THE EFFECT OF CHANGING SLOPE ANGLE ON COMPRESSION TEST RESULTS

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ABSTRACT: Conducting stability tests in avalanche terrain is inherently dangerous since it exposes the observer to the potential of being caught in an avalanche. Recent work shows that such exposure may be unnecessary since the results of extended column tests (ECTs) and propagation saw tests (PSTs) are largely independent of slope angle, allowing for data collection in safer locations. Conversely, some past work shows that compression tests (CTs) are slope angle dependent. In this paper, we test the effect of slope angle on CTs using similar methods as the recent ECT work. We collected field data on three separate days with persistent weak layers in Montana and California. Our slopes exhibited gradual changes in steepness, allowing us to sample a variety of slope angles with minimal snow structure changes. We also employed a second method to reinforce our results. Utilizing the SnowPilot dataset, we analyzed the difference between propagating ECTs and CTs on the same layer, and compared that difference with slope angle. Our fieldwork shows that the CT test results either did not change or increased slightly with increasing slope angle. Further, the SnowPilot data demonstrate that the difference between ECTs and CTs is not statistically dependent on slope angle, reinforcing conclusions from our field work. Our results have significant theoretical implications, but the practical implications are even more important since this work suggests that, in addition to ECTs and PSTs, CTs can be conducted in safer low-angle terrain.

KEYWORDS: compression test, stability test, stability assessment, avalanche forecasting.

1. INTRODUCTION

In March, 2014 a group of backcountry skiers in Montana travelled onto a steep slope to assess the avalanche conditions. Their initial observations indicated unstable conditions, but they moved further down the slope to see if similar conditions existed as it steepened. Tragically, they triggered a slide that killed one person. This accident graphically demonstrates the danger of conducting stability tests in avalanche terrain when conditions are unstable. The consequences of a mistake in these situations can clearly be severe.

Though conducting tests on slopes safe from avalanches will minimize risk to observers, conventional wisdom has been that it is necessary to get into steep terrain to get good data. Recent research on some tests runs contrary that conventional wisdom. For example, Gauthier and Jamieson (2008) and McClung (2009) both show that propagation saw test (PST) cut lengths are similar, or shorter, in lower angled terrain in comparison to steeper slopes. Further, Birkeland et al. (2010) and Simenhois et al. (2012) found that the number of taps required to initiate fracture for extended column tests (ECTs) that propagate completely across the column (ECTPs) is similar or perhaps actually decreases slightly in lower angled terrain as long as the snow structure remains consistent across a slope. This was true for both persistent (Birkeland et al., 2010) and non-persistent (Bair et al., 2012; Simenhois et al., 2012) weak layers.

The compression test (CT) has been used for more than 35 years. Its popularity continues to the present; it was the second most utilized test among SnowPilot users behind the ECT during the 2011/12 winter (Birkeland and Chabot, 2012). Jamieson (1999) found a significant trend in CT test results with changing slope angle in 7 of 11 datasets (64%), and suggested a decrease of approximately one tap in CT score for every 10 degree increase in slope angle. Data collection for this work differed from that with the ECT. The 11 slopes used for the CTs were sampled in two to four locations with varying slope angles, with multiple tests at each sampling location, while the ECT work sampled at multiple (more than 20), closely spaced locations with varying slope angles. Though the CT work runs counter to that with the ECT, the methods differed and the reported

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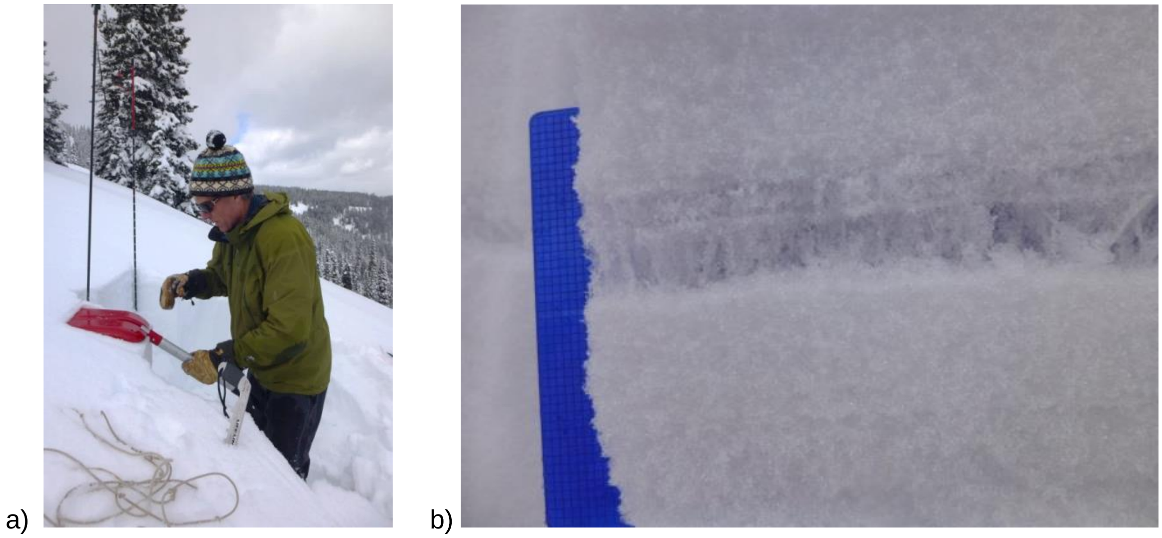

Figure 1: (a) Collecting CT and ECT data (Dataset 1) on varying slope angles at our Lionhead study slope in Montana. (b) Here our tests fractured on a buried layer of surface hoar with crystal sizes ranging from 6 to 15 mm. The grid size on the snow card is 1 mm.

change of one tap for every 10 degrees is small given the potential variability of CT results.

The purpose of this paper is to utilize the techniques and methods of Birkeland et al. (2010) to test the effect of slope angle on CT results. Additionally, we analyze a large amount of data from SnowPilot (Chabot et al., 2004) to compare the difference between ECTs and CTs with changing slope angle. Since ECT results are largely independent of slope angle, the relationship between the difference between ECTs and CTs and slope angle can provide additional information about the slope angle dependence of CT results.

2. METHODS

2.1 Field sites

We used three different slopes for our fieldwork. Our first slope was the same Lionhead study site in southwest Montana that Birkeland et al. (2010) utilized for their ECT study. On this slope we collected 22 side-by-side CTs and ECTs fracturing on surface hoar on slope angles ranging from 17 to 30 degrees (Figure 1). When we tried to access terrain in the low 30 degree range we collapsed the slope and triggered a small avalanche below our study site, attesting to the unstable condition on that sampling day.

Our two other slopes are located in California's Eastern Sierra Range. On these slopes our CTs fractured on depth hoar. We conducted 8 CTs on the first slope with slope angles ranging from 7 to 24 degrees, and 14 CTs on the second slope with slope angles from 0 to 38 degrees.

For this work we specifically sought out uniform slopes. This limited the amount of data we could collect, but we felt this provided optimal datasets for testing the effect of slope angle on CT tests.

2.2 Snowpack structure for field data

The snowpack structure differed between our datasets. The tests in our first dataset fractured on surface hoar buried beneath a recently deposited slab, while the CTs in our other two datasets fractured on depth hoar. The depth hoar for Dataset 2 was dry, while the depth hoar for Dataset 3 was slightly moist (Table 1). We dug one manual pit for each field day following the techniques outlined in Greene et al. (2010).

2.3 Test procedure for field data

A single observer conducted every test in each of our three datasets for consistency. We followed standard procedure for the CT (Greene et al., 2010). Also, at our first slope we conducted our tests side-by-side with ECTs (Simenhois and Birkeland, 2009). 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

Table 1: Geographical location and snowpack characteristics at field sites. N: number of tests, θ : range of slope angles sampled, h: average slope normal slab thickness for all the experiments, Std Dev h: standard deviation of h 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*	*θ* [deg]	*h* [m]	*Std Dev h* [m]	*ρ* [kg-m^{-3}]	*F*	*E* [mm]
1	Henry, Montana	22	17 - 30	0.47	0.012	128	Surface hoar	6 – 15
2	Sierra, California	8	7 – 26	0.87	0.066	NA	Depth hoar	2 – 4
3	Sierra, California	14	0 – 38	0.57	0.040	NA	Depth hoar	2 – 4

this for ease of testing, as well as to minimize any spatial changes in the snow structure.

2.4 SnowPilot data analysis

Because our field data are somewhat limited, we utilized data from SnowPilot (Chabot et al., 2004) to further address our research question. In particular, since previous research suggests that the number of ECT taps is approximately independent of slope angle (Birkeland et al., 2010; Simenhois et al., 2012), testing if the relationship between CTs and ECTs varies by slope angle will give us additional information about the relationship between CTs and slope angle.

In SnowPilot we looked for cases where CTs and ECTs fractured on the same layer and where ECTs fully propagated (ECTP). We had 534 total test pairs on slope angles from zero to 45 degrees. We graphed the data and tested for the existence of statistically significant (p<0.05) linear trends.

3. RESULTS AND DISCUSSION

3.1 Field data

In all three of our field datasets the number of CT taps remained relatively constant or increased slightly with increasing slope angle (Figure 2), paralleling previous work with the ECT (Birkeland et al. 2010). A side-by-side comparison of ECTs and CTs in Dataset 1 shows no trend between the difference between ECTs and CTs and slope angle (Figure 3).

Our results differ from those of Jamieson (1999). We believe the primary reason for this discrepancy lies in our differing methods of data collection. While Jamieson (1999) conducted multiple tests at two to four locations per slope, each of our tests is considered individually and we conducted all our tests in close proximity on relatively uniform slopes with a changing slope angle. A particular strength of our data is the nature of our slopes, which yielded consistent results. The average standard deviation in CT taps for our datasets was just 1.34 (Dataset 1 = 0.83, Dataset 2 = 1.19, Dataset 3 = 1.99). In comparison, Jamieson's average standard deviation was double that at 2.26 (range 0.5-4.0). We believe that our data collection techniques are better able to capture relatively subtle variations in CT scores with slope angle.

The practical implications of our work do not differ much from those of Jamieson (1999). Our work confirms that low angle slopes work well for data collection. Likewise, Jamieson's (1999) conclusion that there may be a 1 tap decrease for every 10 degree increase in steepness means that practitioners can conduct CTs on safer 25 degree slopes rather than more dangerous 35 degree slopes and still expect quite similar results.

3.2 SnowPilot data

A plot of the difference between ECT and CT results versus slope angle shows a great deal of scatter and no statistically significant trend (Figure

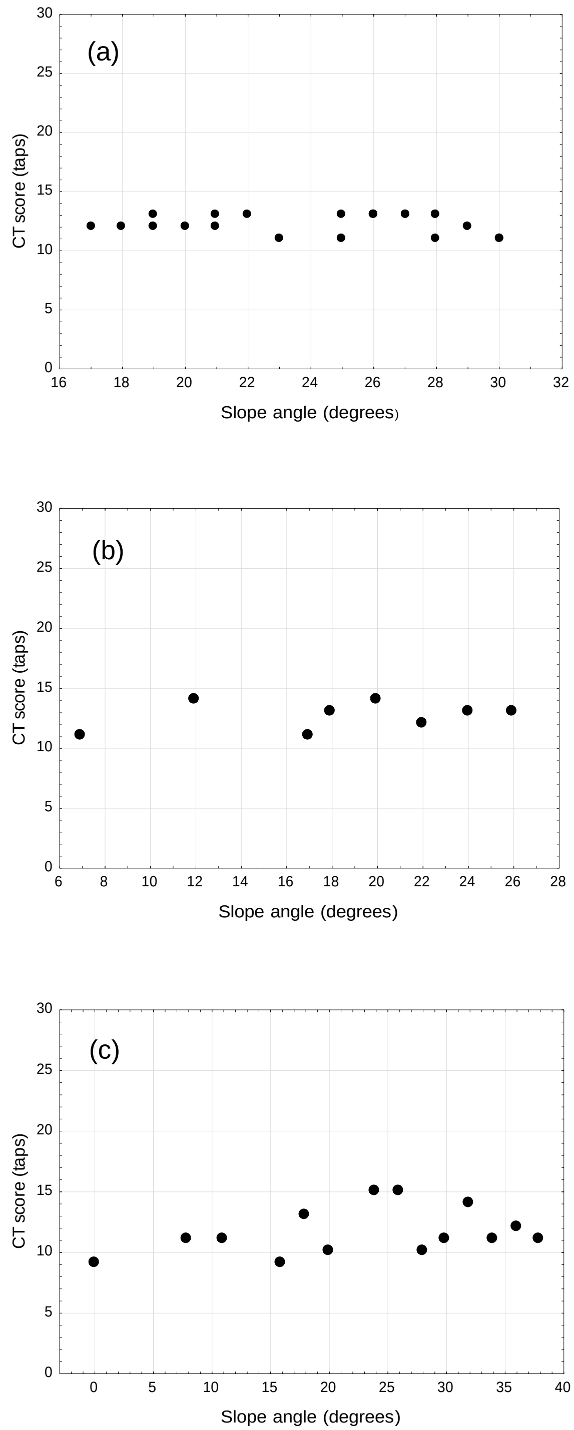

Figure 2: Field data comparing CT results to slope angle for (a) Dataset 1, (b) Dataset 2, and (c) Dataset 3. None of the datasets show a statistically significant trend (p-values: (a) = 0.67, (b) = 0.44, (c) = 0.21).

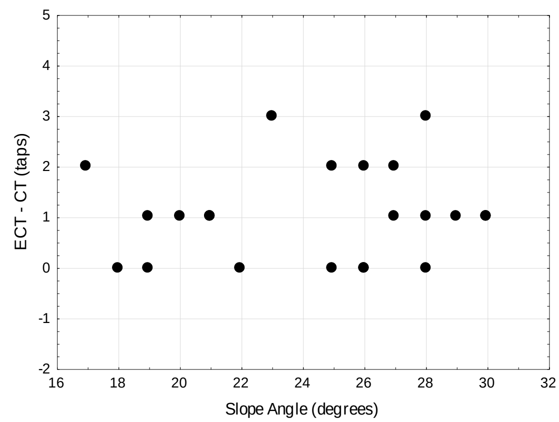

Figure 3: The difference between side-by-side CTs and ECTs from Dataset 1 do not show any statistically significant relationship with slope angle (p-value = 0.64). Throughout the range of slope angles it took between zero and three additional taps to fracture ECTs in comparison to CTs at this site.

4). A least squares linear fit to the data has a slightly downward trend, but it is not plotted since the fit is not significant at the 5% level (p=0.19).

The scatter in these data contrasts sharply with the low scatter in our Montana field data (Figure 3). However, the Montana data were collected on one fairly uniform slope with a well-defined weak layer, while the SnowPilot data represent data from a broad range of observers, snow climates, slopes, slabs, and weak layers. Still, if a relationship exists between the difference between ECTs and CTs and slope angle, we expect that it would be reflected in this large (n=534) dataset.

4. CONCLUSIONS

This research utilized two independent methods to test the slope dependence of CT results. Our first method was field-based and followed Birkeland et al. (2010), and our second method utilized SnowPilot data. Our field data show that the number of CT taps are constant, or increase slightly as slopes steepen. The SnowPilot data reinforce these results by showing that the difference between ECT and CT tests is not statistically dependent on slope angle (p=0.19).

Our results differ from those presented by Jamieson (1999), who found that CT scores decreased slightly as slope angle increased. While Jamieson collected multiple tests from two to four

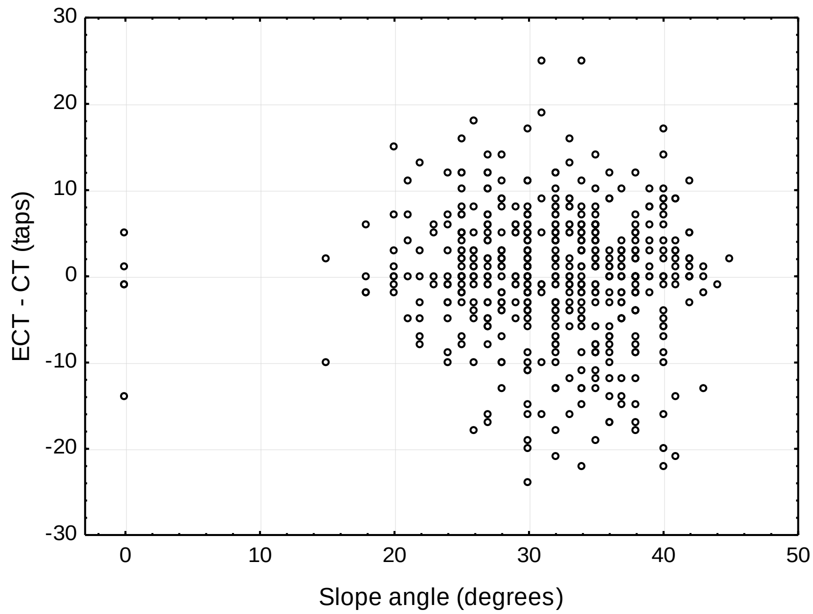

Figure 4: A scatterplot of 534 pairs of CTs and ECTs from the SnowPilot dataset does not show a statistically significant relationship between the difference between ECT and CT results and slope angle (p=0.19). This provides further evidence that CT results are largely independent of slope angle.

locations, we sampled up to 22 per slope and did one test at each location. The slopes we tested had considerably less variation than those tested by Jamieson (1999).

Our results also contradict laboratory tests which showed a decrease in sample strength with increasing slope angle for small (≤ 20 cm in length) samples with weak layers of surface hoar, depth hoar, and facets (Reiweger and Schweizer, 2010; Reiweger and Schweizer, 2013). One explanation for the discrepancy might be a geometrical effect of the CT with changing slope angle. Alternatively, it could have something to do with the difference between methods utilized (lab vs field work and the way the loading method for the snow). Currently, the exact reason for the difference in our results is unclear.

Given that CTs, ECTs, and PSTs all show slope angle independence in their scores (Gauthier and Jamieson, 2008; McClung, 2009; Birkeland et al., 2010; Heierli et al., 2011; Bair et al., 2012; Simenhois et al., 2012), we suggest that crack initiation (measured by the CT), and crack propagation (measured by the ECT and PST) have little dependence on slope angle over the range of angles investigated.

The primary practical consideration of our results is that tests on safer, lower-angled terrain are useful since CTs have similar or perhaps lower scores in lower angled terrain. This result is similar to results previously reported for the ECT (Birkeland et al. 2010) and the PST (Gauthier and Jamieson 2008).

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