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Snow Slab Release, its Mechanism and Conclusion for the Arrangements of Supporting Structures

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ABSTRACT

The paper presents a model of snow slab release based on the concept of the presence of ground-parallel thin super-weak layers. The fact that the same snow type under same state may or may not fracture under a certain stress unless a critical strain-rate and critical fracture-strain is reached highlights the necessity of stress and strain-rate concentrations. Super-weak layer, which cannot or can only insufficiently transmit the shear stress caused by the overlying snow layers, is considered to provide such concentrations. The model establishes that although the existence of weak layers in a snowpack is a necessary condition, yet it is not sufficient for avalanche formation. A minimum length of the super-weak zone is required for the crack to propagate leading to the release of a slab avalanche. Critical crack lengths are found to be of the order of 5 m to 10 m. Critical value of crack length has been found to be dependent on slope, thickness and viscosity of the weak layer. The model does not hold good, if the super-weak zone vanishes. The paper finally discusses the arrangement of supporting structures to minimise the development of super-weak zones.

1. INTRODUCTION

Fracture strength of snow does not only depend on snow type (density, structure, etc.) and state of snow (temperature and free water content), but as strongly on strain rate and fracture strain. Extensive laboratory work[1-3] has shown that the same snow type in the same state may or may not rupture under a certain state of stress, whether or not a critical strain rate (CSR) and fracture strain is attained. This restricts the possibility of fracture of snow slabs considerably and leads directly to the necessity of taking into account stress and strain rate concentrations. McClung[4,5] has mentioned the possibility of stress concentrations in a weak layer and Conway and Abrahamson[6,7] demonstrated, by field tests, the existence of very weak zones within weak layers.

2. FAILURE CRITERION

It is assumed[1] that strength of snow consists of two parts, one based on critical work (elastic or brittle strength) and the other on critical rate of dissipation work (viscous or ductile strength). With increasing strain rate in the first subcritical phase, viscous deformation takes place without fracture. Nevertheless under uniaxial tension–which never occurs under natural conditions–snow fractures in the subcritical range with large deformation due to over-straining. Microscopically, this can be understood by the chain-structure of snow: as soon as a load-carrying chain attains a certain elongation it must break independently of strain rate. With subcritical uniaxial compression, however, new bonds between grains are created continuously, preventing fracture. Under the state of stress of a slope-parallel weak layer-shear and overburden compressive stresses, the same may be true if the normal stresses are large enough. In second phase, when the critical strain rate is reached, snow fractures with maximum strength, the viscous part being predominant. In the third phase, the viscous part is lost gradually and with this strength decreases drastically,

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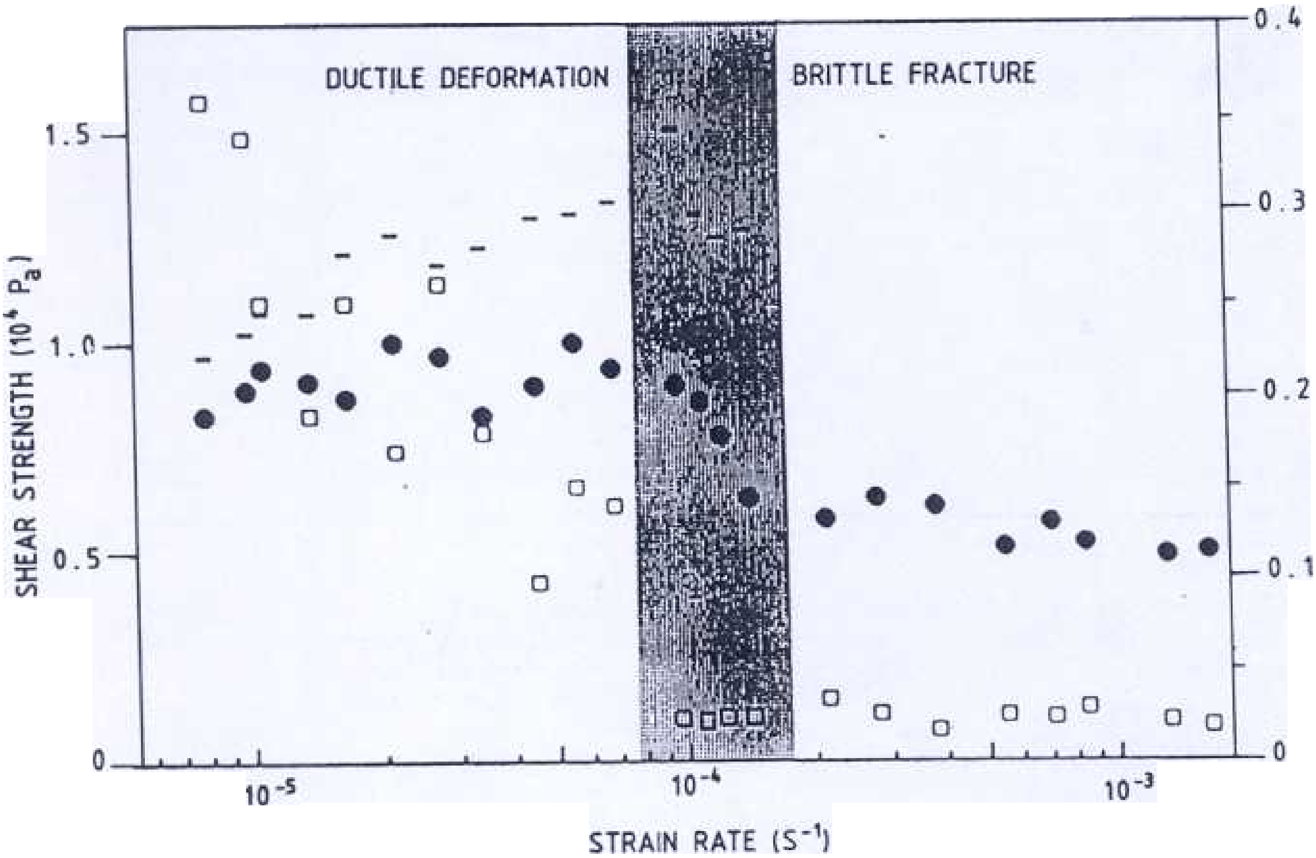

Figure 1. Strain-rate dependence of fracture strain (□), fracture stress (●) and hardening limit stress (—) (after Fukuzawa and Narita[3]).

until only the elastic part remains. With increasing strain rate, fracture strain decreases until a low constant value is reached with pure brittle strength.

For the critical strain rate, Salm[1], McClung[4] and Narita[2] have found in tests a fairly constant value of $10^{-4} s^{-1}$ for different states of stress. The most recent and very conclusive tests (shearing of a depth hoar layer between fine grained, high density snow) have been performed by Fukuzawa and Narita[3]. Figure 1 shows that the critical strain rate mentioned above was confirmed. Note that in their tests no overburden compressive stresses were applied. It is fascinating to see that an order of magnitude of $10^{-4} s^{-1}$ for the CSR seems a fairly 'universal' constant for snow, much in contrast to the widely varying strength values.

3. FRACTURE MODEL

The snowpack on a uniform slope of angle ψ consists of three layers: a top layer of thickness d_0, density ρ_0 and viscosity η_0 is superimposed on a thin weak layer with a thickness d_s (gravitation neglected). The total snow depth–including the bottom layer–is d (Fig. 2 but without supporting structures). Over a distance of $2a$ the thin layer is interrupted by the so-called super-weak zone where no shear stresses can be transmitted to the ground. This zone is assumed to be infinitely long in z-direction (Fig. 2).

Sufficiently far away from the disturbance by the super-weak zone, the shear stress in the weak layer is

$$\tau_\infty = d_0 \rho_0 g \sin \psi \qquad (1)$$

where g is the acceleration due to gravity. With the use of a linear constitutive equation (constant viscosity and Poisson's ratio) and the assumption of a one-dimensional creep movement, we get (approximately) for the shear stresses[8] in the vicinity of the disturbance

$$\frac{\tau_{yx}}{\tau_\infty} = \frac{a_a}{d_0} \exp\left(- \frac{ax}{d_0}\right) + 1 \qquad (2)$$

The origin of x is at the end of the super-weak zone, where

$$a = \left(\frac{\eta_s d_0}{\eta_0 d_s}\right)^{1/2} M \text{ and} \qquad (3)$$

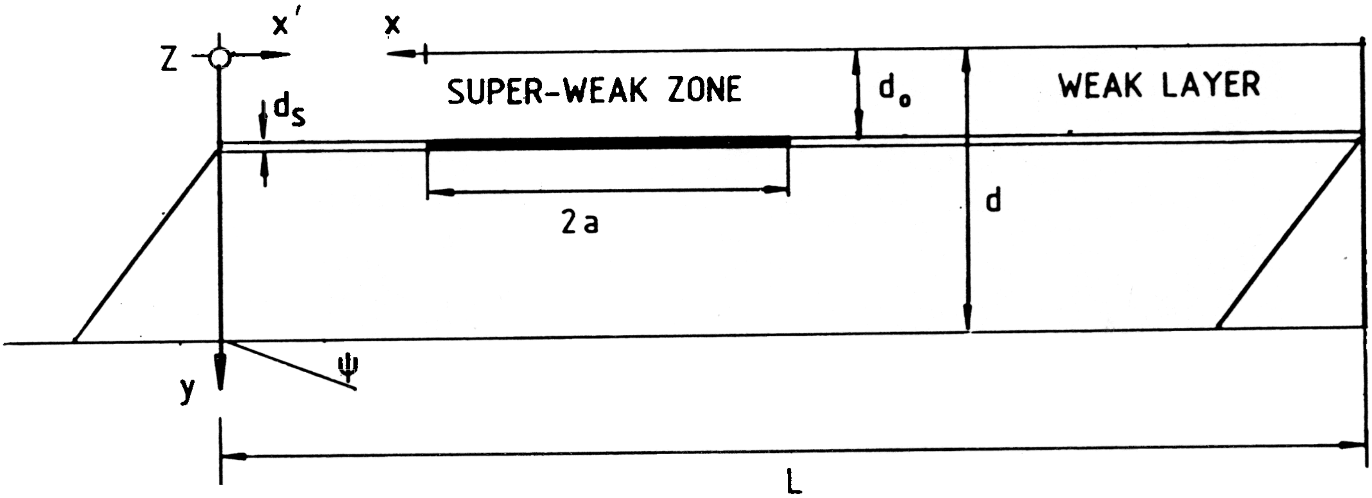

Figure 2. Efficiency of supporting structures for the prevention of snow slab release.

$$M = \left(\frac{m-1}{2m}\right)^{1/2} \qquad (4)$$

with m being the inverse viscous analogue of Poisson's ratio.

If at the crack tip $x = 0$, the strain rate equals the critical one $\dot{\varepsilon}_{cr}$, then $\tau_{yx} = \dot{\varepsilon}_{cr}\,\eta_s$ and a becomes the critical length a_{cr}, where fracture starts to propagate and is given by.

$$a_{cr} = \frac{d_0}{a}\left(\frac{\eta_s\dot{\varepsilon}_{cr}}{\tau_\infty}-1\right) \qquad (5)$$

The above analytical relations have been checked with the finite-element method for the true 2-dimensional movement. Generally, a good agreement was confirmed[8].

The smaller the critical size a_{cr}, the more likely the fracture can start. The close examination of Eqn (5) shows the following results:

(i) Generally critical crack lengths are of the order of 5 m - 10 m.

(ii) The thinner the weak layer, the shorter is the a_{cr}. If the thickness is reduced from 10 mm to 1 mm, a_{cr} decreases by a factor of 3.

(iii) Low viscosity of the weak layer reduces a_{cr}.

(iv) With a decrease of the viscosity of the overburden layer, a_{cr} will be reduced. Thus an increase in temperature of this layer enhances the probability of fracture without any changes in the weak layer.

(v) The steeper a slope is, the shorter the a_{cr} : compared with a slope of 30° the length on a 50° slope is reduced by one third.

(vi) If a_{cr} vanishes, a fracture should start simultaneously on the whole slope. This would imply that d_0 will be of the order of 10 m, which is impossible in nature.

4. INFLUENCE OF SUPPORTING STRUCTURES

The aim of such structures is to increase stability of the snowpack or in other words to enlarge a_{cr}. As this problem cannot be solved analytically in closed form, the solution of Bucher (Salm[9]) is superimposed to the solution without the supporting wall to get a rough approximation. The additional compressive stresses σ_x' over d_0 and shear stresses τ_{yx}' in the weak layer due to the wall are :

$$\sigma_x = \frac{\pi\eta_0 u_\infty}{2Md}\exp\left(-\frac{\pi M x}{2d}\right) \qquad (6)$$

$$\tau_{yx} = \left[1-\exp\left(-\frac{\pi M x}{2d}\right)\right]\tau_\infty \qquad (7)$$

$$u_\infty = \frac{\tau_\infty}{\eta_0 d_0}\,\frac{d^2}{2}\left(1-\frac{y^2}{d^2}\right) \qquad (8)$$

which is the velocity far away from the wall and at a depth y from the snow surface. With Eqns (6), (7) and (2), the maximum shear stress for $x=0$ at the lower crack tip becomes

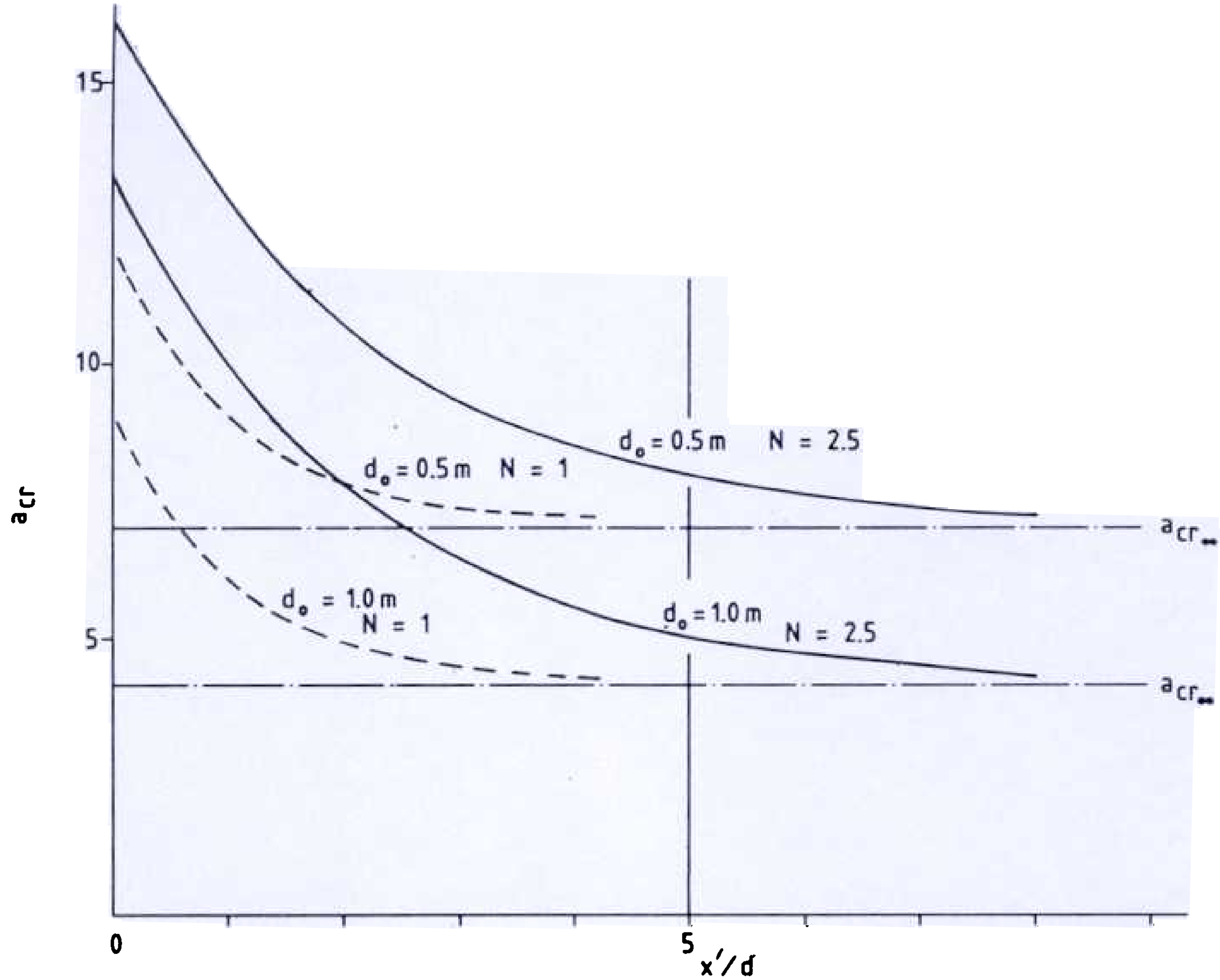

Figure 3. Increase of a_{cr} within the pressure zone: influence of d_0 and N (ψ = 40°).

$$\frac{\tau_{yx\,max}}{\tau_\infty} = \left[\frac{a_a}{d_0} + 1\right] - \left[\frac{\pi \alpha d}{4Md_0}\left(1 - \frac{y^2}{d^2}\right) + 1\right] \exp\left(- \frac{\pi M x}{2d}\right) \qquad (9)$$

The first term originates from the undisturbed crack and the second represents the reduction due to the wall. For small x' – the distance between the wall and the lower crack tip – Eqn (9) is no more valid.

If at the crack tip the strain rate equals the critical one $\dot{\varepsilon}_{cr}$, the critical crack length becomes

$$a_{cr} = \frac{d_0}{a}\left[\frac{\dot{\varepsilon}_{cr}\eta_s}{\tau_\infty} - 1\right] + \left[\frac{\pi d}{4M}\left(1 - \frac{y^2}{d^2}\right) + \frac{d_0}{a}\right] \exp\left(- \frac{\pi M x}{2D}\right) \qquad (10)$$

The second term in Eqn (10) is the increase of a_{cr} due to the supporting wall.

In Fig. 3 the influence of d_0 and gliding of the snowpack on ground on a_{cr} is shown. Gliding is represented by the glide factor N which varies from 1.2 to 3.2 (Swiss Guidelines[10]). It can be taken into account by replacing d by a fictitious depth (Salm[9]). It has to be emphasised that the above calculations are rough approximations, more of a qualitative nature. It is necessary to check them by the finite element method.

5. COMPARISON OF DISTANCE STRUCTURES

In the Swiss Guidelines[10], the distance between two rows of structures L was determined according to three criteria: the structures have to withstand the maximum static and dynamic snow pressures. Further, these acting artificial roughnesses, have to reduce velocities of snow sluffs. The reason is that the possibility of fracture–especially of loose snow avalanches – can never be excluded. However, a relation expressing the mechanics of snow slab formation has not yet been considered. It is therefore interesting to examine the prescribed L's in the light of the presented fracture model.

The location of the super-weak zone is unknown. Therefore all possible situations have to be examined, the worst case representing the minimum efficiency. In the lower end of the super-weak zone, in a distance x' from the wall (Fig. 2), a shear fracture will never propagate because it would enter into a zone with decreasing shear stresses where the strain rate becomes subcritical. In the upper end of this zone the contrary is true, a slab of an assumed length of $L - (x' + 2a_{cr})$ may fracture. If this length is small or negative the efficiency is sufficient.

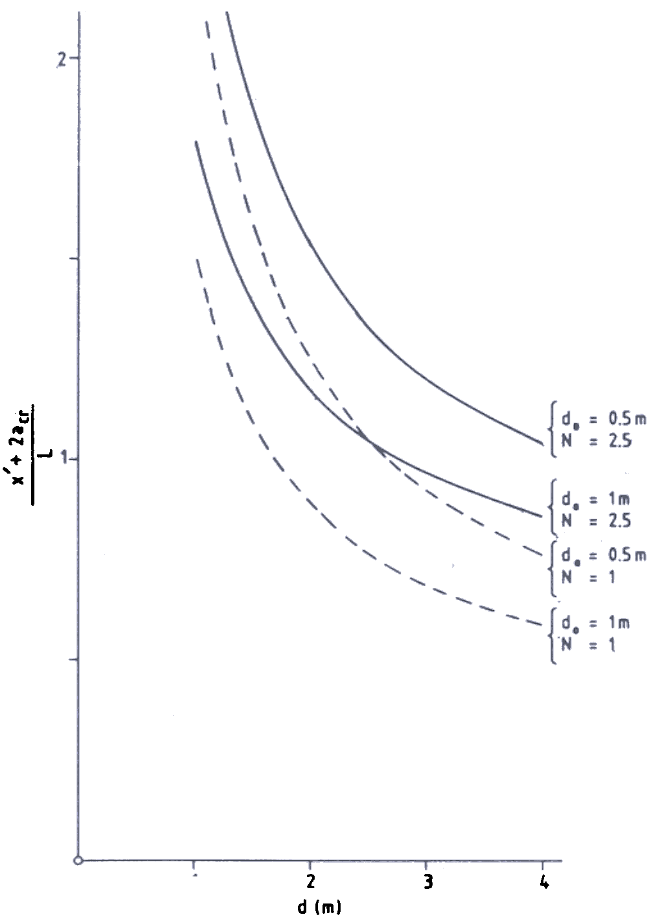

Figure 4. Minimum efficiency of supporting structures for ψ = 40° and f_L = 5.8.

In Fig. 4, L was calculated for ψ= 40° and f_L = 5.8 in the relation $L = f_L H$ with $H = d/\cos\psi$ (Swiss Guidelines[10]). For the depicted worst cases the value of x'/d for the lower end of the super-weak zone is between 1 and 2.5. Figure 4 shows that with a relative high glide factor N = 2.5, the efficiency is generally satisfactory, whereas with no gliding and large d this is not the case. The situation is always improved with smaller d_0. The conclusion can be drawn, that for a low glide factor L should be reduced by 20 to 40 per cent.

It is, however, to be mentioned that above calculations are very pessimistic by assuming a vanishing shear stress in the super-weak zone.

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