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INSTRUMENTS AND METHODS

EXPERIENCE WITH SHEAR FRAMES

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ABSTRACT. The shear frame is a simple *in situ* device for indexing the shear strength of thin weak layers. The index is sensitive to shear-frame geometry, rate-of-pull, and shear-frame mass. It is time-consuming to carefully align the device on the *Gleitschicht* (shear failure plane) in a slab avalanche zone. The ratio *shear frame index/shear stress* of the *Gleitschicht* has a high variance, and may not be a fundamental measure of slab avalanche stability. Corrections for the normal stress on the *Gleitschicht* reduce the variance only slightly. Despite these limitations, the shear frame is a useful tool for gathering statistical data on strength distributions and anisotropies of the *Gleitschicht* until a more fundamental technique is developed.

RÉSUMÉ. *Expériences avec jauges à cisaillement.* La jauge à cisaillement est un simple appareil *in situ* pour indexer la résistance au cisaillement de niveaux faibles et minces. L'indice est sensible à la géométrie de la jauge, à cisaillement, à l'impulsion qu'on lui donne, et à la masse de la jauge. C'est une manoeuvre très longue que de placer avec soin l'appareil sur le "gleitschicht" (plan de rupture au cisaillement) dans une zone d'avalanche de plaque. Le rapport indice de cisaillement/effort de cisaillement sur le "gleitschicht" a une forte variabilité et ne peut constituer une mesure fondamentale de la stabilité des avalanches de plaques. Les corrections pour tenir compte de l'effort normal s'exerçant sur le "gleitschicht" ne réduit que peu cette variabilité. En dépit de ces limites, la jauge à cisaillement est un outil utile pour rassembler des données statistiques sur la distribution des efforts et les anisotropies du "gleitschicht" jusqu'à ce qu'on ait mis au point une méthode plus rationnelle.

ZUSAMMENFASSUNG. *Erfahrungen mit Scher-Rahmen.* Der Scher-Rahmen ist eine einfache Vorrichtung zur *in situ*-Feststellung der Scherfestigkeit dünner und schwacher Schichten. Die Anzeige reagiert auf die Geometrie des Rahmens, die Zugrate und die Rahmenmasse. Die sorgfältige Einpassung des Gerätes in die Gleitschicht einer Lawinenzone erfordert viel Zeit. Das Verhältnis zwischen Scherrahmen-Anzeige zur Scherspannung der Gleitschicht ist stark veränderlich und dürfte kein Grundmass für die Stabilität von Schneebrettern sein. Korrekturen wegen Normalspannung in der Gleitschicht verringern die Schwankungen nur wenig. Trotz dieser Einschränkungen ist der Scher-Rahmen ein brauchbares Mittel zur Gewinnung statistischer Daten über die Festigkeitsverteilung und die Anisotropien in der Gleitschicht, bis eine tiefergreifende Technik entwickelt wird.

INTRODUCTION

The shear failure of a snow slab is often confined to a thin layer (<10 mm) known as the *Gleitschicht* in Swiss avalanche terminology. Because of its relative fragility it is generally not feasible to extract a *Gleitschicht* sample from a slab avalanche site and transport this sample to a laboratory for mechanical testing. Another problem is that the strength of the *Gleitschicht* varies significantly over the slab area, typically 100 m × 100 m. In order to determine statistical distributions it may be necessary to test a large number of samples. Both problems are simplified if the measurements can be conducted *in situ*.

An *in-situ* index of the *Gleitschicht* shear strength can be obtained with a *shear frame* (Fig. 1). Despite its many limitations, which will be discussed in this paper, the shear frame at

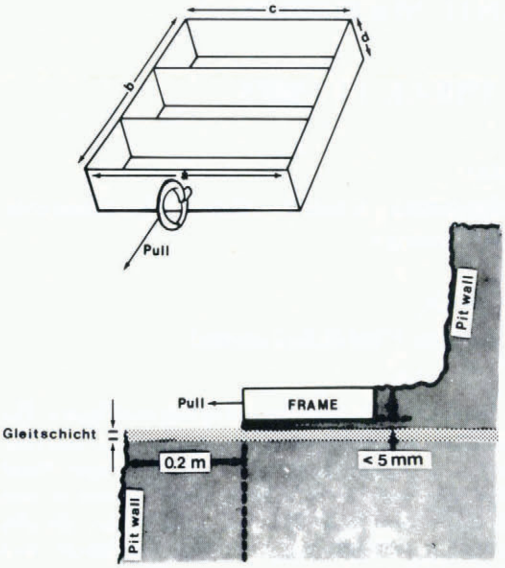

Fig. 1. The shear frame and its alignment on the Gleitschicht.

least provides an index in appropriate units of stress (N/m^2), which is computed by dividing the pull force by the frame area. For the trapezoidal frame (Fig. 1), the frame area is $b(a+c)/2$. In reality, the pull force is not distributed evenly over the "frame area"; on the basis of this limitation alone, it must be emphasized that the shear frame provides only an *index* of shear strength, rather than a fundamental measurement.

The shear frame is used on very thin *Gleitschicht* layers (surface hoar, graupel, recrystallized layers) which would probably be missed in the more convenient ram penetrometer test. Rotary shear vanes (Keeler and Weeks, 1967) can be adapted for testing of thin layers, but these devices also have a complex force distribution over the failure surface due to non-constant strain and strain-rate from rotary axis to vane tips.

Frame design

Roch (1966[a], [b]) experimented with a frame area equal to 0.01 m^2 with $a = 102.5$ mm, $b = 100$ mm, $c = 98.5$ mm, and $d = 25$ mm. This probably represents about the smallest frame area that is practical. Roch selected a trapezoidal shape ($a > c$) to minimize side friction during pull. He kept the d/b ratio relatively small to minimize disturbance when the frame is pushed down into the snow. As the d/b ratio increases there is an increasing tendency for bending stress and tension cracks to form on the shear surface. As d/b increases, there is also an increasing stress normal to the shear surface caused by the snow mass (height d). As discussed later, the shear frame index is sensitive to normal stress. However, as the d/b ratio decreases, the shear stress begins to concentrate closer to the edges, and the index (pull force/frame area) may become even less representative of shear strength. Given these opposing effects, it is not clear that Roch's choice ($d/b \approx \frac{1}{4}$) is optimum.

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Roch's frame included two intermediate fins which are intended to distribute shear stress more evenly, but at the expense of increasing tensile and other disturbances by effectively increasing d/b. It is unknown if two intermediate fins are optimal, or even if the intermediate fins improve performance in preference to adjusting d/b.

Frames may be constructed from aluminum or stainless steel (typical sheet metal thickness 0.5 mm to 2.0 mm). The rigidity of the frame should match the type of snow to be tested as discussed later. The intermediate fins are fabricated from thinner gauge sheet metal (by a factor of $\frac{1}{2}$ to $\frac{2}{3}$) than the outer perimeter which should maintain its rigidity during the pull. Edges are sharpened to minimize disturbance during insertion.

Shear-frame alignment

Alignment on the *Gleitschicht* is time-consuming. As shown in Figure 1, the frame is pushed down into the snow above the *Gleitschicht* so that the bottom edges of the frame are just above (<5 mm), but do not penetrate through the *Gleitschicht*. If the snow above the *Gleitschicht* is "crusty", it may be necessary to precut the shear frame pattern through the crust to minimize disturbance during insertion. As shown in Figure 1, the substratum below the *Gleitschicht* extends forward about 0.2 m. This increases shear rigidity and helps to prevent the failure surface from propagating circularly down from a fin tip, into the substratum, and out through the pit wall. Shear rigidity can also be maintained by pressing a plate against the pit wall, but we found that using the 0.2 m offset was easier operationally.

If the above procedures are followed, and if a weak anomaly does in fact exist at the tested level, then the failure surface should be a plane; the index obtained by dividing pull force by frame area presupposes a plane failure surface. However, even after patient attempts at alignment, a curved irregular surface which propagates from fin tip to fin tip is sometimes observed. This indicates either an alignment error (e.g. fin tip dipping into a stronger layer) or possibly that a stronger, more homogeneous region was encountered.

Figure 2 illustrates two possible orientations for making a measurement at the crown of snow slabs; a *down-slope* orientation, and a *cross-slope* orientation. The down-slope orientation introduces one complication: it is necessary to correct for the gravitational advantages given to the pull force by the combined mass of shear frame and snow (Krasnosel'skiy, 1964). Despite this complication, it may be sounder practice to use the down-slope orientation (and correct for gravity) since deformation on inclined slopes may cause preferential weakening in the down-slope direction. No one yet knows if this is the case for snow, although the effect is considered important in testing soils, clays, and rocks.

Often the boundaries of the *Gleitschicht* are not obvious. For example, the *Gleitschicht* may be either too thin (a single layer of surface hoar) or it may blend into another weakness of total thickness >10 mm. For these cases the shear frame can be aligned *c.* 5 mm above the plane formed by extending the bed surface under the slab crown (Fig. 2). Variance should increase if alignment is based on this alternative.

Size, rate, and mass effects

The shear-frame index is sensitive to the frame construction and the pull-rate. Here is a

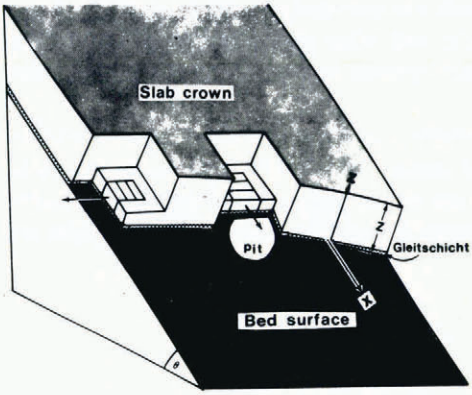

Fig. 2. Cross-slope and down-slope orientation of shear frame at crown of snow slab.

summary of a large number of tests made over a 15 year period at level study plots and avalanche fracture zones:

(1) A frame area 0.01 m^2 is too small to measure indices of low-density, newly fallen snow, and large-grained depth hoar. Repeatability errors on adjacent samples average greater than 10% where snow densities are below about 100 kg/m^3 or where grain sizes exceed about 2 mm.

(2) A frame area 0.05 m^2 is too large for relatively strong cohesive layers where operator pull exceeds 1 000 N, which is about the limit of manual operation. However, the strength index of a *Gleitschicht* will rarely reach that limit (equivalent to 2×10^4 N/m^2).

(3) There appears to be a "size effect" such that the larger the frame, the lower the strength index. In our tests to date, the magnitude of this effect was obscured by statistical scatter (see Perla, 1977, table 3; Stethem and Tweedy, 1981).

(4) A 0.025 m^2 frame area, with $d/b = 0.25$ as suggested by Roch, can be used on a wide variety of alpine snow types. It provides more repeatable measurements than the 0.01 m^2 frame as determined by measuring a surface hoar layer at a level study plot.

(5) The rate-of-pull is difficult to control in manual operation. It appears that the slower the pull, the higher the index. In field practice it is convenient to induce failure within a few seconds by manually pulling on the frame as quickly as possible. We found that decreasing the load rate by an order of magnitude (failure induced in *c.* 30 s instead of *c.* 3 s) increased the strength index by approximately 25%. It is unknown how the index varies at much slower rates.

(6) We compared two frames, each with area 0.05 m^2 and $d/b = 0.25$. One frame had the conventional two intermediate fins; the second, five intermediate fins. The second gave about 15% lower indices.

(7) The shear-frame index of alpine snow varies through at least three orders of magnitude (Perla and others, 1982). To sample this range with a 0.025 m^2 frame it is necessary to use at least three force gauges (e.g. full scale capacity 10 N, 100 N, and 1 000 N) in combination with three frames: a thin (*c.* 0.5 mm) aluminum frame for low density, newly fallen snow (10 N capacity); a thin stainless steel frame (100 N capacity); and a heavier (*c.* 2 mm) stainless steel frame (1 000 N capacity).

(8) Shear-frame indices tend to increase with frame mass. We observed *c.* 10% increase from lightest to heaviest frames tested. This increase is probably related to the normal stress effect (discussed later).

Operator variance

We have no firm data on how repeatability is influenced by change in operators. Keeler and Weeks (1967) have briefly considered how change in operators influences measurements made with a rotary shear vane at a level snow study plot. They found that operator variance could not be separated from "local scatter" (repeatability on adjacent samples).

It is difficult to believe that operator skill and patience are not important in the alignment of a shear frame on the *Gleitschicht* of an inclined slab. In fact, operator variance may be another serious limitation of the shear-frame test.

Strength–load ratios

It is possible to form a nondimensional ratio by dividing the shear frame index (N/m^2) of the *Gleitschicht* by the shear stress (N/m^2) which presumably acted on the *Gleitschicht* at the time of failure. With reference to Figure 2, the shear stress may be approximated as

$$\sigma_{xz} = \rho g Z \sin\theta \tag{1}$$

where ρ is the slab density, Z is the slab thickness, and θ the slab inclination. To date, all measurements (Roch, 1966[b]; Perla, 1977) show that this ratio has too high a variance to be a confident criterion of the slab stability. Sommerfeld (1980) suggests that the larger the frame, the lower the variance, but recognizes that the frame size is necessarily limited (*c*. 0.05 m^2 maximum as discussed earlier), and proposes that the ratio should be based on extreme-value statistics of indices measured with manageable frame areas (*c*. 0.01 m^2 to 0.05 m^2).

However, Gubler (1978) doubts that the failure area tested with a shear frame is representative of the area of initial failure of snow slabs. Irrespective of variance improvement (via operator technique or via statistical analysis) he argues that the shear frame is of questionable utility in stability analysis.

Normal stress correction

Roch (1966[a], [b]) based his strength–load ratio on a shear-frame index that was corrected for the normal stress on the *Gleitschicht*. He used the ratio τ/σ_{xz} where σ_{xz} is computed using Equation (1), and shear "strength" τ is computed using

$$\tau = C + f(\sigma_{zz}, C) \tag{2}$$

where C is the shear-frame index of the *Gleitschicht*, and where f is a function of the snow type, C, and σ_{zz} which is the compressive stress normal to the *Gleitschicht*, computed using

$$\sigma_{zz} = \rho g Z \cos\theta. \tag{3}$$

The function f is determined experimentally at a level study plot by loading the shear frame with various weights. Equation (2) is a Coulomb–Mohr envelope, where C is analogous to the "cohesion" of granular material under zero normal stress, and f is analogous to a correction for friction.

We repeated Roch's test and found that the shear-frame index increased with weights added

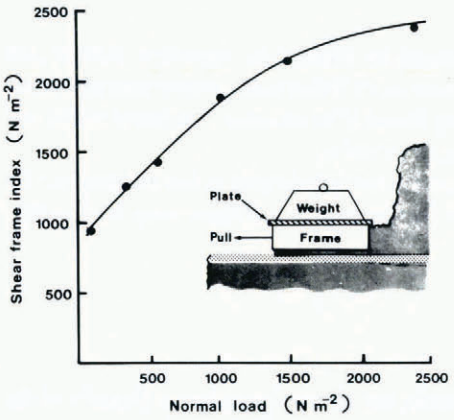

Fig. 3. Typical data which show the increase in the shear frame index with normal load. Each data point is based on the average of five measurements on a layer of partially metamorphosed crystals $\rho = 200$ kg m^{-3}.

to the frame (see Fig. 3). It is not clear how much of this increase can be explained in terms of the Coulomb–Mohr theory, how much is due to inertia since the frame is pulled rather quickly, and how much is due to dynamic resistance after failure (ploughing of granular surfaces) or other peculiarities of the test.

If corrections for σ_{zz} were crucial, then one would expect a significantly negative correlation between the uncorrected ratio C/σ_{xz} and normal stress σ_{zz}. For 35 slabs measured by Roch (1966[b]), the ratio C/σ_{xz} and σ_{zz} correlate with $r = -0.21$; and for 23 slabs measured by Perla (1977); $r = -0.44$. These weak negative correlations show that the normal stress correction is not enough to account for the large variance in the strength–load ratios.

Comments

Although the shear frame has many limitations, no other device has yet been proposed to index the strength of the *Gleitschicht* under adverse field conditions. Interesting future research topics include determination of the spatial distribution of shear-frame indices, and the separation of operator and spatial variances. It would also be interesting to compare down-slope and cross-slope indices of an inclined *Gleitschicht* in connection with strain induced anisotropy.

Ultimately, the shear frame should be replaced by a device that measures a more fundamental index of the *Gleitschicht* strength.

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