THE STARTING MECHANISM OF AVALANCHES

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In regard to the question of how slab avalanches are triggered, Robert Haefeli gave one of the first explanations. He stated, following the logic of W. Paulke, that the cause was due to the shock of a tensile rupture initiated at a convex portion of the slope. This explanation is only a special case, however, and even Haefeli later modified his thinking.

E. Bucher dealt with the stability problem in his doctoral thesis. He defined a stability index as a ratio of strength of a snow layer, T_S, to the stress applied by body forces to that layer, T. When the ratio of these quantities, $S = T_S/T = 1$, a snow layer is at the limit of equilibrium and avalanche formation is imminent. Figure 1 depicts a schematic representation of this situation. When S becomes less than 1, either because of an increase of stress or because of a decrease in strength, avalanches are possible.

In order to estimate stability, I went on slopes to measure the weight of snow laying above the weakest layer and the strength of this layer with a shear frame. In this way, I found that the stability index appeared to be greater than one, while at the same time I observed that avalanches had occurred on similar slopes where the stability index was obviously less than one.

The explanation is that perturbation had suddenly added to the stresses to promote rupture in the weakest layer. Thus, there are two general types of snow slab release. There may be alterations by gradual influences to promote a <u>spontaneous release</u> or there may be a sudden <u>triggering by a shock</u> or other incident.

The spontaneous release occurs when the stress increases slowly to become greater than the strength or when strength diminishes to become smaller than the stress.

Avalanches may be started by triggering incidents which are <u>intrinsic</u>, originating from within the snow cover. Examples of this include weak layer shear fractures precipitated by gradients in creep velocity, tensile fractures in the slab originating due to slope convexity, or compressive fracture at the toe of a slope. The latter case is uncommon because snow is relatively strong in compression.

Avalanches may also be triggered by extrinsic events originating from outside the snow cover which provide ruptures inside the snow cover. Examples of this include the fall of a piece of snow, of stones, of a cornice, of seracs, or the passage of one or several skiers. Vibrations from vehicles moving along roads, from explosives, or from sonic booms are other familiar examples of possible triggers.

Consider now the question of how an avalanche can start from a shock when the stability index is greater than one. The weak layer will have a certain strength which depends upon cohesion, or bond strength, and a coefficient of starting friction (static friction) which depends upon the shape of the disaggregated crystals. If a shock destroys the cohesion locally, the crystals will begin to move and the fraction component will pass from static to kinetic. This kinetic friction coefficient can be expressed in terms of the tangent of an angle which may be compared to the slope angle. If the slope is steeper than the kinetic friction angle the avalanche may release. I determined that for any type of snow the angle of kinetic friction is smaller than that of static friction by approximately 10°. Disaggregated cup crystals, for example, are at the limit of equilibrium on slopes of 45°, but when in motion they have a kinetic friction angle of 35° (Figure 2).

However, it is not certain that an avalanche will start if the cohesion is destroyed locally because the failure must propagate for a great enough distance for the release to occur. If the whole slope is at the limit of equilibrium, the stability index being near one, the avalanche will start. If however, the stability index is greater than one, the snow downslope should also break and move. Whether this will occur depends upon the mass of snow moved by the initial shock and upon the magnitude of the stability index.

It often happens that after the shock of a tensile rupture at the convex part of a slope, there is no avalanche and only a fracture line appears. In this case, avalanches may release on a steeper slope, where the stability index is smaller due to a greater proportion of the body forces being in shear.

It was also found that when the stability index is high it is more probable that avalanches will occur if the slab is hard than if the slab is soft. In hard snow, the fractures can propagate in a more brittle manner and spread over great distances. The liberated slab may be larger in that case due to greater slab cohesion and it has a better chance to jar the undisturbed snow lower down on the slope. In low density snow or in a soft slab the effect of the shock may be damped considerably.

The study of how alternating soft and hard layers are formed in a snow cover is interesting and important in understanding avalanche formation. Some examples of formation of hard layers include formation by the wind and the melting and refreezing of surface snow into hard or ice layers. In addition, the lower part of an abundant snowfall hardens and settles due to the weight of the snow above. In these compact layers the metamorphism is destructive and slow so that the snow stays compressible and can easily settle. It will continue to settle under the weight of later snowfalls.

On the other hand, layers staying a long time at the surface in cold weather recrystallize and lose their resistance to settlement. When covered by new snowfalls, they represent dangerous, weak layers. Covered surface hoar or depth hoar also makes weak layers.

As soon as there is a weak layer underneath a harder layer, slab avalanches are possible. This is a dangerous situation and is difficult to forecast. For example, an avalanche can be started by a shock, when the stability index is high, where with the same stability index a soft snow layer or a soft slab may not produce propagating fractures and an avalanche may not occur.

It is a fact, at least in the Alps, that during winters with not much snow, there are more skiing and climbing accidents because the snow cover is weak due to constructive metamorphism so that avalanches can be started by those on skis. When there is a great deal of snow, the snow cover densifies and settles, and is less prone to break and form avalanches.

The greatest danger to houses or villages exists when abundant snowfalls (over 1 m) occur on weak surface layers which have been recrystallized by strong temperature gradients and thus have lost their resistance to settlement. These layers may stay weak for extended periods.

On slopes near 30°, the accumulation must be great for the snow cover to reach the limit of equilibrium. At this stage, the snow on the entire mountain side will start simultaneously and the avalanches will assume catastrophic proportions. On slopes of a higher angle, slab avalanches will generally be smaller because the proportion of the accumulated load in shear is greater and failure will occur earlier.

There is a last effect of metamorphism of the crystals which should be emphasized: after one to two months without any big snowfall during prolonged cold periods, every layer of the snow cover loses some of its strength. Avalanches may start then without any apparent reason. Actually, however, the stability index has changed through gradual loss of strength even though the load has remained relatively constant.

As a result of these complexities, it seems difficult for a forecaster to estimate the risk. In fact, he should analyze the contributing factors which tend to impair stability. For the natural release of slab avalanches there are four main contributory factors; three come from the meteorology, one from the snow itself:

1. The most important of the contributory factors is loading from snowfall. This adds to the stress and tends to warm up the old layers which can reduce their strength.

2. The wind is also important because it accumulates snow on lee slopes. It augments the strength of the snow layers and forms wind slabs.

3. Warming up of the snow reduces its strength. Temperature increases strongly affect surface layers and penetrate slowly into the snow cover.

4. The constructive metamorphism of the crystals tends to diminish the strength of the layers. These layers lose their resistance to settlement and stay weak and breakable inside the snow cover. They can constitute a potential risk which can last an entire winter.

In conclusion, on one hand it seems simple to estimate the risk, but on the other hand the start of an avalanche is so complex that nature can fool the most experienced specialist. The person who can forecast avalanches with absolute certainty has not yet been born and will never exist.

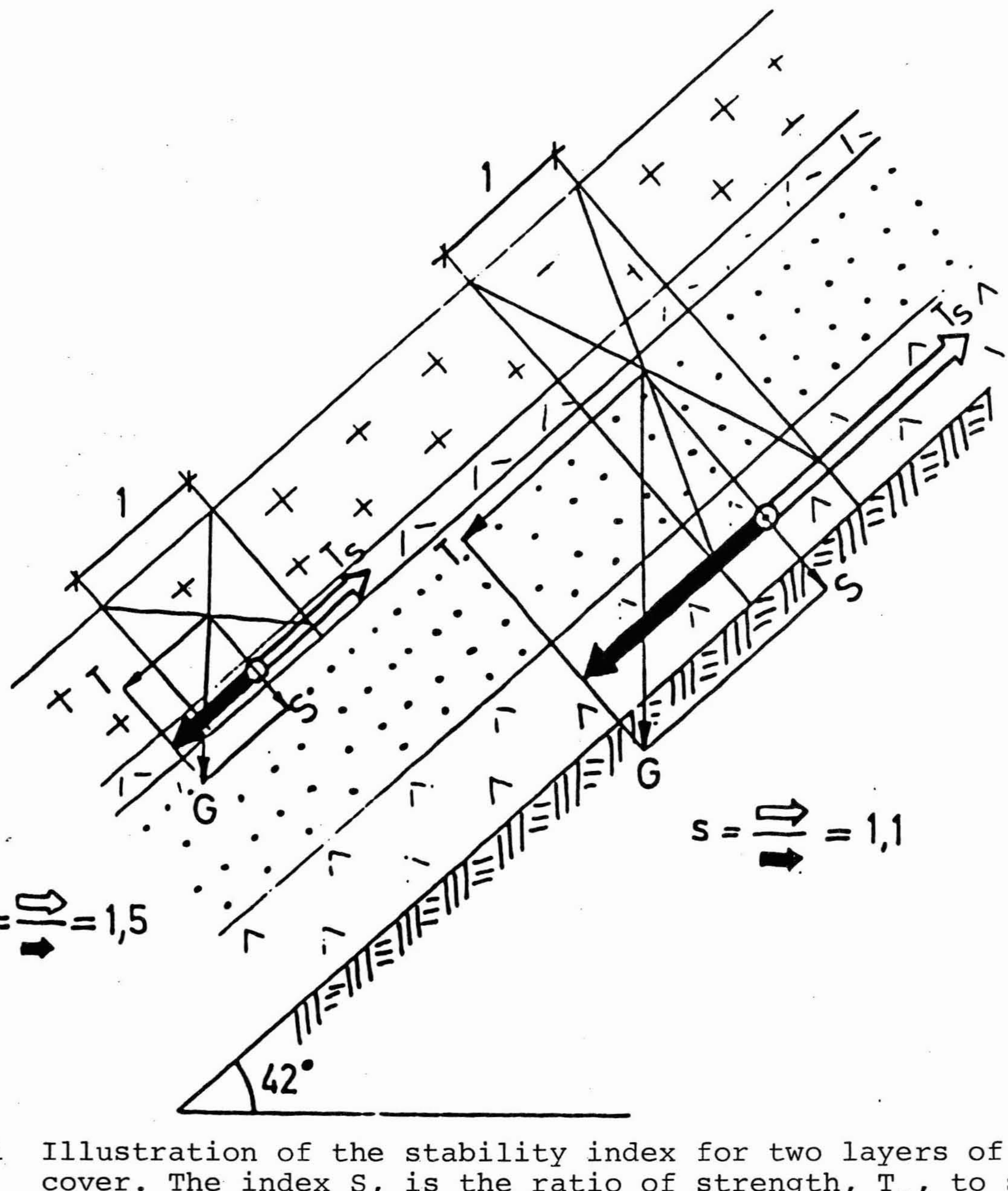

Fig.1 Illustration of the stability index for two layers of a sno
cover. The index S, is the ratio of strength, T_s, to stres
These are shown as white and black arrows respectively.

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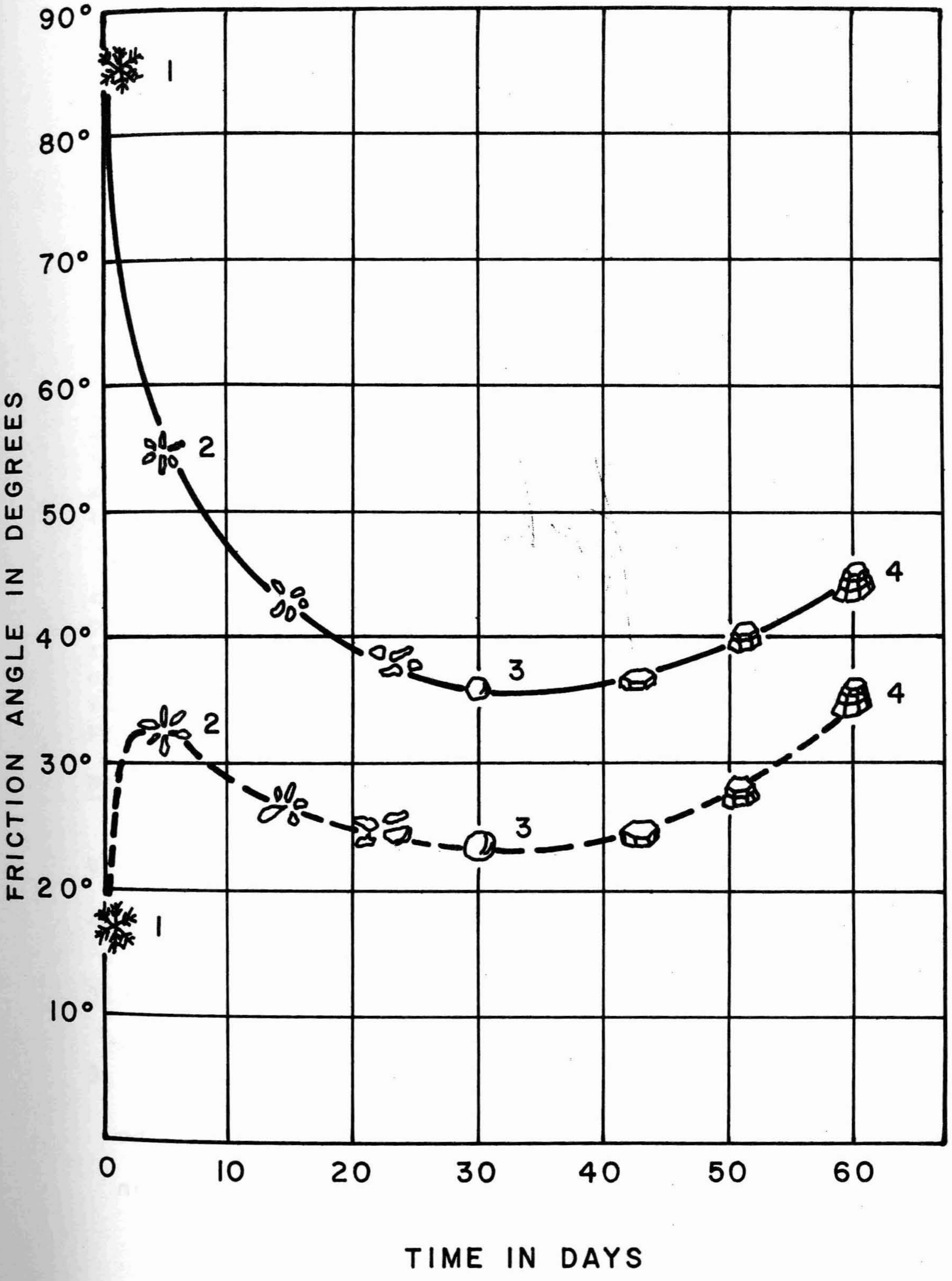

FIG. 2 Static (———) and kinetic (----) friction angles as a function of approximate time in days for four states of crystal metamorphism.

Discussion

Stethem:

You mentioned a stability factor of 4 in one case. Was that an artificially released avalanche?

Roch:

No. It must have been a tensile rupture on the convex part of the slope. Nearly all the avalanches I measured were natural releases.

Stethem:

Did you calculate mean or average values of stability factors for your natural avalanches?

Roch:

No, but I think Sommerfeld calculated a mean value of about 2.

S. Hackett:

Could you expand on your strength versus shear stress concept in evaluating growing instability?

Roch:

When the stability is low and a storm produces a new load, then presumably the snowpack stability is lowered further.

S. Hackett:

Are you referring to how vertical or horizontal strength in the snowpack changes with time?

Roch:

The shear frame was used to measure the shear strength along horizontal layering. However, the measurements may provide some understanding of vertical resistance, that is, resistance against collapse. The direction of the weakest strength may vary, depending on the snow structure and the type of crystals, and may not be parallel to the slope. Thus, the stability index is only an approximation, but it assists in understanding the possibility of avalanche release.