing PSTs and ECTs with minimal spatial variability is shown in figure 3.

Field work was primarily conducted at or below tree line on all aspects and slopes ranging from 0° to 52° with an average slope of approximately 30°. Weak layers tested ranged in depth from 14 cm to 250 cm below surface and included surface hoar layers, faceted layers above or within melt-freeze crusts, and a few shallow storm interfaces. Tests were regularly performed on four specific weak layers during the evolution of the overlying slab. The four regularly tested layers as dated by burial in Glacier National Park, B.C., were the December 5th rain crust, January 26th surface hoar, February 23rd surface hoar, and March 9th surface hoar. All four layers had widespread prevalence throughout parts of B.C. and Alberta with burial dates that varied slightly.

A snow profile was conducted in every pit to at least one layer below the weak layer of interest, and included temperatures, grain size and type, hand resistance, and densities in conformance with Canadian Avalanche Association (CAA) Observation Guidelines and Recording Standards (OGRS) (CAA, 2007). Any local avalanche activity, including whumpfs, was also recorded.

Fig. 3: Typical pit layout for comparing the PST and ECT

In addition to the PST and ECT, other standard stability tests such as the CT, RB, and deep tap test (DTT) were performed and recorded according to OGRS guidelines along with descriptions of fracture character and release type which have been shown to relate to propagation propensity (Schweizer and Wiesinger, 2001; van Herwijnen and Jamieson, 2004). A DTT was performed if a targeted weak layer was too deep to fracture in the regular CT. Sufficient snow (15 cm minimum) was cut away from around the sides and back after individual PST and ECT tests to ensure the saw blade or shovel had not damaged the slab or weak layer in subsequent tests.

In winter 2008, 91 pits in 88 days were devoted to comparing PST and ECT results directly, resulting in 432 comparable results in 99 test groups. A test group was defined as all PSTs and ECTs within one pit with results on a specific weak layer. With the prevalence of two reactive persistent weak layers (PWL) during mid-to-late March, multiple test groups resulted from the same set of tests within a single pit. During this time, it was decided that multiple weak layers could be tested in a single PST column provided the operator worked from the bottom layer up, maintaining the integrity of the overlying slab during each test. An additional 10 days were devoted to testing the deeply buried Dec. 5th crust with only the PST.

3. STUDY AREAS

Most of the tests from the winter season of 2008 were conducted in the Columbia Mountains of British Columbia, primarily in the Selkirks within Glacier National Park and in the Monashees and Cariboos around Blue River, B.C. Some additional data were collected in the Purcell Mountains near Kicking Horse Mountain Resort in Golden, B.C., and in the Columbia Mountains within the Chatter Creek Cat Skiing tenure north of Donald, B.C.

4. ANALYSIS AND RESULTS

Initial observations in the field had hinted at snowpack characteristics – particularly weak layer depth and slab hardness – that influenced PST and/or ECT results. To assess individual strengths and limitations of each test method as the slab thickened, PST and ECT results were compared separately against weak layer depth.

4.1 Effect of snowpack properties on PST results

The results of 365 PSTs from 2008 are plotted against weak layer depth in figure 4. The percentage of the PST column cut required to initiate propagation was used to measure test results, and three different symbols were used to distinguish the propagation result that followed initiation (arr/sf/end). A trend indicating increased cut lengths with depth is apparent for initiating propagation in shallower layers. Many of these shallow layer results ended in slab fractures or short propagations arresting within the layer. The first fracture that propagated to end occurred in a slab 27 cm thick, and results indicating propagation was likely continued in slabs up to 230 cm deep. Short propagations, whether arresting within the layer or going to the end after over half of the column had been cut, are widely dispersed through the dataset.

We had observed in the field that shallow weak layers with soft overlying slabs usually resulted in slab fracture results. We had also observed that a minimum slab thickness, and perhaps hardness, was required to facilitate propagation to the end, and that propagation propensity could remain high as layer depths exceeded two meters. Some of these observations are reflected in figure 4. It is evident that slab fractures occurred most commonly in thin slabs between 14 cm and 40 cm thick. The hand hardness of the slab in these cases was generally fist (F) to fist-plus (F+). Conversely, propagation to the end of the column did not occur until the slab was at least 27 cm thick, and appeared to peak when slab depths reached 50-60 cm. At greater depths, it appears that results propagating to end predominantly required cuts between 30% and 55%, or greater than 80%. It is also interesting to note the number of tests between 120 cm and 230 cm deep in which propagation propensity in the layer was still high; particularly the two tests that propagated to end after less than 30% of the column had been cut. Both had a 20-30 cm thick pencil-hard slab immediately overlaying the weak layer.

4.2 Effect of snowpack properties on ECT results

Similar observations about the ECT had been made in the field, specifically, that the ECT also seemed to require a minimum slab thickness, and possibly hardness, before propagation would occur. Often, fractures would initiate in shallow soft slabs but would not propagate to the end of the column. In many cases, the shovel pushed into the upper snowpack easily during the ECT and shovel edges were sometimes found to cut into shallow weak layers inhibiting potential propagation. Simenhois and Birkeland (2006) also acknowledged this limitation. In addition, a limiting depth at which the ECT would not propagate, and rarely initiate, fractures in the weak layer was observed.

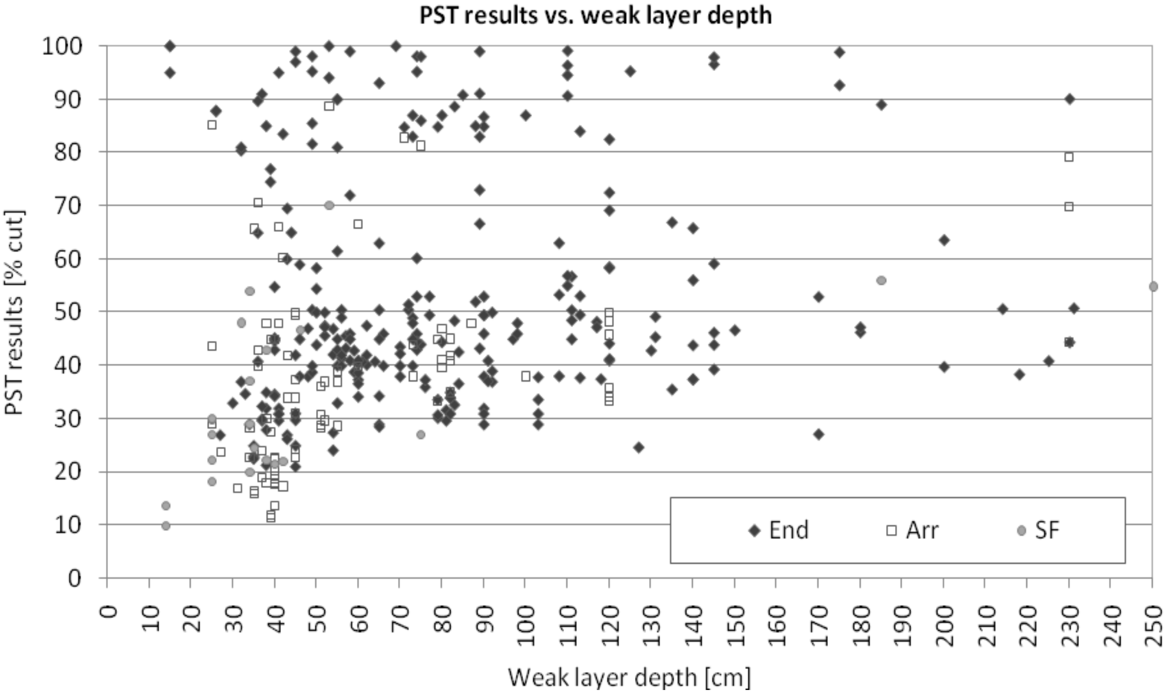

Fig. 4: PST results (% of column cut) versus weak layer depth. The results of 365 PSTs from 2008 were plotted. Three symbols were used to distinguish the types of PST results. Only \`End\` *results up to 50% cut indicate propagation is likely (Gauthier, 2007, pg 156).*

Test scores from 242 ECT results are plotted against weak layer depth in figure 5. Number of taps to initiate a fracture was used to measure results and three symbols are used to represent whether a fracture only initiated (ECTN), initiated and propagated to the end (ECTP), or was not initiated (ECTNR). ECTNR results were given the value of 35 taps in order to be plotted.

ECT results in figure 5 show a clear dependence on depth, with thicker slabs requiring more taps to initiate and potentially propagate fractures. In slabs between 30 cm and 70 cm deep, ECTN versus ECTP results do not show a dependence on depth. For weak layers deeper than 70 cm, most tests ended in no result with a few propagating results for layers up to 92 cm deep and some additional initiation results up to 114 cm.

Since the number of ECT taps is assumed to be an indicator of the ease of fracture initiation, it was no surprise that as layer depth increased, an increased number of taps was required to initiate, and potentially propagate, fractures. What is interesting is that 85% of results that propagated across the column fell within a range of slab thickness between 27 cm and 71 cm. An additional 13% fell between 71 cm and 92 cm, with only one incidence of propagation in a slab thinner than 27 cm. This particular case occurred on a storm snow interface 13 cm deep with an overlying fist to fist-plus slab. In weak layers less than 27 cm deep initiation was common without propagation. In slabs thicker than 92 cm, a few instances of initiation occurred – all without propagation, but most tests had no result. This confirmed what we had been seeing in the field: that the ECT seemed to be a reliable indicator of propagation propensity when snowpack conditions conducive to initiation were present, but could not indicate propagation propensity once the weak layer was too deep to be initiated in the standard loading steps.

4.3 Comparison of PST and ECT results

Direct comparison of the PST and ECT was initially based on the interpretive results of tests, in other words, whether results suggested propagation was likely (propL) or unlikely (propUL). From a forecaster’s perspective, agreement between interpretive test results is desirable. In this particular study, we looked at how often test results were in agreement, although we do not attempt to validate the test results with

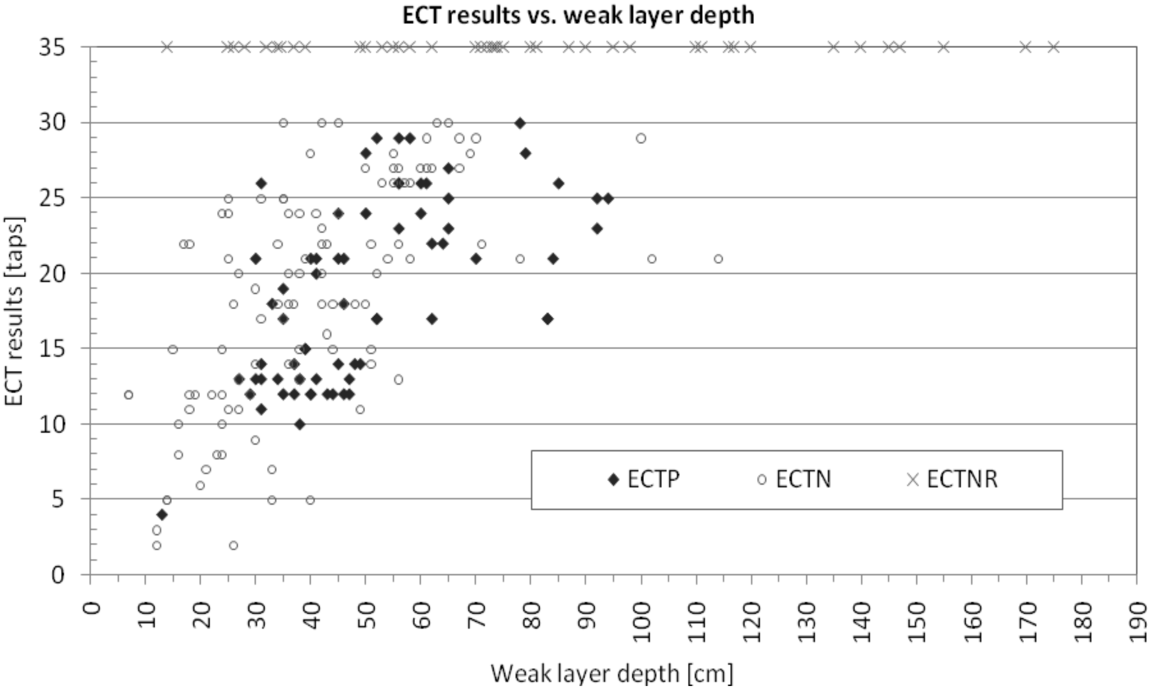

Fig. 5: ECT results (number of taps) versus weak layer depth. Test scores of 242 ECT results were plotted including multiple results in some individual test columns. Three symbols were used to distinguish the observed ECT results. ECTNR results were assigned a value of 35 taps in order to be plotted.

independent observations of propagation in the field such as avalanches or whumpfs. Within each of the 99 groups of comparable tests, the first two valid ECTs and first two valid PSTs performed were compared based on *propL* and *propUL*. All four tests agreed on propagation propensity 51% of the time, with three of four tests agreeing an additional 21% of the time. The remaining 28% of the time (29 groups), both PST results disagreed with both ECT results. There were no cases where only one of each test agreed. Of the 29 pairs of conflicting results between different test methods, 23 (79%) of those involved the PST suggesting *propL* while the ECT suggested *propUL*. In all but three of those cases the weak layer of interest was greater than 70 cm deep, and in only one case did a fracture initiate within the standard loading steps of the ECT. When only slabs 70 cm and shallower are considered, three or four of four tests within a comparison group agreed 83% of the time while the number of ECT *propUL* versus PST *propL* comparisons was reduced to 8%.

The remaining six test groups in which the PST and ECT disagreed saw the ECT suggesting *propL* when the PST suggested otherwise. One of these groups was likely due to the previous collapse of the weak layer during a nearby avalanche. Another four of these groups occurred over a five day period of testing the January 26 surface hoar layer, in which the slab was generally finger-hard (1F) rounds or mixed forms overlying four-finger (4F) hard surface hoar with grain sizes of 2-6 mm.

The above observations were reinforced when a one-to-many comparison was conducted on individual tests within each test group. In other words, each PST was compared to each ECT in the group, generating *m* x *n* comparisons, where *m* and *n* are the number of PSTs and ECTs in each group, respectively (Table 1). This resulted in 432 direct comparisons, of which 264 (61%) agreed on whether propagation propensity was likely or unlikely. Again, a large number of PSTs suggested high propagation propensity when the ECT suggested otherwise (30%), primarily for deep weak layers where failure did not initiate in the ECT. Only 9% of the comparisons saw the PST suggesting *propUL* while the ECT suggested *propL*.

When the same comparison analysis was conducted on slabs 70 cm and shallower (Table 2), 72% of compared tests agreed on propagation propensity and the number of ECT *propUL* versus PST *propL* comparisons was reduced from 30% to 14%.

Table 1: Comparisons of PSTs and ECTs based on interpretive results suggesting propagation is likely (propL) or unlikely (propUL). Compared tests are from the same snow-pit and targeted the same weak layer.

		PST	
		PropL	**PropUL**
ECT	**PropL**	96 (22%)	38 (9%)
	PropUL	130 (30%)	168 (39%)

Table 2: Comparison of PSTs and ECTs with only slabs 70 cm and shallower included.

		PST	
		PropL	**PropUL**
ECT	**PropL**	77 (32%)	32 (13%)
	PropUL	33 (14%)	96 (40%)

These results confirmed what we had been observing in the field: that where the ECT no longer initiated failures in deeply buried weak layers, the PST was capable of testing deep weak layers that, in some cases, still had high propagation propensity.

To further compare tests, PST results were plotted against ECT results (figure 6). This analysis utilized a one-to-one comparison of PST to ECT results rather than the one-to-many comparison used previously. In other words, the first PST and ECT from a test group were compared, as were the second PST and ECT, but the first PST and second ECT were not, for example. Although this reduced the number of compared results, the trends in the data were still apparent. Percentage of the PST column cut and number of ECT taps were the basis of comparison and four symbols enabled us to distinguish the interpretive results in terms of *propL* and *propUL*.

Most comparisons agreeing that propagation was likely (PP) occurred within the 20-40% cut length range and the 10 to 30 taps range. Additionally, most of the comparisons in which the

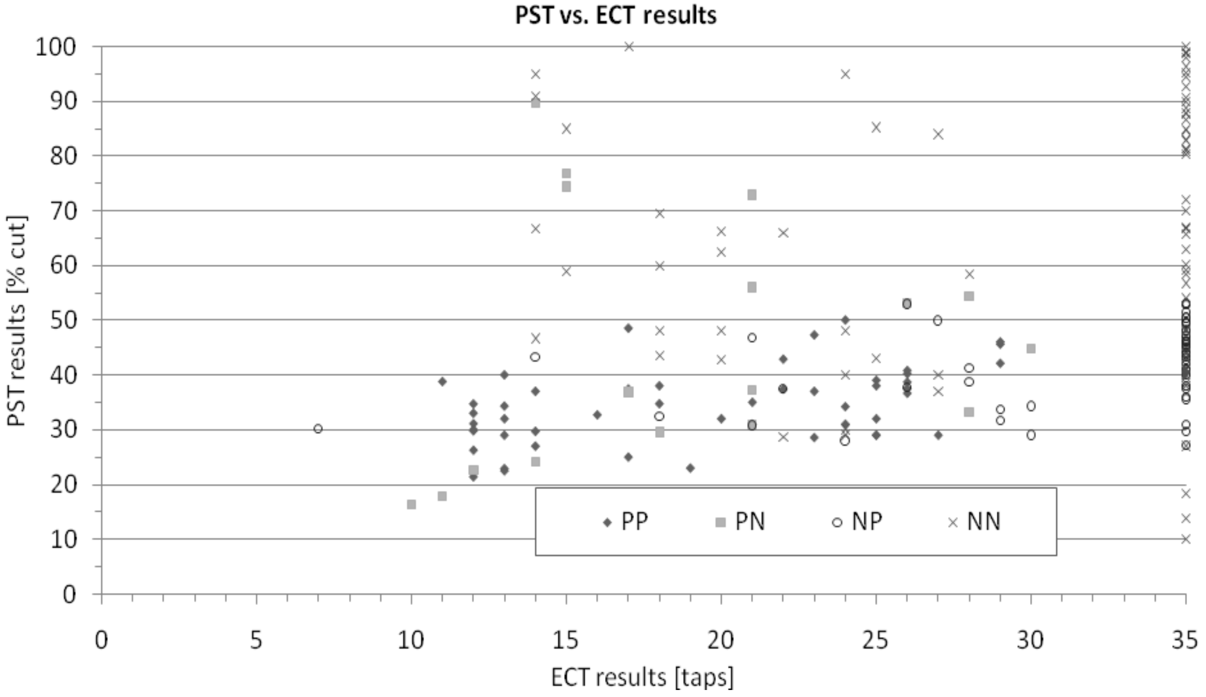

Fig. 6: PST results (% of column cut) versus ECT results (number of taps) compared one-to-one for opposing pairs of tests in each test group (n =203). The data series 'PP' indicate that both tests suggested propagation was likely. 'PN' indicates the ECT suggested propL and the PST suggested propUL, while 'NP' indicates the opposite situation. Finally, 'NN' indicates both tests suggested propagation was unlikely.

PST suggested propL and the ECT suggested propUL (NP) required cuts between 40 and 50%. This coincides with the results presented earlier indicating that deeper weak layers required longer cuts in the PST and were more difficult to initiate in the ECT. The few comparisons in which the ECT suggested propL and the PST suggested propUL (PN) are widely dispersed throughout the range of ECT taps and PST percent cuts.

5. DISCUSSION

Results from 2008 suggest that both the PST and ECT generally agree in predicting propagation propensity for weak layer and slab combinations up to a maximum depth of about 70 cm, after which initiating a failure in the ECT becomes difficult and it can no longer reliably indicate propagation propensity. This was evident from the large number of comparisons in which the interpretation of ECT results suggested propagation was unlikely while the PST was suggesting propagation was likely.

The PST, on the other hand, is capable of assessing deeply buried weak layers where fracture initiation by skiers is rare but in some cases propagation propensity remains high. The PST requires the user to select and identify a weak layer of interest prior to conducting the test, which may present a problem if the user is unfamiliar with the snowpack in the area, or uncertain of which layers may potentially have a high propensity to propagate. In most cases, the layer of interest is obvious within the snowpack, particularly for well preserved surface hoar layers that tend to show the highest propagation propensity. In other cases, a compression test or deep tap test performed first beside the PST site will identify potential layers of interest. The advantage of having to pre-select a weak layer for the PST is for the ability to target specific layers, particularly when monitoring propagation propensity over time. The PST has been shown to provide results indicating propagation is likely in slab and weak layer combinations from 30 cm up to 250 cm deep. For these reasons, the PST may be most suitable to avalanche forecasting teams working within their operating area. In addition, since the PST indicates propagation propensity independent from the ease of initiation, site selection is less critical when testing propagation propensity in a deeper weak layer (70+ cm) that may be triggered in a thin spot.

The ECT has the advantageous capacity to test both initiation and propagation in a single snowpack test, and has been shown here to effectively give consistent results for slab thicknesses between 30 cm and 70 cm, with some propagating results up to 90 cm. Below 90 cm, the stresses transferred from the shovel appear to rarely extend deep enough to initiate fracture in the weak layer. For a recreationalist attempting to assess slope stability in an unfamiliar snowpack, the ECT may be a suitable single stability test that can be performed quickly and provide more information than a standard compression test.

It also appears that both the ECT and PST require minimum slab thicknesses of about 30 cm before propagation can be observed. In the case of the PST, tests shallower than 30 cm seem to most frequently result in slab fractures, while in the ECT, fractures are often initiated but do not propagate. In one case, the ECT was able to show propagation propensity in a shallow storm interface.

We found that PST and ECT results indicate that for prominent PWLs that we selected to test, propagation propensity generally increased as slabs thickened and stiffened, at least to a certain point, after which propagation propensity did not increase, but persisted for much of the winter. Only fracture initiation became more difficult. As slabs thickened under new snow and began to settle and harden, propagation propensity became increasingly dependent on the slab and weak layer`s combined ability to sustain propagation. It is the specific combined characteristics with high propagation propensity that are of most interest to forecasters. In a study on skier tested slopes, van Herwijnen and Jamieson (2007) determined that thicker harder slabs favoured propagation; and that thin, soft, large grained weak layers with large differences in hand hardness between the weak layer and slab were specific snowpack characteristics conducive to propagation. Although we did not explore weak layer variables in detail in this study, similar observations were made relating slabs, and the slab and weak layer combination, to PST and ECT predictions of propagation propensity.

It is important to note that the observations in this study pertain to the typical Columbia Mountain snowpack, and observations may differ substantially in other mountain regions of Canada and the world. Additionally, almost all our data comes from testing persistent weak layers (PWLs), particularly surface hoar and ice crust/facet layers; and rarely from storm interfaces which often fail in other standard stability tests and were even shown to propagate occasionally in the ECT. Two reasons exist for this bias: one is that well defined surface hoar and ice layers are easy to find and follow with the saw in the PST, and the other is that highly reactive layers are more exciting to test.

6. SUMMARY AND SUGGESTIONS

This study attempted to build on the current state of knowledge on how snowpack characteristics like slab hardness and weak layer depth affect propagation propensity through the application and analysis of two emerging snowpack tests aimed at testing propagation propensity. Although numerous studies have examined snowpack characteristics associated with skier-triggered avalanches (e.g. Schweizer and Lutschg, 2001; van Herwijnen and Jamieson, 2007), this is an attempt to utilize the PST and ECT to relate snowpack characteristics to propagation propensity. Consequently, we were able to establish some strengths and limitations of each test for effectively predicting propagation propensity under certain snowpack conditions.

In summary:

- Interpretive PST and ECT results commonly agreed on predictions of propagation propensity in slabs up to 70 cm deep on PWLs, although we have not validated the results with independent observations of propagation in the field.
- Both tests indicated a minimum slab thickness of approximately 30 cm before propagation was observed.
- The PST requires pre-selecting a weak layer which can aid in tracking propagation propensity and testing deeply buried weak layers. This may present an obstacle to inexperienced recreationalists unfamiliar with the snowpack, but may also make the PST more suitable to avalanche forecasters concerned with the propagation propensity of certain layers.
- The PST has been shown to indicate propagation propensity in weak layers buried 250 cm deep, and we have not found a limiting depth to the test.
- The ECT effectively indicated both fracture initiation and propagation in slabs overlying PWLs from 30 cm to 70 cm deep, below which fractures were often hard to initiate. For this reason, the ECT may be particularly suitable for recreationalists familiar with the CT assessing snowpack stability.
- Thicker, stiffer slabs were harder to initiate in both the PST and ECT (longer cuts/more taps) and generally indicated higher propagation propensity.

Both the PST and ECT have been shown to be useful tests in the field toolbox; however, additional evaluation of both tests will help validate their ability for predicting propagation propensity and further clarify the limits in which they perform best.

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