WHAT DO LONGER TESTS TELL US ABOUT FRACTURE AND STABILITY?

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ABSRACT: Extended Column Tests (ECT) and Propagation Saw Tests (PST) are used to assess crack propagation; that is, the likelihood of a crack self-propagating. Yet, we present findings that show that full crack propagation to the end of the beam depends on beam length. The practical question is: are beams about 1 m long optimal for assessing stability? Finite element modeling shows that the so called “far edge attraction” becomes insignificant for beams longer than 2 m. In other words, full crack propagation becomes independent of beam length when beams ≥ 2 m are used. To test the accuracy of 2 m tests for stability evaluation, we collected data on 135 side-by-side standard length ECTPs (full propagation) followed by 2 m ECTs. We only focused on ECTPs because we assumed 2 m ECTs would not propagate if standard length tests did not. These tests were preceded by an *a priori* stability assessment to reduce circularity or stability ratings based on test results. Our results show that the proportion of tests in agreement, i.e. ECTP and 2 m ECTP, increase with decreasing stability. We conclude that an ECTP followed by a 2 m ECTP is a clear red flag. The interpretation of an ECTP followed by a 2 m ECTN/X (no propagation) is not clear. The main finding for practitioners is that a 2 m ECT can be used to give additional information about slope stability following an ECTP.

KEYWORDS: stability tests, Extended Column Test, Propagation Saw Test, fracture.

1 INTRODUCTION

Stability tests are one of the most commonly used methods to assess avalanche danger. The concept is to attempt to simulate a small failure that can be correlated to slope scale avalanche danger. Stability tests involve isolating a column or beam of snow, primarily to intensify stress, such that the test will fail before the slope, given similar loads. In this manner, a stability test should be conservative: the test should fail before failure of a slope is imminent. Conversely, if a test fails too often, users lose confidence in its predictive skill.

In previous work (Bair et al., 2014) we showed that in Propagation Saw Tests (PST, Gauthier and Jamieson, 2008a) and Extended Column Tests (ECT, Simenhois and Birkeland, 2009), shorter beams have higher energy release rates for a given crack length. We concluded the higher rates were caused by stress intensification from the far edge of the beam. For beams ≥ 2 m, the energy release rates became asymptotic for typical critical crack lengths r_c. Thus, we suggested that shorter tests could reach the critical energy release rate when longer tests may never reach that critical rate. This size effect could lead to propagation (e.g. PST End or ECTP) in shorter tests, but not in longer tests for identical snowpacks.

When the ECT guidelines were developed, its 0.9 m length was not extensively tested against other beam lengths. When PST guidelines were developed, multiple beam lengths were tested (Gauthier and Jamieson, 2008a). Two cases were identified: 1) tests where r_c depended on the beam length, and 2) tests where r_c did not depend on beam length. The authors noted a transition from case 1) to 2) for beam lengths at 1-3X the slab thickness. Thus, they concluded that PST beams should be the greater of 1 m or the slab thickness.

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2 METHODS

Given our finding that 2 m tests eliminate the size effect on propagation, we tested the accuracy of 2 m tests performed after standard length tests. Tests were performed by avalanche professionals in California, Alaska, Nevada, Montana, and Switzerland. Volunteers were given instructions to record an *a priori* slope stability rating. Information for this rating could come from any source except a stability test done on that slope on that day. This provision ensured that volunteers would not base their stability rating on test results.

The *a priori* stability rating is based on a five point scale: “Very Poor”, “Poor”, “Fair”, “Good”, and “Very Good.” These five choices offer a more detailed assessment of slope stability than the binary “stable/unstable” rating that has been used in previous studies (Gauthier and Jamieson, 2008b; Simenhois and Birkeland, 2009; Winkler and Schweizer, 2009; Schweizer and Jamieson, 2010).

After recording an *a priori* stability rating, volunteers performed a standard length ECT or PST. If the standard length test propagated (ECTP or PST End), a second 2 m long test was performed. If the standard length test did not propagate (ECTN/X or PST SF/Arr), no further tests were done. Since longer tests create less stress intensification at the crack tip, we assumed that if a standard length test did not propagate, a longer test would not either. We tested and confirmed this assumption informally with several 2 m tests following ECTN/X results throughout the winter. Since a 2 m test requires about twice as much excavation as a standard length test, we decided that these guidelines were the most efficient for volunteers with limited time to perform stability tests.

3 RESULTS

We received results from 135 ECTPs followed by 2 m ECTs, but only 10 PST Ends followed by 2 m PSTs. Because of the limited number of PSTs, we did not analyze the PST data. Given our assumption that a 2 m test would not propagate if a standard length test did not, we concentrated solely on analyzing cases where the standard length ECT propagated (ECTP) and then a second test was performed.

There is a trend of increasing agreement between the 0.9 m ECTP and the 2.0 m ECT as stability decreases (Figure 1). Tests in agreement (ECTP and 2 m ECTP) increase from: 0% for “Very Good”, to 10% for “Good”, to 36% for “Fair”, to 54% for “Poor”, to 55% for “Very Poor.” All of the

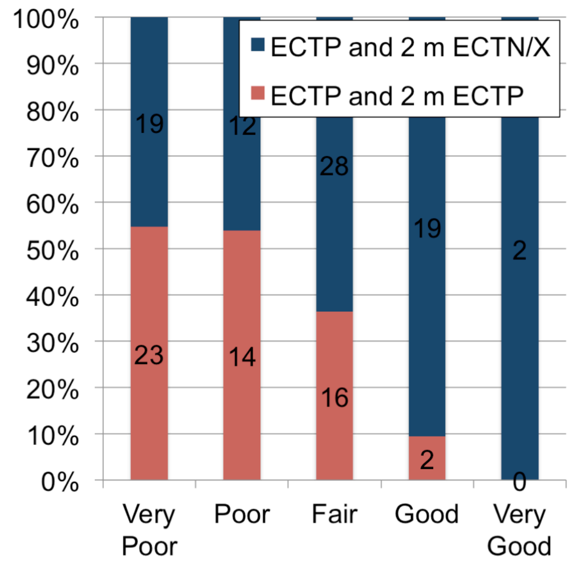

Figure 1 Percentage of standard length and 2 m ECTs in agreement, grouped by *a priori* stability rating. The black numbers in each bar are the numbers of paired tests in each category.

stability classes had more than 20 observations, except “Very Good” which only had 2 pairs of ECTP and 2 m ECTs. Of note is that 41/42 pairs in “Very Poor” came from tests done at avalanches.

The 2 m ECTs took significantly more taps to fail (*t*-test $p < 0.001$, Figure 2). On average, a 2 m ECT (with or without propagation) took 2.8 more taps to fail on the same layer as an ECTP.

Propagation in the 2 m ECTs depended on slab thickness. The median slab thickness (slope normal) was 43 cm for 2 m ECTP but only 27 cm for 2 m ECTN/X (Figure 3). The two groups were statistically different (KS test *p*-value < 0.01).

The average propagation distance for ECTP followed by a 2 m ECTN was about 120 cm, measured from the trigger edge (Figure 4). Thus, cracks traveled about a shovel width further than the standard length tests, on average, in the longer tests that did not propagate.

Other snow profile variables (e.g. slab/weak layer hardness, crystal type, crystal size) did not show a relationship to propagation in the 2 m ECT.

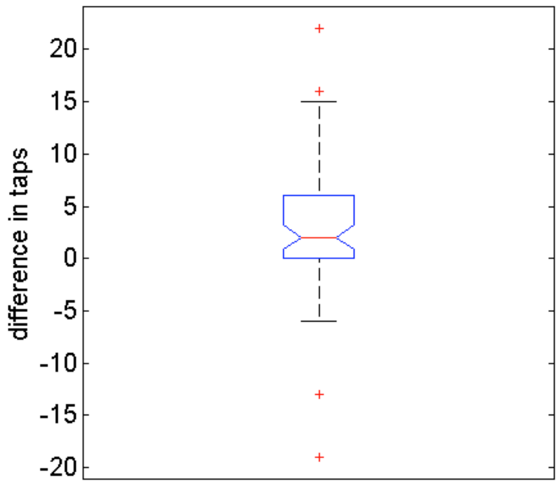

Figure 2 The difference in taps for a 2 m ECTP/N that failed on the same layer as an ECTP. Positive numbers indicate that the 2 m ECT required more taps than the standard length ECT, N=66. Median is red, the 25th-75th percentile is blue, the whiskers are ranges, and the crosses are outliers. The notched area signifies a 95% confidence interval for the median.

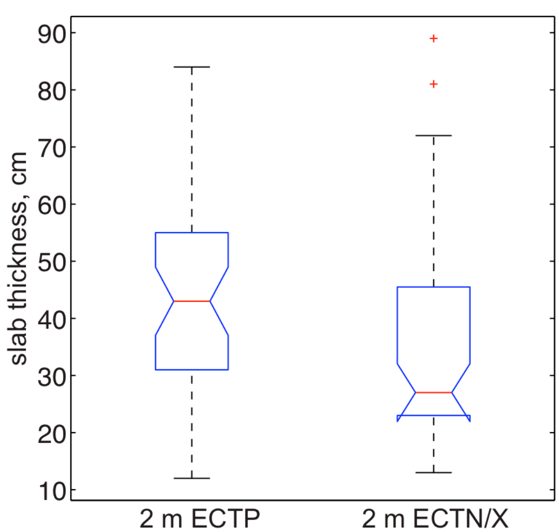

Figure 3 Slab thickness for 2 m tests with (ECTP) and without (ECTN/X) propagation; N=40 ECTP and 49 ECTN/X where slab thickness (slope normal) was measured. The non-overlapping notches indicate statistically different groups.

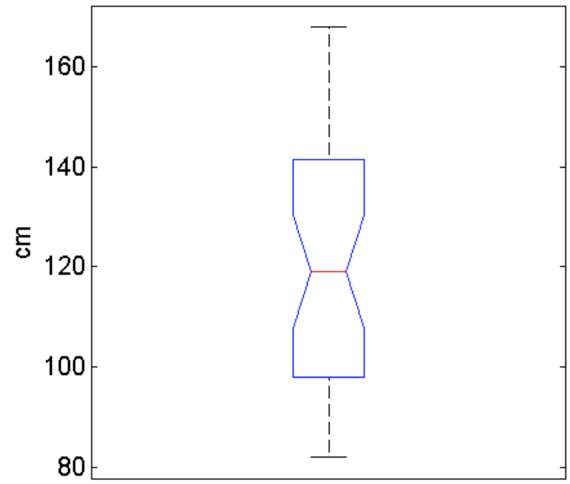

Figure 4 Crack propagation length for 2 m ECTN, following ECTP. Measured from the trigger edge of the beam, N=36.

4 DISCUSSION

As we have already mentioned, we assumed a longer test would not propagate if a shorter test did not, therefore we'd expect 100% agreement between the two tests if the first test result is ECTN/X, given identical snowpacks.

For tests with ECTP, the increasing agreement (ECTP and 2 m ECTP) as stability decreases suggests that propagation in both tests is a clear red flag. We suggest this is a strong sign of instability. The interpretation of an ECTP followed by a 2 m ECTN/X is not clear. Even in "Poor" and "Very Poor" stability, 46 and 45% of 2 m ECTs did not propagate. Also, 2 m ECTs required more taps (Figure 2) and thicker slabs (Figure 3) to fail compared to standard length ECTs.

It's possible that the ECTs in the "Very Poor" category are biased towards a lack of propagation since 41/42 or 98% of the pairs came from avalanche sites. Avalanche sites have disturbed snowpacks that may extend beyond the perimeter of the slab. Additionally, the most unstable snow on the slope has already slid and, especially with weak layers of precipitation particles, the stability can change rapidly. Thus, there are problems with verifying stability tests at avalanche sites. For example, the probability of detection (POD, unstable test/all unstable slopes) of the ECT is reported to be 83-100% (summarized in Schweizer and Jamieson, 2010). Yet, at avalanche accident sites, ECTs propagated 64-75% of time (Figure 5).

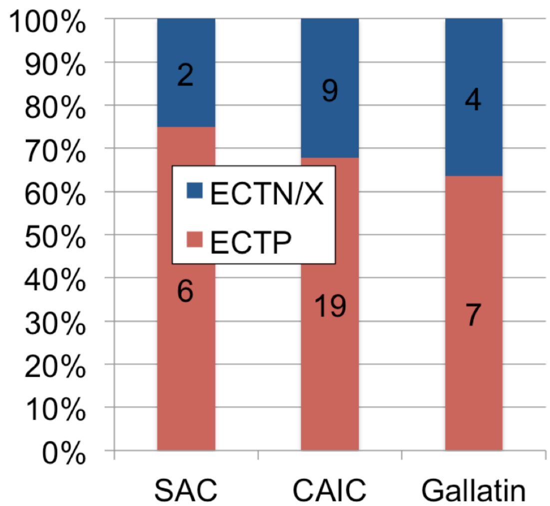

Figure 5: ECTs at avalanche accidents. Data from The Sierra Avalanche Center (SAC), The Colorado Avalanche Information Center (CAIC), and the Gallatin National Forest Avalanche Center (Gallatin).

One reason the longer tests did not propagate as often as the shorter tests may have been that avalanching on that slope was not imminent, even though stability was “Poor” and “Very Poor in general. If this were the case, the test may have been accurate in simulating the failure process (by not failing), but it would have violated the conservative criterion discussed in Section 1. In other words, the test should fail with far less stress than the slope requires for failure.

Another reason the longer tests did not propagate may be because a self-propagating crack in the weak layer of an avalanche is fundamentally different than in an ECT. For instance, one main difference is that ECTs force cracks to travel straight ahead, while cracks likely propagate radially in an avalanche. Also, in ECTs, cracks extend to both sides of the slab and are termed *through cracks*. In an avalanche, cracks are *embedded*; they are surrounded by snow that has not been cracked. In previous work (Bair et al., 2014), we did not observe crack propagation of more than 7 m in an ECT or PST, even in “Very Poor” stability on undisturbed (non-avalanched) slopes. We attempted several 10 m tests that did not fully propagate after we observed full propagation in 7 m tests. Since cracks during the failure of a slope travel much further than 7 m, this observation suggests that long ECTs may not be an accurate simulation of the avalanche failure process. Possibly *pinned areas* (Conway and Abrahamson, 1984), i.e. areas of greater strength in the weak layer, are more likely to arrest fracture in an ECT, while cracks in an avalanche may be able to bridge stress around such areas and continue to propagate.

5 CONCLUSION

Previous work (Bair et al., 2014) showed that standard 0.9 m long ECTs may propagate when longer tests will not because of a far edge effect. Models show this far edge effect disappears for tests ≥ 2 m in length. Thus, we tested 0.9 m ECTs side-by-side with 2 m ECTs, using an *a priori* stability rating for verification. We assumed that an ECTN/X would be followed by a 2 m ECTN/X; thus we concentrated solely on 2 m tests following ECTPs. We made 135 side-by-side comparisons of this situation. Our results showed that the proportion of tests in agreement (ECTP and 2 m ECTP) increased with decreasing stability. Still, even at “Poor” and “Very Poor” stability, 46 and 45% of the 2 m ECTs did not propagate. The 2 m ECTs also required deeper slabs and more taps to fail than the standard length ECTs.

We conclude that an ECTP followed by a 2 m ECTP is clear sign of avalanche danger. The interpretation of an ECTP followed by a 2 m ECTN/X is not clear. The lack of propagation in the longer tests brings up questions about how accurately the ECT simulates crack propagation in an avalanche.

We find that the 2 m ECT gives additional information about slope stability after an ECTP. Yet, we caution potential users that a 2 m ECT may not propagate, even in “Poor” and “Very Poor” stability. Given that stability tests are one of many pieces of information used to assess slope stability, our hope is that the 2 m ECT provides practitioners with an additional tool.

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