A FIELD METHOD FOR MEASURING SLAB STIFFNESS AND WEAK LAYER FRACTURE ENERGY

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ABSTRACT: Traditional field measurements, such as snow profiles and stability tests, are widely used to provide information on snow cover stability for avalanche forecasting. Considerable research has been devoted to better interpret these measurements. However, these measurements are rather qualitative, somewhat subjective and the relation to the mechanical properties of snow is unclear. The two main mechanical parameters which influence the initiation of failure in the weak layer are slab stiffness and weak layer fracture energy. Recently, a method was introduced to determine the weak layer fracture energy using finite element modelling. This method requires estimating slab stiffness from digital snow micro-penetrometer measurements. In this contribution we propose a simple field method which can be used to determine the fracture energy and the slab stiffness independently. Using a digital camera to track the displacements induced by cutting into the weak layer in propagation saw tests, the changes in the mechanical energy prior to fracture propagation can be determined. The fracture energy of the weak layer is thus obtained without requiring the elastic modulus of the snow slab. The same method also allows for the separate determination of an equivalent stiffness of the slab by comparing the measured displacement field of the slab with that of a homogeneous and isotropic Timoshenko beam.

1. INTRODUCTION

In the absence of avalanche activity, avalanche forecasters often rely on snow cover observations in order to obtain information on snow cover stability. Traditional field measurements, such as snow profiles and stability tests, provide valuable but somewhat subjective data on snow cover stratigraphy and the ease of triggering weak snowpack layers. The employed methods to analyse these data are mainly empirical or statistical. Usually snow cover observations are compared to observed avalanche activity or estimated avalanche hazard. Thus an empirical relation between test results and avalanche hazard is established. Since a theoretical backing of the test methods is usually unclear, considerable research has been devoted to interpret these measurements, especially with regards to snow cover stability classes (e.g. Schweizer and Jamieson, 2002; Winkler and Schweizer, 2009).

In the following we use a different approach based on a physical understanding of the fracture process in weak snowpack layers (Heierli and others, 2008). Therefore, stability against triggering is not directly tested. Instead, we use a procedure in which the main fracture mechanical properties of the weak layer are measured. In a second step these data are used to model the state of deformation of the snowpack under arbitrary loads. In the simplest case the relevant mechanical properties are the fracture energy of the weak layer and the stiffness of the slab.

In-situ measurements of the mechanical properties of snow are cumbersome and rare (e.g. Föhn and others, 1998). Laboratory experiments on layered snow samples are difficult to perform due to the fragile nature of weak snowpack layers (e.g. Reiweger and others, 2009). A method with many parallels to the present one was proposed by Sigrist and Schweizer (2007), who determined the stifness of the slab material indirectly using a digital snow micro-penetrometer (SMP; Schneebeli and Johnson, 1998). The stiffness thus obtained was used to determine the fracture energy of the weak layer. The method requires to take an SMP measurement in the field and to use finite element modelling to obtain the fracture energy. While this study provided valuable first data, no further results have been published up to now (Schweizer and others, 2010; this issue). We conclude that there is a need for a simple experimental procedure that can be carried out in the field. Such a method is proposed here. We outline how to perform the measurements of the elastic modulus of the slab and the fracture energy of the weak layer independently of each other using nothing more than a standard digital camera.

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2. FIELD METHOD

The present field method is based on the 'propagation saw test' (PST; Gauthier and others, 2008; Sigrist and Schweizer, 2007), with some changes to the size and geometry of the test sample and the test procedure. Before saw cutting the weak layer, 20 to 50 black markers are placed on the exposed side of the sample to visualize the deformation of the slab while saw cutting. The PST is performed and recorded on video using a normal digital camera. A high-speed video camera is not necessary for this experiment, but a relatively fast shutter time and an image size of at least 640x480 pixels at 15 frames per second (fps) are preferable. Using particle tracking velocimetry (PIV) the deformation of the slab can be measured directly on the video images with sub-pixel accuracy. This measurement allows us to determine the average elastic modulus of the slab and the fracture energy of the weak layer with good precision (see section 3).

2.1 Equipment

The equipment required to perform the experiments is:

- Snow study kit to observe a snow profile, including densities.
- Snow shovel, snow saw and a rutschblock cord (optional) to isolate the column of snow.
- A modern digital camera and a tripod to record the experiment.
- Black circular markers which can be inserted like needles into the side of the sample.

The diameter of the markers is very important since measurement accuracy depends on it. For large samples we use black plastic caps (diameter 2.5 cm) with a metal spike attached to the back (about 10 cm long; Figure 1). For small samples we use black nails with a flat head (diameter of about one centimeter). The diameter of the markers on the digital images should be at least 10 pixels. Depending on the resolution of the movie images and the field of view, the minimum required size of the marker disks can be calculated as follows:

$$D\ [cm] \geq 10[px] \times \frac{FOV[cm]}{w[px]}$$

where *D* is the diameter of the marker disk in cm, *FOV* is the width of the field of view in cm and *w* is

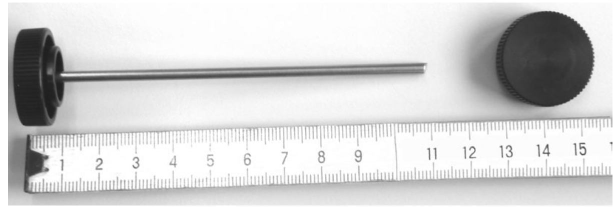

Figure 1: Black markers are used to visualize the deformation of the slab in the videos of the experiment. Shown here is an example of markers we use.

the number of horizontal pixels of the digital movie in pixels (i.e. the width of the movie). For example, for a typical field of view of 200 cm and a resolution of 680 x 480 pixel (*w* = 680 px in landscape orientation), the marker should at least have a diameter of 3 cm. Decreasing the field of view by recording a smaller portion of the column increases the accuracy of the measurements and allows using smaller markers (e.g. nails or large thumbnails). However, there is no disadvantage in using the 3 cm markers for smaller fields of view. For most snowpack conditions we recommend a field of view between 100 and 200 cm and a marker diameter of D = 3 cm for a camera with a resolution of 680 x 480 pixel and D = 2 cm for a resolution of 1024 x 724 pixel.

2.2 Test preparation

The experiments should be carried out under good, even illumination. In order to perform the experiment, isolate a column of snow 30 cm wide, as for a standard PST. However, in order to reduce boundary effects, the test samples are cut longer than the usual 1 m. We recommend a sample length of at least $L = r_c + 2 \times H$, where r_c is the critical cut length (i.e. the cut length at which the fracture starts to propagate) and *H* is the slab thickness. The length of the column should never be less than $3r_c$. A very important difference with the standard PST column is that the down-slope and up-slope edge of the beam must be made slope-perpendicular, not vertical (see Figure 2). This condition is required due to the mathematical method for the analysis. The column should be isolated to a depth below the weak layer being tested.

Before recording the experiment with the digital camera, perform one or two PST's to estimate the critical cut length. Then compute the length L of the sample for the video. In general, r_c only varies only slightly between successive experiments. On the exposed side of the sample

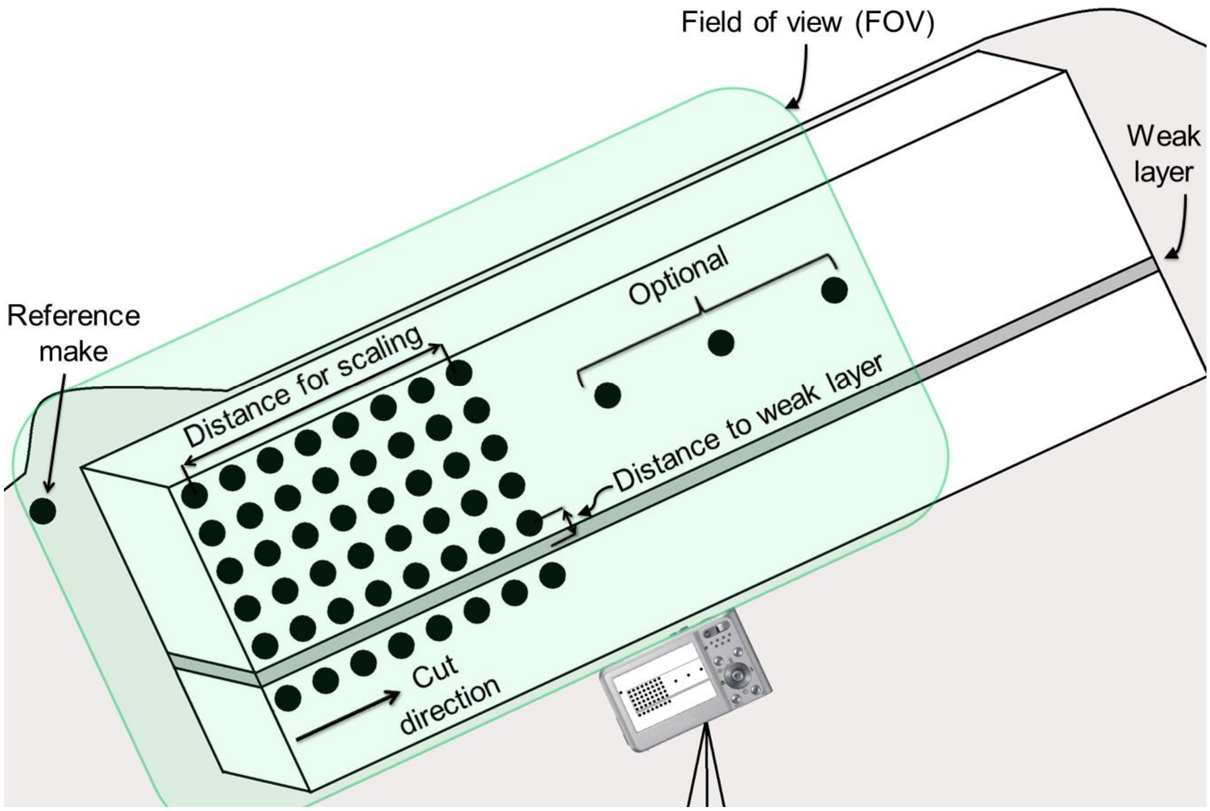

Figure 2: Schematic representation of the experimental setup in the field. Many markers are inserted in the down-slope section of the beam where the saw cut will be made. Additional markers can be placed further in the column. A reference marker should be placed on the snow next to the column. Measure the distance of the bottom row of markers to the weak layer and the distance between the outer most markers in the top row. The camera is mounted on a tripod and tilted parallel to the slope. Not to scale.

insert the markers for the video. Proceed as follows (see Figure 2):

- At the down-slope edge of the column, in a section of the column three times as long as the critical cut length, insert four to five rows of 5 to 8 markers above the weak layer in an approximately rectangular pattern (N.B. there is no need to precisely measure the positions). Thus a minimum of 20 markers (4 rows with 5 markers) are inserted in this section of the column. As always, more is better, but there should be some room between the markers.
- Insert an extra row of markers below the weak layer.
- Place one or two markers on the snow around the exposed column but not in the column itself (e.g. the pit wall on either side of the beam). These markers will serve as reference markers to calibrate possible movements of the camera while recording.
- You can also choose to insert a few more markers further away. If the fracture entirely propagates, these markers will allow for measuring the amount of collapse during fracture propagation and, if the slope is steep enough, the coefficient of friction during sliding.
- Take the camera and, if you can zoom, put the lens in between wide angle and telephoto (about 50-70 mm of 35 mm equivalent focal length). Holding the camera parallel to the slope, step back until you can see all markers in the frame. Place the camera on the tripod facing the exposed side of the column. Tilt the camera parallel to the slope. This increases the field of view of the exposed column, especially on steeper slopes.
- Excavate a small niche behind the down-slope free edge of the column, somewhat larger than the size of the critical cut length. The person who will cut the weak layer will have to stay behind the column so as not to obscur the view or throw a shadow on the sample.

When preparing the experiment, make sure to position the camera at such a distance that all markers are in view. Do not go too far back as the size of the markers would be reduced. Ensure that the camera is in the middle of your field of view and that its optical axis is as perpendicular as possible to the exposed face of the column.

2.3 Performing the experiment and recording the video

After the test column is prepared, take your positions, make sure no shades are thrown on the sample, stand still, start recording the movie and allow the camera to immobilize. Then, a few seconds later, start saw cutting. Do not move around while performing the experiment. Even small jitters from the camera can drastically reduce the accuracy of the measurements, even with reference markers. To perform the experiment, proceed as follows:

- Clearly mark the location of the weak layer with your finger or a crystal card along the back side of the column.
- Insert the snow saw at the down-slope edge of the column with the blunt side facing uphill.
- Slowly drag the saw uphill until the fracture propagates ahead of the saw, at which point stop dragging the saw and mark the point.
- If the saw deviated from the weak layer or if the critical cut length was longer than half the length in which markers were placed, the experiment must be repeated.

We have performed numerous side-by-side tests to study the influence of drag speed on the critical cut length. All our experiments clearly show that the drag speed has no influence on the measured critical cut length. We therefore strongly advise to slowly drag the saw uphill (i.e. < 5 cm per second). This increases the length of the movie, and therefore the number of images that can be analyzed. This in turn increases the accuracy of the measurement.

2.4 Recording experimental parameters

In order to properly analyse the video sequence, several parameters have to be recorded and a full snow profile, including layer densities, is needed. The densities of the all the layers above the weak layer and the first layer below the weak layer are required. Before performing the experiment record the following parameters:

- Average depth of the weak layer (measured vertically).
- Slope angle.
- Length of the test column.
- Average distance between the bottom row of markers and the weak layer.
- Distance between the outer markers of the top row of markers. This distance should be measured as accurately as possible since it will be used to scale the digital images and in turn affect the value of the derived elastic modulus and fracture energy.

After the experiment is performed record the following parameters:

- Critical cut length.
- Note if the fracture propagated through the entire column or if it arrested before reaching the end of the column. If the fracture arrested, try to visually determine how far beyond the saw cut the fracture propagated.

While the description of the test method given here is relatively long, in the field the test does not take much longer than a standard PST test. Once well-organised and familiar with the procedure, it should not take more than 20 extra minutes.

3. ANALYSIS OF THE VIDEO

Particle tracking software is used to analyze the motion of the markers. The instant position of the markers in each video frame can be determined with an accuracy of 0.1 mm or better. By connecting the dots the trajectories of the markers is determined.

In order to determine the fracture energy of the weak layer, the change in the mechanical energy with increasing cut length is determined prior to fracture propagation. This is done by analysing the displacement of the markers during the saw cut. With the displacement field and snow densities at hand, it is an easy task to calculate the work of gravity. Considering the force of gravity as constant, and with no other forces involved during the cut, the mechanical energy equals minus half the work of gravity (e.g. Lawn, 1993). It is calculated for several cut lengths and the result is plotted on a graph. The fracture energy is then obtained by fitting the data and taking the slope at the critical cut length.

In order to determine the elastic modulus of the slab, two methods are used. First, for method A the graph obtained for the mechanical

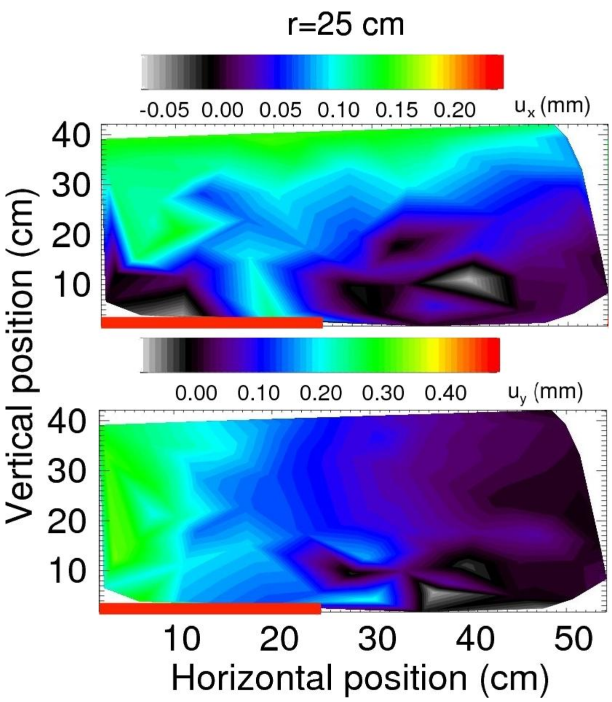

Figure 3: Displacement field for experiment A with a cut length of 25 cm. Upper panel: slope parallel displacement. Lower panel: slope normal displacement.

energy can also be used to compute an equivalent elastic modulus for the slab material (Heierli and others, 2008). Second, with method B the elastic modulus can be determined by finding the best fit of a Timoshenko beam calculation with the measured displacement field. Since the only two physical parameters of a homogeneous and isotropic Timoshenko beam are the shear modulus and the elastic modulus of the material, their values can be found by optimization (least squares).

4. RESULTS AND DISCUSSION

We illustrate the method with one example. We recorded a video of a PST on 12 March 2010 using a camera recording at 77 frames per second. We tested a weak snowpack layer consisting of rounded facets (1.5 to 2.5 mm) at a depth of 47 cm (measured vertically) on a 20 degree slope . The average slab dentisy was 260 kgm^{-3}. The displacement field at a saw cut length of 25 cm is shown in Figure 3. The slope parallel displacement (top panel), which was on the order of 0.1 mm, was largest close to the snow surface, as predicted by the theory. The slope normal displacement was comparatively larger and was close to identical for markers in the same column. The observed displacement field is consistent with elastic

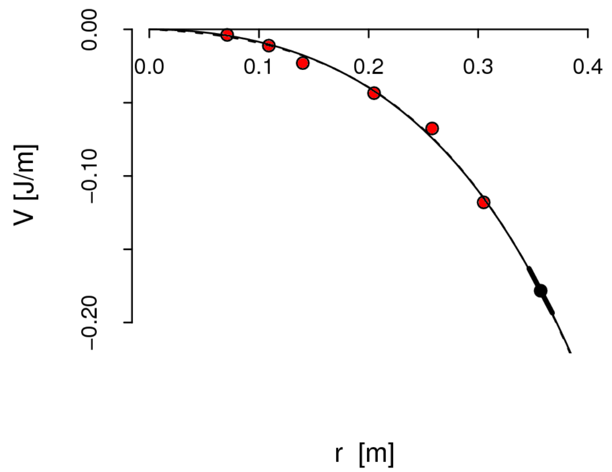

Figure 4: The mechanical energy (*V; red dots*) was calculated for several cut lengths (*r*). The slope of the fitted curve at the critical cut length (black dot with thick line) corresponds to the weak layer fracture energy.

bending of the slab.

The mechanical energy was determined for six saw cut lengths (Figure 4). The fracture energy obtained for this experiment was 1.4 Jm^{-2}. This is substantially larger (one order of magnitude) than values obtained in previous studies (Sigrist and Schweizer, 2007). One possibility is that the weak layers we tested were much stronger. Another possibility is that the previously published results underestimated the fracture energy (see Schweizer and others, 2010; this issue). We note that our method is very direct and does not depend on assumption made to determine the elastic modulus of the slab. The only assumption is that the slab material can be considered linear elastic.

The values for the elastic modulus of the slab for this experiment are 1.3 MPa using method A and 1.6 MPa using method B. For a slab with a mean density of 260 kgm^{-3}, this is within the range of previously published values obtained for homogeneous samples (e.g. Sigrist, 2006), thus validating the method and confirming the linear elastic behaviour of the slab material.

5. CONCLUSIONS

We presented a new, simple experimental field method which is used to derive the fracture energy of a weak layer and the elastic modulus of a slab. No special equipment is required for the field measurements since a snow saw, a bag of markers and a modern digital camera suffice.

The example presented here demonstrates the feasibility of the method. If properly recorded, snowpack displacement can be measured in the field with an accuracy on the order of 0.1 mm using a standard digital camera. The measured deformation of the slab prior to fracture propagation closely matches that of a homogeneous, isotropic and elastic Timoshenko beam. The derived values for the elastic moduli of the slab are comparable to previously published values, inspiring confidence in the method. The derived fracture energy of the weak layer, on the contrary, is considerably larger than previously published values.

Encouraged by the promising results, we would like to invite field workers from the avalanche community to try the method, send us their data for analysis and participate in the subsequent publication of the results. This common effort would enable the fast compilation of a database for diverse snow types and conditions, which for a single research team would probably take many years to compile. We are convinced that this participation will help better understand and predict avalanches in the near future.

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