# THE EFFECT OF CHANGING SLOPE ANGLE ON EXTENDED COLUMN TEST RESULTS: CAN WE DIG PITS IN SAFER LOCATIONS?

Karl W. Birkeland[1,*], Ron Simenhois[2], and Joachim Heierli[3]

[1]USDA Forest Service National Avalanche Center, Bozeman, Montana, USA
[2]Coeur Alaska, Juneau, Alaska, USA
[3]Karlsruhe Institute of Technology, Karlsruhe, Germany

Abstract: Avalanche practitioners often assume that weak snowpack layers fracture more easily in steeper terrain. We are typically reluctant to conduct stability tests in safer, gentler terrain because we believe the results may not be reliably extrapolated to steeper areas. However, recent fracture mechanics research as well as propagation saw testing suggest that increasing slope angle has a small effect on fracture initiation. This paper investigates the effect of changes in slope angle on extended column test (ECT) results. We conducted ECTs on slopes in Montana and Alaska where gradual changes in slope angle allow us to sample a variety of angles with minimal changes in snow structure. The slope angles in the Montana datasets range from 7° to 35°, while those in the Alaska datasets range from 30° to 44°. On all slopes the weak layer consisted of buried surface hoar. The results show that the number of ECT taps required to initiate fracture that propagates across the entire column (ECTP) either did not change or increased slightly as the slope angle increased. From a theoretical perspective, this result is in line with the predictions of the mixed-mode anticrack model of fracture propagation in snow. From a practical perspective, our results suggest that, as long as the snow structure remains reasonably consistent in space, observers can conduct dependable tests in gentler, safer terrain before committing themselves to more exposed areas.

## 1. INTRODUCTION

Digging a snowpit can be risky. In order to adequately characterize avalanche conditions, we try to dig pits and conduct stability tests on slope angles steep enough – or nearly steep enough – to slide. This presents a challenge because digging a pit in steep terrain often exposes a person to avalanche danger. Despite our best efforts to be conservative, we sometimes make mistakes. This can result in a frightening case of a person triggering an avalanche while approaching or digging a snowpit (Figure 1).

We dig snowpits in steep terrain because these areas are usually the most similar to

*Figure 1: Collecting snowpit data in avalanche terrain can be dangerous. Two avalanche forecasters triggered this avalanche as they stepped one meter below the snowpit they had finished digging. Luckily, the fracture broke just below the pit, leaving them safely behind but with wide eyes and shaking legs.*

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** Corresponding author address: Karl Birkeland, USDA Forest Service National Avalanche Center, P.O. Box 130, Bozeman, MT 59771, tel: 406-587-6954, email: kbirkeland@fs.fed.us* conditions we expect to find in surrounding avalanche terrain. As Bridger Bowl Ski Area's Doug Richmond is fond of saying, "To know there, go there!" This makes sense conceptually since our goal is to minimize any differences between the snow where we dig and the areas we wish to travel. Further, until recently, most data collected supported the assumption of weaker stability test results in steeper terrain. For example, Jamieson and Johnston (1993) obtained decreasing rutschblock scores with increasing slope angles, concluding that a 10° increase in slope angle decreased the rutschblock score by one step over a range of slope angles from about 22° up to about 45°. However, they qualified their conclusion by noting that natural variability often obscures these effects and they only observed significant trends in ten of 24 sets of measurements. Campbell and Jamieson (2007) had less convincing rutschblock results. Out of nine datasets only two had a significant negative relationship, while one had a significant positive relationship and the other six had no discernable trend. For the compression test, Jamieson (1999) presented data suggesting a decrease of approximately one tap in the compression test score for each 10° increase in slope angle, finding significant trends in seven of 11 datasets.

Recent evidence suggests some stability tests do not show increasing instability on steeper slope angles. Gauthier and Jamieson (2008) report that propagation saw test (PST) cut lengths remain similar, or increase, as slope angle increases. McClung (2009) also collected some data using a test similar to the PST and found critical cut lengths to be less on lower angled terrain. These results are consistent with the anticrack model for avalanche release (Heierli et al., 2008), which predicts that slope angle has a small effect on the ease of fracture initiation, and that fracture is actually slightly more difficult to trigger in steeper terrain. Heierli et al. (submitted; 2010) apply the anticrack model to skier triggering.

In this paper we investigate the effect of changing slope angle on Extended Column Test (ECT) results. The ECT is an increasingly popular test whereby the observer isolates a 0.90 m cross-slope by 0.30 m upslope column and then loads one side by tapping on a shovel (Simenhois and Birkeland, 2006; 2009). Our results show that the number of taps required to initiate fracture in an ECT stays the same, or increases, as slope angle increases. From a practical perspective our results suggest that we can consider placing our snowpits and some stability tests in gentler, safer terrain before venturing into steeper areas. The present paper is a presentation of a portion of the field data used in Heierli et al. (submitted).

## 2. METHODS

### *2.1 Field area*

Our study utilized three different slopes (Table 1). The first two datasets are from the Lionhead study site in southwest Montana, U.S.A.

*Table 1: Geographical location and snowpack characteristics at field sites. θ : slope angle at sample, N: number of tests, h: average slope normal thickness of the slab for all the experiments, Std Dev h: standard deviation of h for all experiments, a: average slope normal penetration of the shovel blade at weak layer fracture for all experiments, ρ: average density of the slab measured at the site of the snow profile, F: weak layer crystal type, E: weak layer grain size. NA = Data not available for that dataset.*

| Dataset | Mountain Range | $N$ | $\theta$ [deg] | $h$ [m] | *Std Dev h* [m] | $a$ [m] | $\rho$ [kg-m$^{-3}$] | $F$ | $E$ [mm] |
|---|---|---|---|---|---|---|---|---|---|
| 1 | Henry, Montana | 26 | 7 - 34 | 0.27 | 0.012 | NA | 178 | Surface hoar | 4 – 8 |
| 2 | Henry, Montana | 30 | 14 - 35 | 0.30 | 0.022 | 0.13 | 182 | Surface hoar | 4 – 8 |
| 3 | Chugach, Alaska | 10 | 38 - 43 | 0.24 | 0.010 | 0.11 | NA | Surface hoar | 6 – 10 |
| 4 | Chugach, Alaska | 18 | 30 - 45 | 0.27 | 0.040 | NA | 161 | Surface hoar | 4 – 6 |

*Figure 2: The Loneliness Shoulder slope in Alaska's Chugach Range, where we collected dataset 4. The area sampled is immediately downhill of the two people on the ridge.*

Located about 10 km west of West Yellowstone, this northeast-facing slope has been used for previous research (e.g., Landry et al., 2004; Birkeland et al., 2006). Slope angles on these two sites ranged from 7° to 35°. The other two datasets are from two slopes in Alaska, U.S.A. near Thompson Pass. Located close to Mile 45 on the Richardson Highway, the first slope is known as Mikey Likes It and the second slope is called Loneliness Shoulder (Figure 2). Slope angles on these two slopes are steeper, ranging from 30° to 45°.

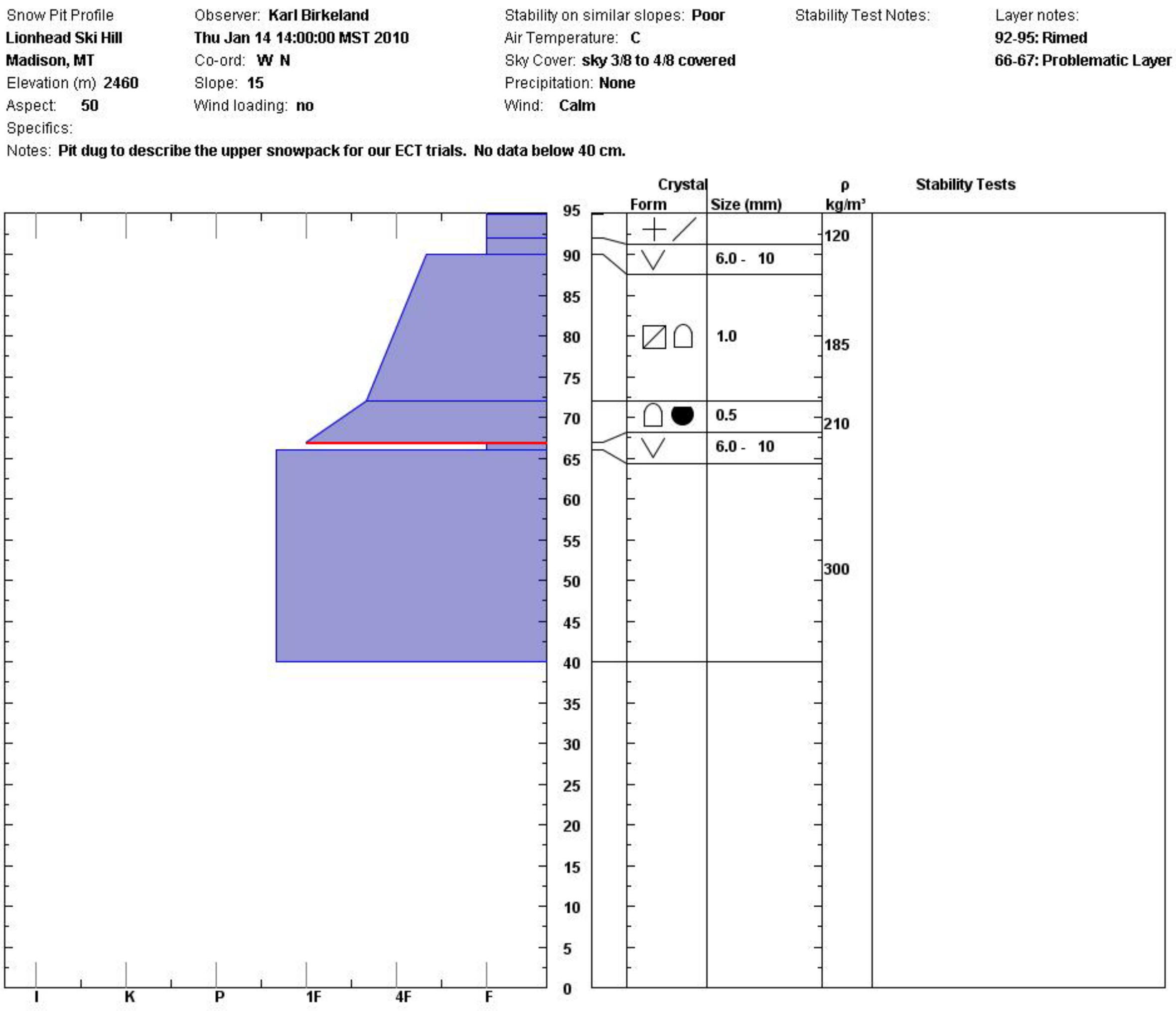
### 2.2 Snowpack structure

The snowpack structure was reasonably similar for all four of our datasets. Average slab depths varied from 0.26 to 0.38 m, with average slab densities ranging from about 160 to 180 kg-m$^{-3}$ (Table 1). In all cases the weak layer of interest consisted of surface hoar varying in size from 4 to 10 mm. We dug one manual pit for each field day following the techniques outlined in Greene et al. (2009) (Figure 3).

### 2.3 Test procedure

A single observer conducted every test in our four datasets for consistency. We followed standard procedure for the ECT (Simenhois and Birkeland, 2009). However, we extended the cross-slope width to twice the slab depth plus the width of the shovel (0.25 m), but no less than the standard 0.90 m. We did this to minimize boundary effects on the test, but did not test even larger samples in order to keep test preparation time reasonable. Prior to each test, we sighted up the snow surface with a Suunto clinometer, measuring the slope angle to an estimated accuracy of ±1°. In most cases tests were immediately upslope, or within a meter, of one another. We did this for ease of testing, as well as to minimize any spatial changes in the snow structure. In dataset 1 we moved about 5 m at two different points to sample gentler terrain that was not significantly affected by trees.

For the analysis we only considered tests that fractured across the entire column on the weak layer of interest on a single tap. This was typically not a problem since all tests we conducted fractured in this manner in datasets 1 through 3, with the exception of two tests in dataset 1 that we did not consider because they fractured on a weak depth hoar layer. Dataset 4 was more challenging because the snowpack contained a second layer of buried surface hoar that occasionally fractured. At this location, 18 of 32 tests fully fractured on our weak layer of interest, and these are the tests we used for our analysis.



Snow Pit Profile
**Lionhead Ski Hill**
**Madison, MT**
Elevation (m) **2460**
Aspect: **50**
Specifics:
Notes: **Pit dug to describe the upper snowpack for our ECT trials. No data below 40 cm.**

Observer: **Karl Birkeland**
**Thu Jan 14 14:00:00 MST 2010**
Co-ord: **W N**
Slope: **15**
Wind loading: **no**

Stability on similar slopes: **Poor**
Air Temperature: **C**
Sky Cover: **sky 3/8 to 4/8 covered**
Precipitation: **None**
Wind: **Calm**

Stability Test Notes:

Layer notes:
**92-95: Rimed**
**66-67: Problematic Layer**

*Figure 3: Manual profile for dataset 2. The upper surface hoar layer around 60 cm comprised our weak layer of interest for this both this sampling day and for dataset 1, which was sampled two days earlier on the same slope.*

## 3. RESULTS AND DISCUSSION

In all cases, the number of shovel taps required for weak layer fracture remained reasonably constant, or increased slightly, with increasing slope angle (Figure 4). For dataset 1, ECTs varied from ECTP12 to ECTP16. Between slope angles from 7° to 28° there is no trend in the data, while the group of tests on slopes from 28° to 34° required slightly more taps to fracture. We collected our second dataset on the same slope and only two days after the first dataset. Our results are again consistent, ranging from ECTP12 to ECTP15. Like the previous dataset, there is a slight tendency toward an increasing number of taps on the steeper parts of the slope. The third dataset covers the smallest range of slope angles (38° to 43°) and is also our smallest dataset (N = 10). Test results were either ECTP12 or ECTP13 at all locations, and no trend in exists in these data. We investigated our steepest slope angles in our fourth dataset, in which a rollover allowed us to sample from 30° to 44°. This is also where we observed the largest range of results, varying from ECTP12 to ECTP22. Here the trend of weak layer fractures requiring additional taps in steeper terrain is more evident. From 30° to 39°, all our results were ECTP14 or below, while all our results from 40° to 44° were all ECTP15 or greater.

Our results provide strong evidence that ECT triggering of persistent snowpack weak layers

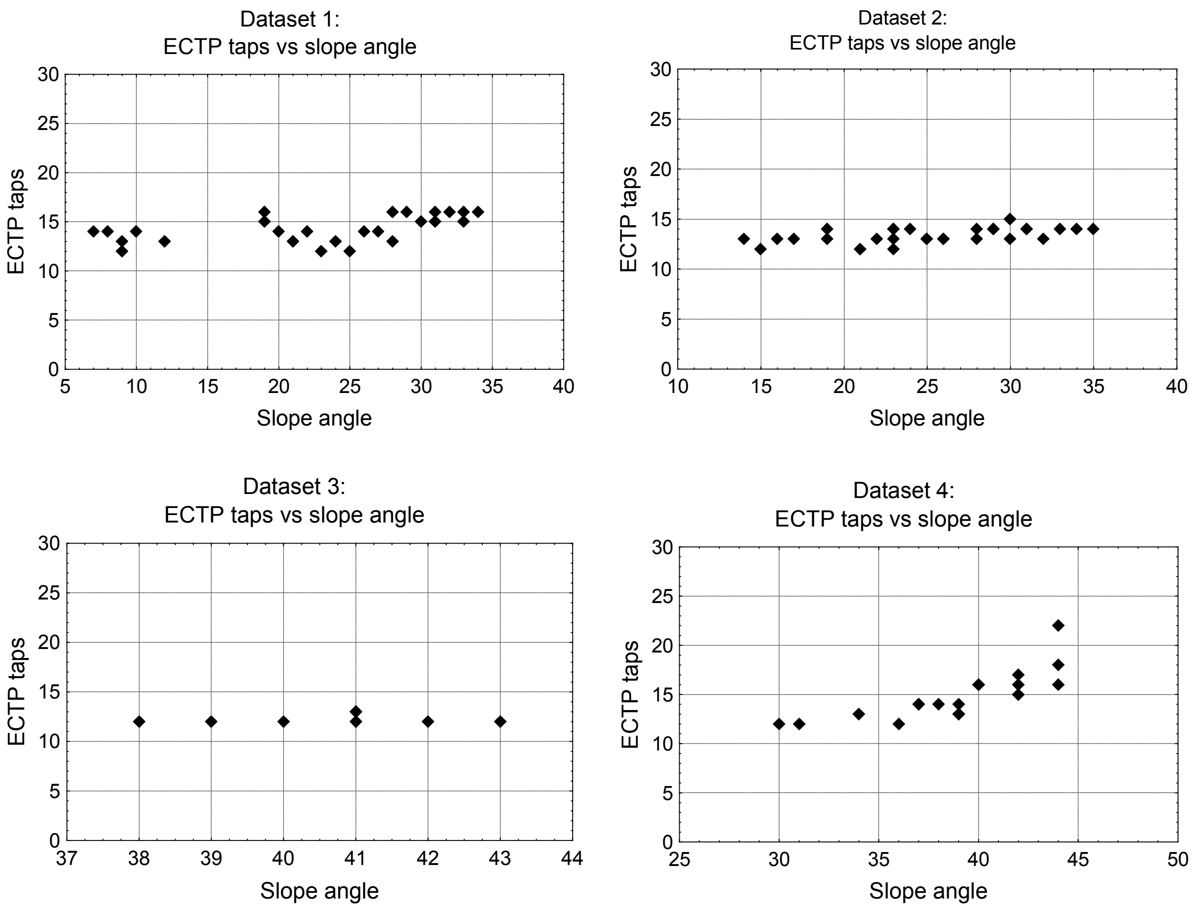


*Figure 4: Scatterplots of ECTP taps versus slope angle for each of our four datasets shows a slightly increasing number of taps required to initiate fracture on steeper slopes.*

such as surface hoar does not vary, or increases slightly, as slope angle increases. This runs counter to some previous work with the rutschblock and compression tests (Jamieson, 1999; Jamieson and Johnston, 1993). However, our results are not inconsistent with other rutschblock research. Of nine datasets collected by Campbell and Jamieson (2007), one had a positive correlation with slope angle (increasing scores in steeper terrain), six had no trend, and only two had significant negative correlations. Our results are also consistent with work on the PST and PST-like tests that show decreasing cut lengths in lower angled terrain (Gauthier and Jamieson, 2008; McClung, 2009).

The results are further confirmed by our work with the Centered ECT (CECT) that we present in Heierli et al. (submitted). The CECT differs from the ECT in that we apply the taps to the tail of a ski located at the center of the block, and the width to each side of the block has to be greater than twice the slab depth. The greater width of the block, and the fact that we are applying the force to the center of the block, helps to further reduce the boundary effects of this test. In our one set of CECT data on changing slope angles, we found that the number of taps necessary to initiate fracture that fully propagated across the entire block increased as slope angle increased, similar to our ECT results (Heierli et al., submitted).

## 4. CONCLUSIONS

Our results have both theoretical and practical implications. From a theoretical perspective, they confirm a prediction of the mixed-mode anticrack model of fracture propagation in snow (Heierli et al., 2008). Indeed, the prediction by this model that fracture should be equally or slightly more difficult to trigger in steeper terrain seemed *a priori* somewhat counterintuitive, but was confirmed by the field data. Finding the answer to this research question motivated our research.

From a practical perspective, our results show that, as long as the snow structure remains reasonably consistent in space, observers can conduct dependable tests on persistent weak layers such as surface hoar in gentler, safer terrain before committing themselves to more exposed areas. Of course, it is still critically important for observers to carefully assess whether or not the snowpack structure in that lower angled terrain is sufficiently similar to the snowpack structure on the surrounding steeper slopes. The bottom line for avalanche practitioners is that being able to conduct at least some initial tests in safer locations has the potential to greatly increase the safety of stability assessments. In conclusion, the answer to the title question is 'yes' if the goal is to collect ECT data on a persistent weak layer such as surface hoar, and the snowpack in the test area is consistent with that on the slopes.

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