SNOWCOVER STABILITY TESTS AND THE AREAL VARIABILITY OF SNOW STRENGTH

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ABSTRACT

This paper describes in a first part the advantages and drawbacks of the following tests: wedge test, shovel test, "Rutschblock-"test, shear frame test. The theoretical background and the pratical value of each test are discussed. Whereas the wedge and the shovel test require smaller shoveling effort than the others, they both are hampered by a bending mode of failure, which is not easy to compensate for. The "Rutschblock"-test, which simulates a basal shear failure by a skier, is shown to be a useful tool for practitioners as long as certain precautions are taken. The shear frame test, which yields together with previous shovel or "Rutschblock"-tests numerical indices for weak sublayers, is a delicate method, which is rather confined to special investigations.

In a second part the paper deals with the representativity of such snowcover stability tests. Recent studies (e.g. Conway and Abrahamson, 1988) claim that a snow slope contains many irregular, small failure spots. Such irregularities would render any snowcover test illusory. In order to illuminate these aspects for Alpine conditions several measuring series (shear frame and/or "Rutschblock") along the peripheries of slabs and across extended slopes that had not avalanched are presented. Although stability variations were found - mainly depending on aspect, underground, terrain geometry and sliding layer depth - the variations were explainable and by all means smaller than the ones reported in previous work. Most of the apparent discrepancies may be explained by a different shear frame procedure and/or by climatological reasons. There are several indications that for a slab release many small or a few large "deficit areas" are needed.

INTRODUCTION

Most techniques used in the past decades to assess snow slope stability, were based on indirect evidence (weather parameters, snow-stratigraphy, ram profiles, etc.) i.e. data from level measuring sites were extrapolated with some interpretative skills to the inclined snow slopes. Because these techniques often did not reveal potential failure planes direct tests of snow slope stability were initiated on inclined snow slopes. The following tests are analysed and compared: Shovel test, wedge test, shear frame test and the "Rutschblock"-test. Because the shear frame test and the "Rutschblock"-test have proven to be the most reliable ones, these two tests have been

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used to control the variability of shear strength and/or the thereof calulated stability on slopes.

STABILITY TESTS

The shovel (shear) test, described by Faarlund (1985) has first been used in Norway and was originally concepted for identification of weak shear layers. Lateron a rough spring balance has been built into the shaft of a clasp shovel in order to measure the effort to separate layers. Because the snow block is not a rigid body of minimal depth y the separating force R shown in Figure 1 is not identical with the force Z measured above. It results a bending mode of failure. If the working point of P is deep (i.e. loose surface snow and stiff layers rather at the base of the block , a usual case), we measure a lower force Z and underestimate the strength of the sample. These aspects have been described by Reinhard (1987) in a separate study. The shovel test is well to detect possible shear failures planes but the strength of these planes (layers) may not be measured properly. The test area is commonly 0.1-0.3 m^2.

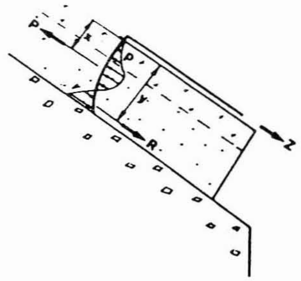

Fig. 1 Section of a snow block pulled by a curved shovel. The pull is denoted by Z.

The wedge test, first described by LaChapelle (1980), is some combination of the known ram hardness test and a shovel test. In an excavated, small trench snow layers are separated by forcing down a relatively large wedge (β= 5-10°, width 0.2-0.3 m), similar to a ram penetrometer. As a separate study of Beer (1985) has shown, the original equation of LaChapelle, yielding a wedge number (W_n) for each gliding layer, had to be corrected for friction losses (large wedge surface) and also for bending modes of failures . The procedure is represented in Figure 2.

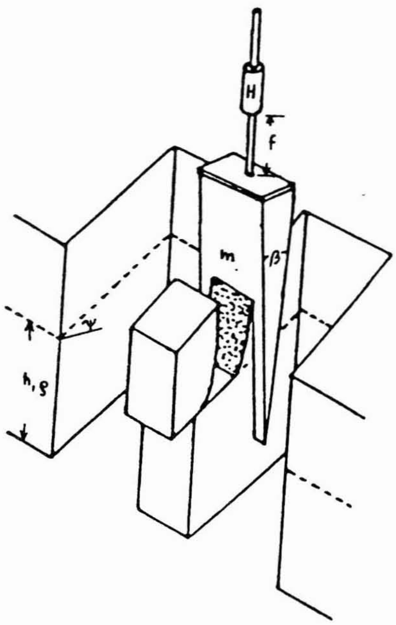

Fig. 2 Sketch of wedge test and notations.

$$W_n = \left(\frac{n \cdot f \cdot H}{p} + m \right) \sin\beta \cos(\psi - \beta) + \frac{h \cdot \varrho \cdot g}{2} \sin 2\psi \qquad (1)$$

where n = the number of blows with the hammer of weight H, f = the fall height, p = penatration depth, m = weight of wedge plus hammer, ψ = the slope angle, β = the wedge angle, h = the slab thickness, ρ = mean density of slab layer, and g = the acceleration of gravity. If one assumes that the last blow is deciding the first part of "Eq. 1" could be written as:

$$W_n = \frac{1}{2\ell \cdot b}\left(\frac{n f H^2}{m p} + m\right)\frac{\cos\beta}{\sin(\psi-\beta)} + \dots \qquad (2)$$

where ℓ = length of snow block and b = width of snow block. As smaller the wedge number W_n, as more likely a failure could occur in a given layer. However the improvement by "Eq. 2" was slight compared with shear frame values. Because the method is time consuming, requires heavy instruments and yields opaque results, it is not recommended for practical work.

The shear frame test, is a well known method which often has been described in detail. Because of size effects a frame area of 0.05-0.1 m^2 is most convenient. Although the placing of the frame and the alignment with each layer are delicate and the rate of pull effects are still a pending problem, it yields at least an index of shear strength. A section of a shear frame, which minimizes bending mode failures, is shown in Figure 3. It is obvious that meaningful measurements are not obtained, if a hard layer tops a thin, weak layer or a weak interface, because of the frame may not be inserted into the hard layer without breaking the weak layer beneath.

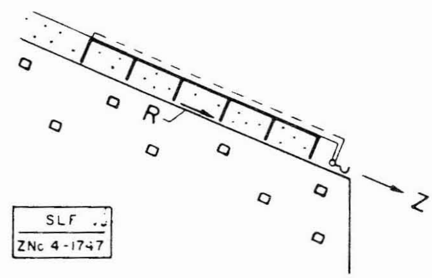

Fig. 3 Section of a shear frame.

Procedures to calculate the stability index S using the shear frame values are described in Sommerfeld (1976). In order to assess additionally the possibility of human triggering an extended calculation procedure of Föhn (1987) may be used, which yields a S' (stability index including human triggering mechanisms).

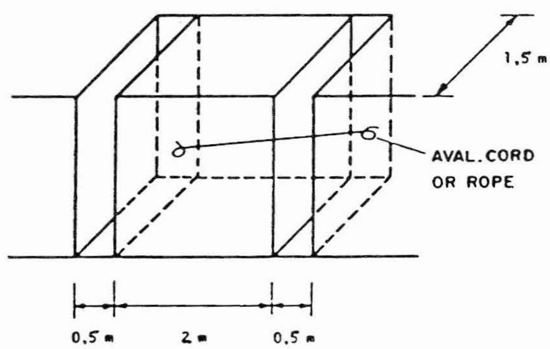

Fig. 4 Sketch of a "Rutschblock" and dimensions.

The "Rutschblock"-test may be rated as a simple and self-consistent field method, which reveals potential failure planes and a qualitative measure of stability, the so-called "Rutschblock"-degree. Figure 4 shows the dimensions of a "Rutschblock". It is also possible to excavate a wedge-shaped block of similar area. The calibration of this method has been described by Föhn (1987). The simple procedure, the large sample area (3 m^2) and the 1:1 scale loading by skier favour this test for all practitioners.

AREAL VARIABILITY OF SNOW STRENGTH

Problem

After settling the question which field methods were best suited to measure an index of snow strength and to derive a stability criterion, we have to tackle the problem where to measure.

It is obvious that during periods of very unstable snowpack any measurements in large avalanche slopes are impossible, then the measurements have to be executed on small, representative slopes, which are much less endangered by terrain reasons. The principle of "substitutional testing"- commonly accepted in material science - comes into debate. Is it also valid under the given circumstances or do we have to rely in future solely on remote sensing methods? At the present time there is too litte conclusive information around to answer this question, however this article shall deliver some arguments.

Literature

In the past the mechanics of slab failure, which are very important in this context, have been viewed in a more general way. The discussion concentrated first on the question if a primary fracture happens in tension or shear. Once this question was rather settled in favour of initial bed surface failures in shear, methods and ways have been searched to measure shear strength or an index of it. Parallel to this slope stability evaluations evolved (Sommerfeld et al., 1976; Perla, 1977) and strain softening effects were debated (McClung, 1979). The situation is best characterized by Perla et al. (1975): "There may be rather widespread shear fractures, or possible slow, progressive straining".

There was general agreement that the strength (or the stability) of some weak interface fluctuates on homogeneous slopes around some mean as other snow properties (snow height, density). In recent times failure initiation processes came into discussion (Sommerfeld and Gubler, 1983) and failure initiation may best be explained by flaws or "deficit zones". Conway and Abrahamson (1984) were apparently the first who reported about measured "deficit zones", which they defined as zones "where the basal shear strength was less than the gravitational shear stress". The known stability index S or, the same thing in another form, the safety margin SM defines such areas:

$$S = \frac{\tau_s}{\tau_{xz}}, \tag{3}$$

or

$$SM = \tau_s - \tau_{xz} \tag{4}$$

where τ_s is the basal shear strength and τ_{xz} the shear component of gravitational load. A basal shear deficit occurs when $S < 1$ or SM is negative.

In the same paper the authors reported high variability of basal shear strength over small distances (0.5 m) and suggested that a critical length for fracturing was reached if such a "deficit zone" was 1 m or even less. In the most recent paper of Conway and Abrahamson (1988) this critical length has been enlarged, namely 1.8 to 7.2 m. To sum up the state of the art: Dry slabs initiate from relatively small zones of deficit, one or a few such small deficit zones are necessary and sufficient for slab formation. Consequently it is very difficult to locate such a deficit with just a few tests.

Nothing has been said so far about the number and the size differences of such deficit zones inside a potential slab area and outside of such an area (e.g. measuring across the crownwall and along the flankwall of released slabs).

Shear frame measurements

In order to verify the above statements in our climatic conditions, we measured last winter in a similar way as Conway and Abrahamson did. Instead of executing shear measurements as earlier over an area of 2-3 m^2 beside a "Rutschblock", we measured in fairly regular intervals across potential avalanche slopes the shear frame index, layer thickness, snow density and slope angle to derive the stability index S and S' (accounting for gravitational load and static loading of a skier). An example of results is given in Figure 5.

In order to decide if the short-scale fluctuation pattern S' may be treated as random process, a nonparametric test, counting the number of iterations V around the median S'=1.73 has been used. The probability function f(v) is according to Kreyszig (1968):

$$f(v) = P(V=v) = 2\binom{m-1}{\frac{1}{2}(v-2)}\binom{m-1}{\frac{1}{2}(v-3)}\Big/\binom{2m}{m}, \quad v = \text{impair} \qquad (5)$$

The letter m signifies the number of S'-values above the median. With a significance level of 5 % the number of iterations is between 6 and 15 in our case (acc. to tables). Because our number of iterations (v = 9) is right in these limits, we may conclude that the measured series are randomly distributed and hence these 20 "point" measurements yield a mean value and a standard deviation, which characterizes this slope well. However more such test series have to be analysed with statistical methods to gain generally valid results.

The two traces of S and S' show fluctuations around the mean as usually (15%≤S.D.≤30%). If we include the two "outliers", the S.D. of S amounts to 38 %, the one of S' to 50 %. These fluctuations are still two to four times smaller than the ones reported by Conway and Abrahamson (1988) for slopes of similar size. Partly this may be due to climatological reasons (stronger winds and hence ripples on snow surface), partly this is caused by the measuring technique. Conway and Abrahamson (1984, 1988) embedded their shear frame (0.1 m^2) on the snow surface and cutted

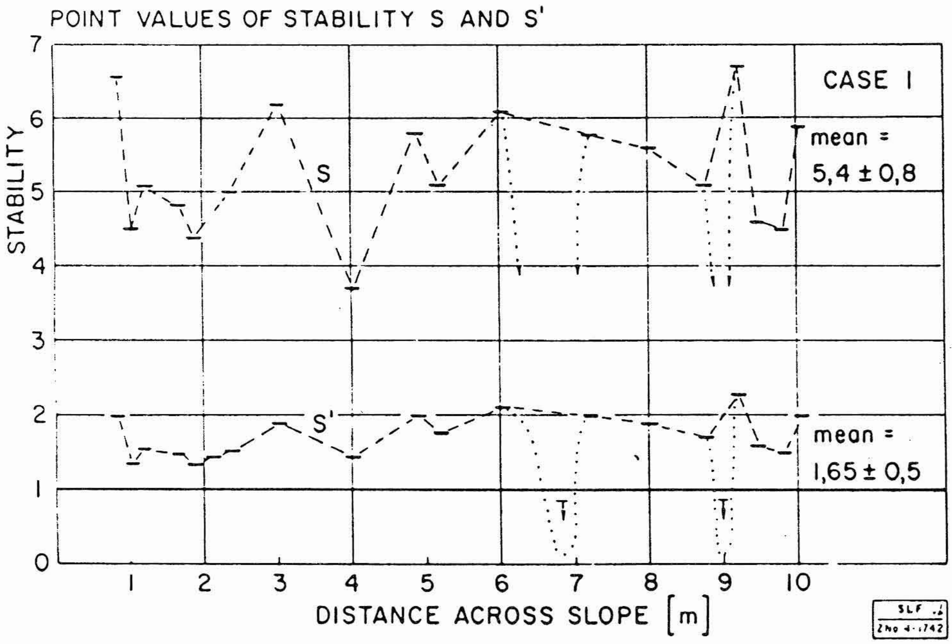

Fig. 5 Point stability S and S' measured across a potential avalanche slope.

with the saw a column around the frame down to the weak basal layer. Sometimes measuring columns of 1.5 m or more, they had a bending mode of failure and depending on the stiffness of the column the measured shear index was more or less too low. Additionally columns that slid during preparation of the sample were assigned an index S less than 1 (≡ deficit area). Embedding the frame and preparing the sample is sometimes such a delicate work that obvious rupturing happens by this handling. In our work such trials have been discarded (cf. "outliers" in Fig. 5). These two special features of their measuring prodecure imply that the variation in stability becomes large and that the snowcover seems to contain many small deficit areas. An argument in favour of our interpretation of "outliers" (when samples ruptured during preparation) is the fact that a slope containing so many "deficit areas" as outliers would have to rupture as a whole by the loading through a measuring team (at least according to the theories of failure initiation process mentioned above). Figure 5 dispays clearly the fact that the natural stability S as a mean has to be well above one when measuring in the centre of a slope which did not yet avalanche.

The present slope did neither fracture with intensive skiing after the shear measuremnts. Indeed the lower trace of S' does not contain along x some "deficit areas" according to our interpretation.

In the course of six winters 110 shear test compaigns have been carried out, which are listed in detail by Föhn (1987). On every slope at least then shear frame measurements distributed over an area of several m^2 have been executed. Only two mean values out of 110 values resulted in a natural stability index S less than one, whereas S' (including human triggering) often was close to one or less than one. All this confirms our interpretation of our "outliers" as "non deficit areas", otherwise we would not have survived 110 field campaigns. Sure, deficit areas as to S may be present on avalanche slopes in a great number but rather at times when the snowpack is so brittle that we can not measure in such slopes.

Figure 6 shows a situation which is different in this respect that a large slab has been triggered by four climbers ascending the slope in a row. The slab and the position of the climbers are marked on the left--side sketch. Some hours after the accident shear frame measurements have been carried out along the crown wall. The thereof calculated mean stability indices S and S' (loading of climber included) are drawn as a function of the crown wall length. The large dispersion of the single values is clearly visible, the pooled standard deviation of S amounts to 33 %. We used the same probabilistic approach of Vanmarke (1977) which has been used by Conway and Abrahamson (1988), to clear the question if the fluctuations were randomly distributed. According to the fast growing variance function Γ^2 they are not. This function is defined as:

$$\Gamma^2 = \frac{var\,\tau_{sL}}{var\,\tau_{so}} \qquad (6)$$

where var τ_{sL} and var τ_{so} are the variance of shear values averaged over length L, and the variance of "point" measurements respectively. The averaging process of τ_s over increasing length L diminishes the function Γ^2 not in a way as random values would do. The values are dependent or areally correlated and we have to assume that the values at point E - well above the median S = 3.5 - represent a socalled "pinned area". Again we see that all values of S are well above the limit of one, which would imply a possible natural release of the slab. The additionally assessed stability index S' indicates that at least four spots of the crown wall were "deficit areas". If we link the "deficit areas" left and right of the upper slab triangle (cf. Fig. 6), we see that three bands of deficit would result, where the climbers could have triggered the slab.

Because this is a typical lee-side slope, the pattern of wind accumulated snow could have some bearing on shear strength and stability. As Föhn and Meister (1983) pointed out, we have to expect behind crests a snow depth crossprofile in the form of a damped sine wave. Looking at the slab depth data, we find at the points in the deficit areas (dotted areas) 30-40 % lower slab depth values than in the areas in between. Areas of low snow or slab depth seem to be areas of low shear strength, the same holds naturally also for tensile strength.

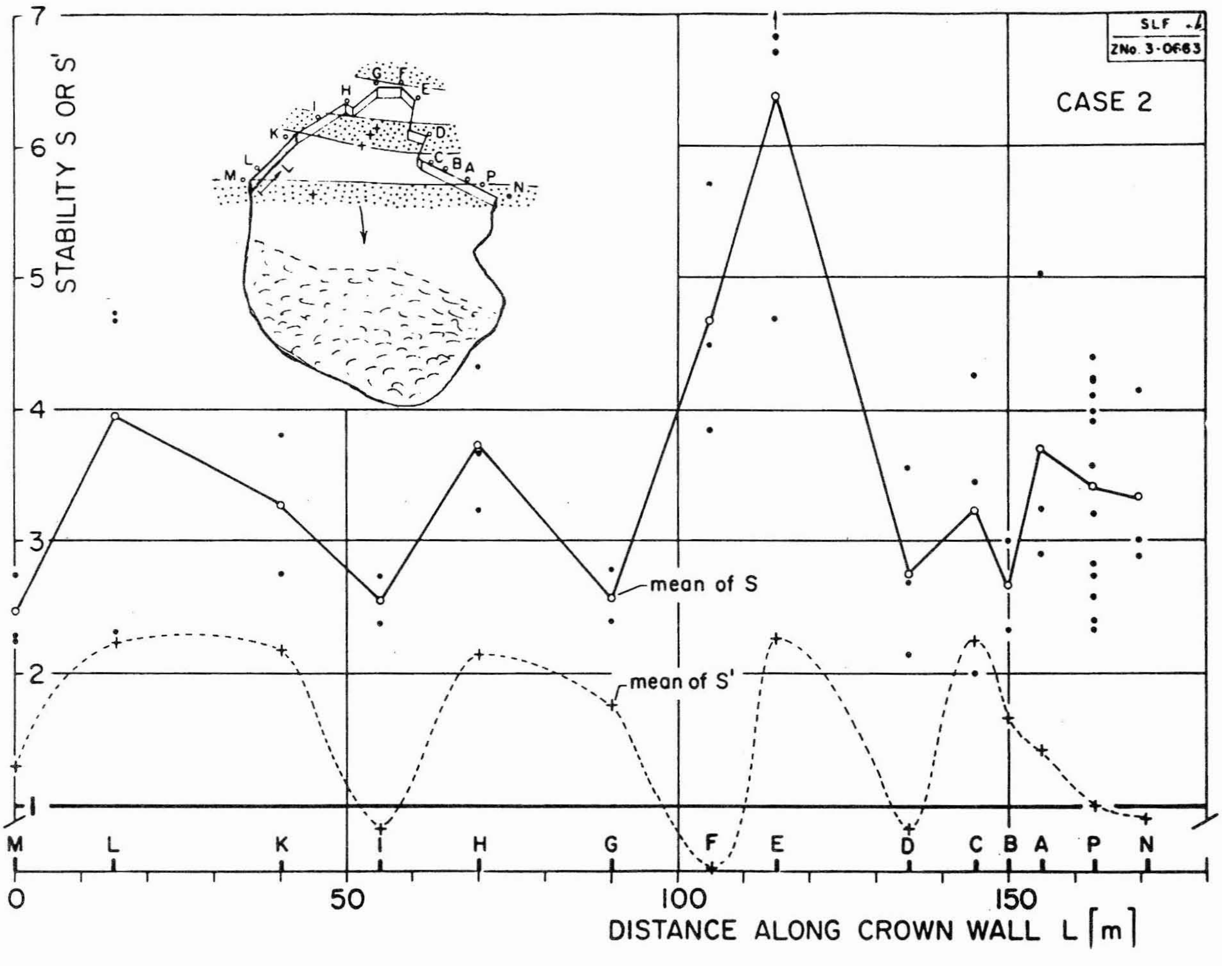

Fig. 6.Mean values of S and S' along a triangular crownwall.
Slab has been triggered by 4 climbers.

A separate study about the areal variability of various snowcover parameters of König (1988) shows that variability of the shear frame index and the stability index has the same order of magnitude (mean coefficient of variation: 15.6-19.3%) as the other snowcover parameters (snowdepth, depth of slab layer, density of slab layer, ram res~~t~~istance).

"Rutschblock"-series

For pratical purposes it is most convenient to assess the slope stability by "Rutschblock"-tests. Föhn (1987) has calibrated this method against the stability index S':

$$Y = a + b \cdot S'^{1/2} \qquad (7)$$

where Y signifies the "Rutschblock"-degree (1-7), and a = -2.52, b = 5.91. With the aid of this equation, the two methods may be transposed.

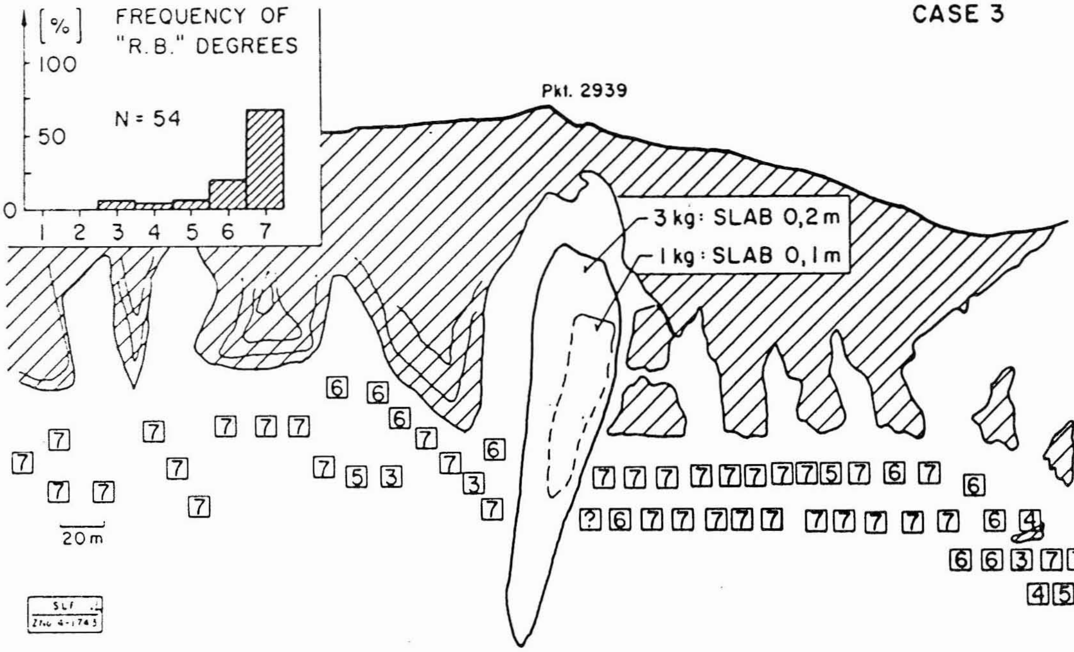

Fig. 7 Large slope where the variation of stability has been assessed by "Rutschblock"-degrees. After the measurements the slope has been skiied and tested for ultimate strength by explosives (1 kg Plastex in air, then 3 kg).

In order to verify the variability of snow strength (stability) on large avalanche slopes at the same time interval, this type of test is ideal. Additionally it is well known by the avalanche unit of the Swiss Army. On a given day about 100 "avalanche"-soldiers have been commanded to execute "Rutschblocks" at prefixed spots. The N-facing, steep (32-44°) slope and the position of these tests are given in Figure 7. The R.B.-degree is quoted on the rectangular spot. R.B.-degrees between 1-3 signify stability levels (S') lower than one ("deficit areas"), degrees 4 and 5 a stability between one and two and degrees 6 and 7 mean higher stability ("pinned areas"). This glacerized slope, almost 300 m wide and 200 m long shows a homogeneous pattern of stability. The three single "deficit areas" which resulted in a R.B.-degree 3, showed only a loose sliding layer of about 0.2 m at the surface, which usually may not be assessed as real slab layer. At the right side, where rock outcrops existed and left to the larger slab there were small areas of metastable snowpack. The intensive skiing after the tests and the two explosions executed afterwards, which only resulted in sliding of a small surface layer, show that the whole area was essentially "pinned". Flaws or "deficit areas" seemed not to exist between the test locations, otherwise the explosions would have triggered there a deeper slab.

Figure 8 shows a smaller, NW-facing slope (60 x 80m), whose stability pattern is more complex. Beside well "pinned areas" we have sandwiched metastable zones and one "deficit area" at the lower left side of the slope. Despite the fact that (according to the relative frequency diagramm) the majority of tests were in the metastable range, intensive skiing and an explosive charge of 1.5 kg could not trigger a slab. This case 4 suggests that for a metastable snowpack the number or the size of "deficit areas" has to be much larger for having widespread fracturing.

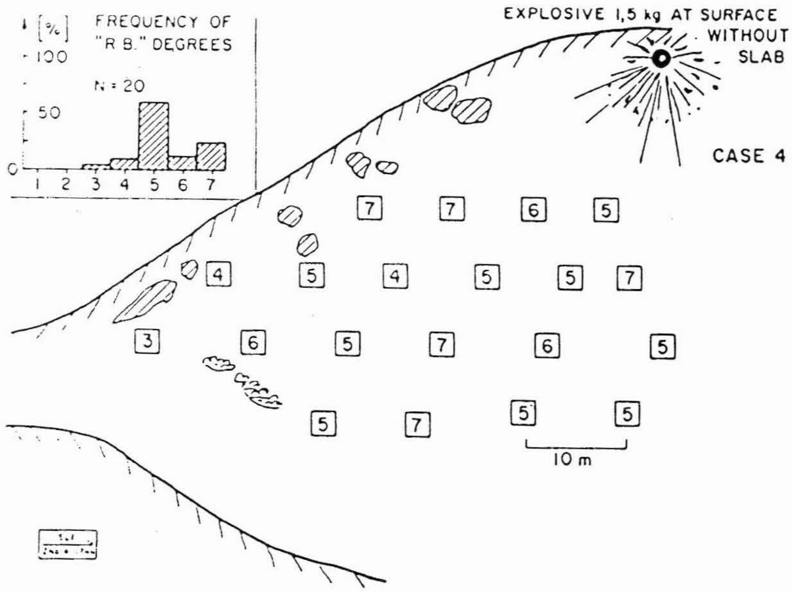

Fig. 8 Small slope where the variation of stability has been assessed by "Rutschblock"-degrees. Finally the slope has been skiied and tested with explosives without positive result.

Figure 9 yields a summary of all tested slopes with various aspects. From the relative frequency diagramms faded in on Figure 7 and 8 one may see that the distribution functions of the R.B.-degrees are not of Gaussian type, they are bimodal and more or less skewed to the right or to the left. Therefore nonparametric statistics have been used to represent the data of the five slopes. The thick line in each box represents the median, the box ends the upper (75%) and the lower quartile (25%) and the dashed line with the horizontal end line the upper and lower adjacent values. Outside values are marked with an asterix. Using decimal fractions, the medians are, with one exception, between 6 and 7 and the values are almost all "on the safe side". "Deficit areas" are on all slopes very scarce.

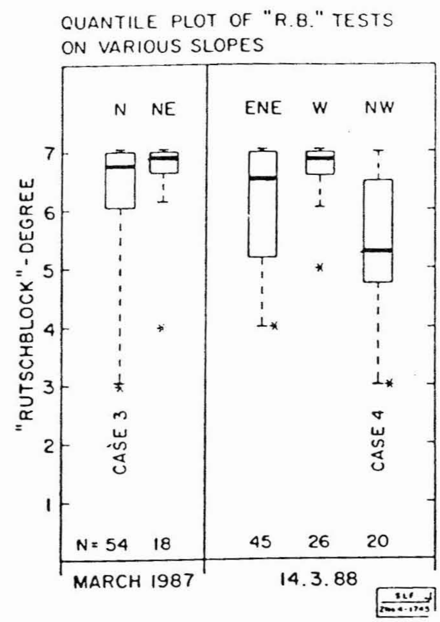

Fig. 9 Summary of order statistics for all investigated slopes of different aspects.

Conclusions

Snow slope stability may be assessed by three field methods: The simple **shovel test** (but without measuring the separating force) is suited for practitioners together with a hasty pit investigation. Such tests yield possible depth and approximate strength of weak layers, both influenced subjectively. The **"Rutschblock"-test** allows objective detection of weak layers or interfaces in relation to skier loading and a relative measure of strength of weak layers. Higher objectivity due the larger sample area (3 m^2) and fixed test load (skier) is in favour of this test. The **shear frame test**, which reveals together with previous shovel- or "Rutschblock"-tests numerical indices for the shear strength of weak layers, is a delicate method, which is rather recommended for special investigations.

The areal variability of snow strength (stability) on avalanche slopes could only be investigated during stable or metastable snowcover conditions or along the peripheries of released slabs. At these conditions stability varies with the same order of magnitude (15-30%) as other snow parameters.

Small "deficit areas" ($S < 1$) as defined by Conway and Abrahamson (1984, 1988), i.e. basal shear strength deficits in relation to the gravitational shear stress could not be detected on various slopes, if the samples which ruptured during preparation were discarded.

A few "deficit areas" ($S' < 1$) and many weak zones ($1 \leqslant S' \leqslant 2$) in relation to the local shear stress and the **additional** loading (skier, climber) have been found on all slopes. Their number and possibly their size could depend on the mean slope stability.

Whereas the stability varies across homogeneous slopes in an apparent random pattern, it shows e.g. large-scale fluctuations on extended lee slopes, possibly due to wind influences.

Because none of the investigated slopes could be triggered as slab by intensive skiing and bombing afterwards despite some "deficit areas", we may suspect that singular small "deficit areas" or weak zones are not a sufficient reason for widespread shear fractures. Either many small "deficit areas" or a few large "deficit zones" are needed to overcome the other resistance forces which are also present in a potential avalanche slope. An all deciding, singular and small "deficit area" could not be verified with our measurements.

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