

# THE EFFECT OF PROPAGATION SAW TEST GEOMETRIES ON CRITICAL CUT LENGTH

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**ABSTRACT:** Information on failure initiation and crack propagation is essential for assessing avalanche triggering potential. The Propagation Saw Test (PST) is a field test that provides valuable data on the propensity of crack propagation. The first PSTs were performed about 20 years ago and standards have been established. However, there are still differences in how the PST is performed. Standards in North America require the column ends to be cut vertically, whereas in Europe they are typically cut at a normal angle. In this study, we investigate the effect of these different column geometries on the cut length. To this end, we carried out field tests. In total, we conducted 28 pairs of PST experiments, each pair consisting of one PST with normal cut ends and one PST with vertical cut ends. Our experiments showed that PSTs with normal cut ends have shorter critical cut lengths (up to 50% shorter). The influence of the different column geometries on the cut length depends on the slope angle and the slab. We have also developed a model to convert critical cut lengths into both, slab normal and slab vertical PSTs. In addition, we interpret our results with a modern fracture mechanics model that reproduces our measured data. For uniform slabs both models were in excellent agreement. For layered slabs the model predictions suggest that the simplified model also provides a reliable approximation. This study is intended to make practitioners and researchers alike aware of the influence that the geometry of field tests and the slope angle of the field site have on test results. It also shows that only accurately prepared field tests can be reliable and therefore meaningful.

**KEYWORDS:** stability test, Propagation Saw Test, edge effect, failure initiation

## 1. INTRODUCTION

Accurate assessment of fracture initiation and crack propagation is essential to evaluate the potential for triggering avalanches. The Propagation Saw Test (PST) is a field test that provides valuable insight into the propensity of cracks to propagate. Although PSTs have been performed for about 20 years and have been used in various studies (Bair et al., 2013; Bergfeld et al., 2022; Bergfeld et al., 2021; Birkeland et al., 2019; Gauthier and Jamieson, 2008), the lack of widely accepted standards for the PST hinders its consistent and reproducible application across locations and practitioners. Standards in North America require the PST column ends to be cut vertically (CAA, 2016; Greene et al., 2022), whereas in Europe they are typically cut at a normal slope (Sigrist and Schweizer, 2007; van Herwijnen et al., 2016). Most commonly, the weak layer is cut upslope, but in rare cases, the weak layer is also cut downslope from the top.

These geometric and/or methodological differences are likely to affect the results of PSTs. In this study, we aim to investigate the effect of different column geometries and cutting directions on the critical cut length, a major structural property. To achieve this, we conducted a series of side-by-side PST experiments with normal and vertical ends. In addition, we also investigated the influence of cutting direction (upslope or downslope).

The aim of these experiments was to demonstrate the influence of PST column geometry and cutting direction on the critical cut length. We also wanted to explain where these differences come from and how the stratification of the snowpack influence these geometric effects. To this end, we developed a conversion model for different PST geometries and compared it with a validated modern fracture mechanics model (Rosendahl and Weissgraeber, 2020; Weißgraeber and Rosendahl, 2023).

## 2. METHODS

### 2.1 *Field Experiments*

In January and March 2021, we performed field experiments above Davos in the Eastern Swiss Alps, and in Montana, United States. All field sites were around 2400 m.a.s.l. and PSTs resulted in all possible propagation outcomes (slab fracture, crack arrest and full propagation). In Davos, we tested a weak layer consisting of surface hoar (grain size: 2-4 mm),

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in Montana the weak layer consisted of depth hoar (grain size: 1-4 mm). Slab normal thicknesses ranged from 52 to 96 cm.

In total 28 pairs of PSTs were performed, with each pair consisting of one test using slope normal ends and the other with vertical ends. For 6 pairs we additionally performed PSTs in which the weak layer was cut in upslope as well as in downslope direction.

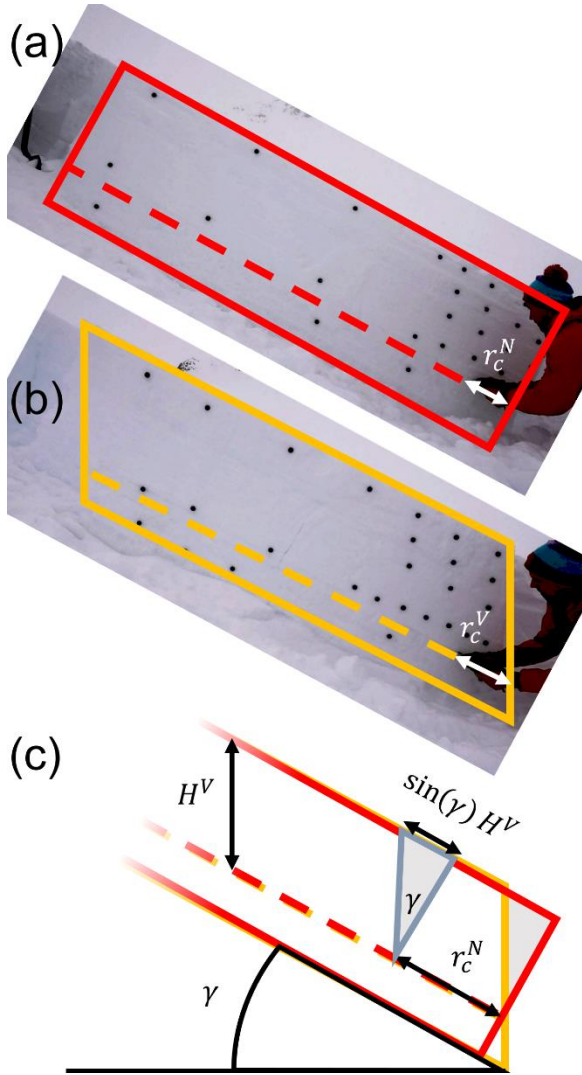


Figure 1: (a) PST with normal ends and a critical cut length  $r_c^N$ . The red outline indicates the PST geometry. The dashed line indicates the weak layer. (b) PST with vertical ends and a critical cut length  $r_c^V$ . (c) Difference in PST geometry. The main difference is the additional slab load for the slope normal geometry shown by the grey triangle.  $H^V$  is the vertical measured slab thickness and  $\gamma$  the slope angle.

For all PSTs, we recorded the critical crack length as  $r_c^N$  and  $r_c^V$  for the PSTs with normal and vertical ends, respectively. We then compute the ratio of both cut lengths  $r_c^V / r_c^N$ . To compare the cutting directions,

we used the ratio  $r_c^{\text{up}} / r_c^{\text{down}}$ , where  $r_c^{\text{up}}$  and  $r_c^{\text{down}}$  indicate the critical cut length measured in upslope and downslope direction, respectively.

## 2.2 Conversion Models

**Load Model.** To find a relationship between  $r_c^N$  and  $r_c^V$ , we assume that the ratio of the crack lengths is inversely proportional to the ratio of the associated slab loads:

$$\frac{r_c^V}{r_c^N} \propto \frac{\sigma^N}{\sigma^V} = 1 + \frac{\sin(\gamma) H^V}{2r_c^N} \quad (1)$$

If the loads are expressed through snowpack properties, the expression on the right-hand side is obtained, where  $H^V$  is the vertically measured slab thickness and  $\gamma$  the slope angle. Other snow and geometrical properties (e.g., slab density, beam width, etc.) cancel each other out. This results in the following model for the conversion between the two critical crack lengths:

$$r_c^V = r_c^N + \frac{\tan(\gamma) H^N}{2} \quad (2)$$

**Mechanical Model.** As a further tool for interpreting our experiments, we used a validated (Bergfeld et al., 2023) closed-form analytical model for layered snowpacks (Weißgraeber and Rosendahl, 2023). This model describes the slab as shear-formable, layered, and allows cylindrical bending, while the weak layer is represented as a layer of smeared springs. We used the model to determine the critical energy release rate from the measured critical cut length, regardless of the geometric configuration ( $G_c^N$  or  $G_c^V$ , respectively). This critical energy release rate, also called specific fracture energy, is considered to be a material property of the weak layer describing its resistance to crack growth. Then, we used the critical energy release rate determined from an experiment with slope normal beam ends to calculate back to the critical cut length of a vertically cut PST. This model is therefore also suitable to convert a critical cut length measured in one PST configuration to another. Compared to the simple loading model (Equation 2), the mechanical model requires many more snowpack properties. However, it represents the specific snowpack layering of a PST and its influence on the critical cut length in a much more detailed manner. We therefore used the mechanical model to check the influence of an asymmetrically layered slab on our load model.

### 3. RESULTS AND DISCUSSION

#### 3.1 *Normal vs. vertical PST ends*

The dataset contains 28 pairs of PSTs, for which we measured critical cut lengths between 14 and 70 cm. Overall,  $r_c^V$  was systematically larger than  $r_c^N$ , on average almost 50 % (colored boxes in Figure 2).

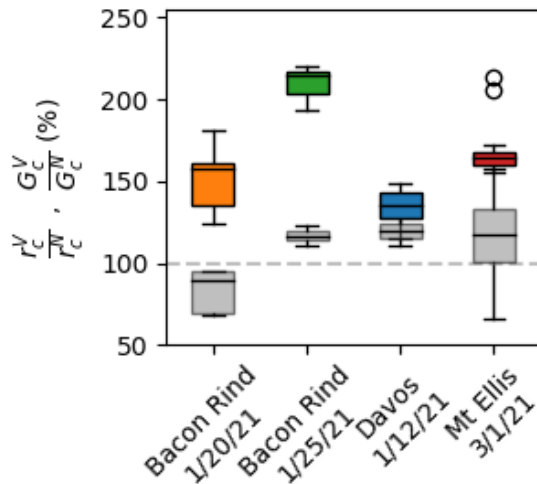


Figure 2: Ratio of critical cut lengths shown as box-plots for the different field days (colored). Ratio of the critical energy release rates computed with the mechanical model using the critical cut lengths of the experiments (grey). Boxes represent the inter-quartile range with the middle line representing the median value. The dashed line represents a ratio of critical cut lengths or critical energy release rates of 1.

Differences in snowpack conditions at the various field sites resulted in different deviations. Median deviations ranged from 136 % to 214 % (Figure 2, horizontal lines in the colored boxes).

These differences can be explained with different PST geometries and the corresponding slab-induced loading of the weak layer. We assume that PST beams were long enough, so that the tail end of the PST beam remains mechanically unchanged when the saw cut is increased and is therefore not relevant. The constellation is as shown schematically in Figure 1c. Even with no saw cut, the normal cut geometry already has an "unsupported" portion of the slab above the weak layer (gray triangle in Figure 1c). This additional load, in normal geometry, generates higher stresses in the weak layer, leading to shorter cut lengths. The differences in critical cut length can thus be explained. However, the extent of the difference depends on snowpack properties.

#### 3.2 *Upslope vs. Downslope cutting*

Beside PST geometry, the cutting direction also affects the critical cut length. For PSTs with normal

ends,  $r_c^{up}$  was about 40% of  $r_c^{down}$  (orange box in Figure 3), while for vertical PST ends  $r_c^{up}$  was about 20% longer than  $r_c^{down}$  (green box in Figure 3). Again, these rather large differences can be explained by slab loading and slab mechanics.

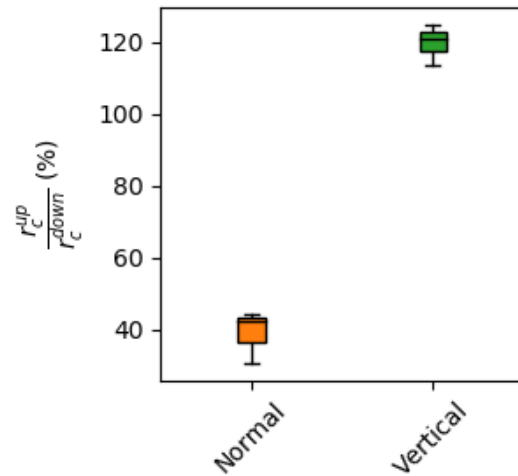


Figure 3: Ratio of critical cut length from PSTs with downslope and upslope cuts. Results are shown for PSTs with normal (orange) and vertical (green) PST ends. Boxes represent the inter-quartile range with the middle line representing the median value.

For a PST with normal ends, when cutting upslope, there is an additional part of the slab that induces an extra load on the weak layer in slope normal direction (Figure 4a, blue area at the right beam end). When cutting from the top, however, a part of the slab is missing, and there is no additional load (Figure 4a, blue area at the left beam end). The critical cut length of the upslope cut is thus much shorter, in our experiments about 60% shorter (Orange box, in Figure 3).

In the vertical configuration, on the other hand, the load over the saw cut is always the same, independent of the cutting direction. The observed differences, however, come from the differences in shear stress at the crack tip. Indeed, at the weak layer, there are two shear stress components: (i) shear stress from the slope parallel gravitational pull on the slab (Figure 4b, arrows in the middle), and (ii) bending induced shear stresses (Figure 4b, arrows at the left and right beam end). The slope parallel gravitational pull is always in the same direction (downslope). The bending induced shear stresses at the height of the weak layer, on the other hand, are always in the cut direction. When cutting from the bottom, both contributions thus have an opposite effect and partially cancel each other out, while when cutting from the top, both shear stresses have the same sign and add up. This results in longer critical cut lengths when sawing upslope in vertical PSTs. In our measurements, these were 20% longer (green box in Figure 3).

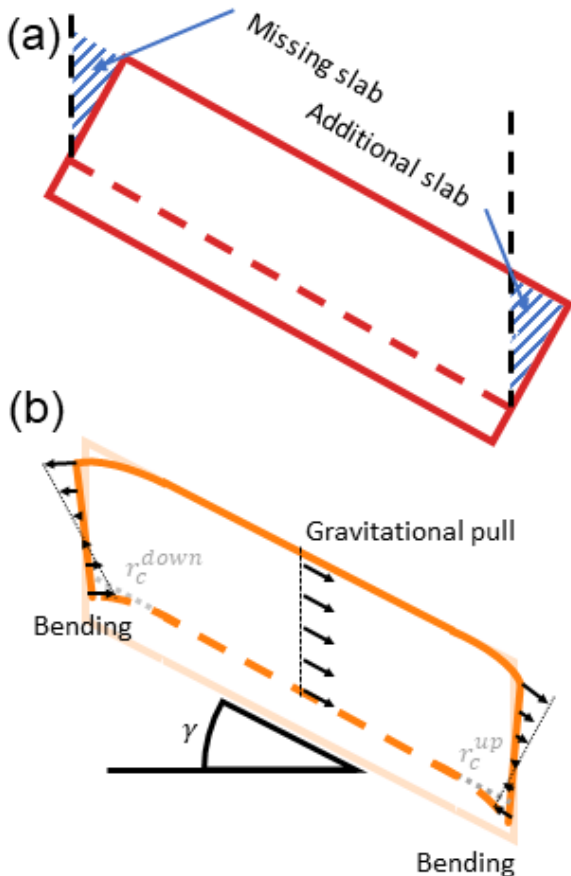


Figure 4: (a) Schematic representation of a PST with normal ends and without a saw cut. The blue marked areas, at the right and left of the PST beam, indicate the additional and missing slab load, respectively, relative to vertical ends (black dashed lines). (b) PST with vertical ends and critical cut lengths  $r_c^{up}$  and  $r_c^{down}$  for upslope and downslope cutting, respectively. At both PST beam ends the saw cut leads to bending, which results in a stress profile across the slab thickness (black arrows). In the middle part of the PST, the black arrows represent stress in the slab due to the slope parallel gravitational pull.  $\gamma$  is the slope angle.

### 3.3 Drivers and mechanical model

With Equation (2) we provide a simple model to convert critical cut lengths between the different PST geometries. Our experiments show very good agreement with the model (Figure 5). The RMSE between the measured critical cut lengths in normal geometry  $r_c^N$  and the modeled counterpart is 4.4 cm.

However, PSTs from 20 January 2021 seem to have a systematic offset (orange dots in Figure 5). We suspect that in these PSTs the beam length was too short, the ratio between slab height and beam length was only about 0.5. It is therefore very likely that the geometric difference at the tail end of the beam was also relevant. Overall, our results thus show that the

PST geometry plays an important role in the measured critical cut length, and this is mostly driven by differences in load from the slab.

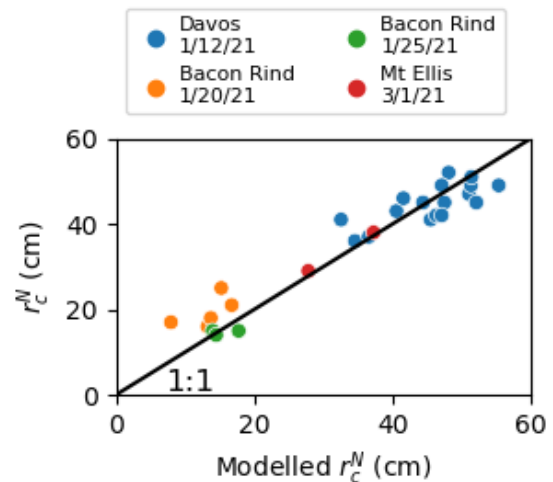


Figure 5: Measured critical cut lengths for upslope cuts with normal PST geometry  $r_c^N$  with the corresponding modelled values, according to Equation 2. Different colors indicate the different field days. The black line is the 1:1 line.

Using the mechanical model to analyze the global energy balance at the onset of crack growth, we derived critical energy release rates from the experimental data. The model considers the layering and geometrical configuration of a PST experiment to determine the critical energy release rate at the critical cut length, i.e., the specific fracture energy. Unlike the critical cut length, the critical energy release rate is a material property of the weak layer and should thus not depend on test geometry. In fact, the determined critical energy release rates, measured in the different PST configurations (vertical or normal beam ends), differed by a maximum of 20% (Figure 2, grey boxes), whereas the deviations of the critical cut length were up to a factor of six larger (Figure 2, colored boxes). This emphasizes that an absolute value of a measured critical cut length can only be interpreted for stability assessment if the applied geometric PST configuration (including slope angle) is considered. In other words, our data show that two equal snowpacks, which should exhibit a similar stability, likely result in completely different critical cut lengths depending on how (including how precise) the PST beam ends were cut and on which slope angle the PST was performed. To ensure comparability of measured critical cut lengths, it is thus imperative to account for the geometrical configuration and snowpack layering, using the models presented here.

Our load model considers a homogeneous slab and gives a tangential slope dependence (see Equation 2 and black line in Figure 6). For comparison, the mechanical model was evaluated for many different

slope angles and 3 different generic slab configurations (Figure 6, top). The mean slab density matched the observed snow cover in Davos. In the asymmetric profiles A and B, additional layers with the minimum and maximum density of the Davos snow profile were inserted. The direct comparison shows a very good agreement between the load model and the mechanical model with a homogeneous slab (compare black and blue lines in Figure 6). The deviations of the critical cut lengths ( $r_c^V - r_c^N$ ) measured in Davos can be reproduced very accurately with both models (Figure 6, red dot).

For highly asymmetric slabs (orange and green lines in Figure 6) there is a deviation between the two models. This seems plausible as the load model does not include slab layering. However, as mentioned above, the difference in crack lengths can be explained by the additional load above the saw cut of a normal cut PST (Figure 4a, blue area). If higher density layers are close to the snow surface, they contribute more to the additional load than if they are deeper in the snowpack. Critical cut lengths are expected to vary more (profile A) or less (profile B) than predicted by the load model.

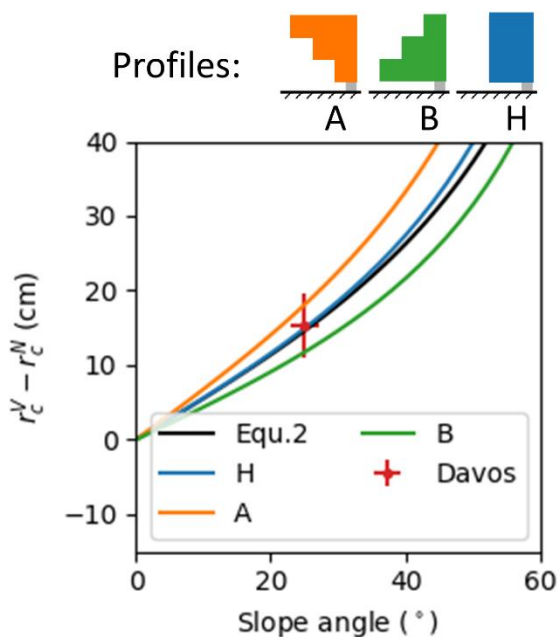


Figure 6: Difference in critical cut lengths with slope angle. The red dot represents the mean and uncertainty of the measurements in Davos. The black line is the load model and the colored lines result from the mechanical model according to different slab profiles given at the top of the figure.

#### 4. CONCLUSION AND OUTLOOK

This work has shown that the result of a PST, i.e., the measured critical cut length, is strongly influenced by the test geometry and cutting direction. PSTs with slope normal beam ends systematically produce shorter critical cut lengths (48% on average). It also makes a significant difference whether the saw cut in

a PST is made in the upslope or downslope direction (deviations up to 60%). Both deviations can be explained mechanically and are largely controlled by the difference in slab induced loads. Based on the slab loads, a simple model was derived which agrees well with the experimental results. The comparison with a more sophisticated validated mechanical model is valid for uniform slabs and shows deviations for layered slabs. Overall, our results show that the interpretation of measured critical cut length in a PST is not straightforward, as it is influenced by weak layer properties (specific fracture energy), slab properties (e.g. layering) and test geometry.

Based on our findings, we suggest that PSTs with slope normal ends should be performed with a saw cut in the upslope direction (Figure 1a). This will ensure that the recorded cut lengths are as short as possible and that the overall test geometry, particularly the column length, has less influence on the test result. However, this has the disadvantage that the effects of slope angle are greater than for vertically cut PSTs. In order to compare tests on different slopes, this effect must be compensated for using the models provided here. For example, recalculation to derive a hypothetical critical cut length of a corresponding flat field PST.

In general, the use of consistent PST standards will ensure that PST results are easy to interpret, will ensure scientific rigor and will improve the comparability of tests and their results. In addition, standardization and conversion models facilitate the comparison of results between researchers, leading to a deeper understanding of snowpack behavior. Practitioners also benefit from standardized methods and interpretation aids that are invaluable in assessing avalanche risk based on stability tests.

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