ON THE MECHANICS OF THE HARD SLAB AVALANCHE

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ABSTRACT

The buckling of snow slabs is proposed as a failure mechanism of avalanche slopes. Preliminary results indicate that buckling may initiate and grow under a wide range of conditions. To study the problem further, nonlinear constitutive equations and nonlinear failure theories are being considered. Acoustic emission techniques will be used to characterize the behavior of snow.

Introduction

Various factors contribute to the recognized uncertainty over the mechanism of hard slab snow avalanche release. Perhaps the greatest difficulty is the hazard of field observation of other than the crown region of an avalanche-sensitive slope. Additionally, downslope preavalanche material and conditions of geometry are largely obliterated following the avalanche. The upslope or crown region postavalanche geometry remains intact, and has been monitored and studied in some detail. Theories of release have been formulated assuming initial disturbance in the crown region, as by a tensile stress fracture, and subsequent propagation downslope (Sommerfeld 1969).

Snow, not being an easy material to characterize rheologically, has complex load-deformation properties and exhibits unique structure changes under certain thermal history conditions. In general, load, deformation, microstructure, and thermal characteristics of snow *in situ* on slopes have not been systematically measured, so that quantitization of factors relevant to subsurface conditions are not known. However, recognizing the fact that physical changes occur in the interior of snowpack, release theories have been formulated based upon some type of basal layer inhomogeneity. It is assumed that material transformation or a form of inclusion produces a weakened state or an unstable structural configuration. Either from local collapse or a shear failure, the release ensues (Bradley and Bowles 1970, Haefeli 1966, Roch 1966). Recent work which supports this concept of a weak sublayer are the theoretical studies of the stress state associated with this geometry (Perla 1971, Brown et al. 1972a), and an order-of-magnitude evaluation of the feasibility of a buckling mechanism contributing to the enhancement of slope failure (Lang et al. 1973). These studies relate to subsurface and toe region influence upon the release question.

If, indeed, these mechanisms exist and affect release, then experimental and modeling techniques will have to be developed to aid in evaluating their importance. Based upon evidence now known, it is reasonable to assume the existence of a weakened basal layer condition. But there may be a number of disturbance types or imperfections which induce the triggering of the avalanche as the slope, by some process or other, reaches a critical stability state. If monitoring and control of the avalanche sensitivity of a slope is desired, then the important question is what physical changes occur early enough and with sufficient magnitude to reliably serve as a measure of slope stability. One possible macroscopic mechanism that may be detectable is local buckling of the slope. Evidence of long term large-amplitude buckling of snowpack is well documented, and the question arises whether buckling is a primary or secondary mechanism in avalanche release. Lacking conclusive experimental evidence of the importance of buckling, the concept is further explored in the remainder of this paper.

Material Representation for Buckling Analysis

The formulation of a possible buckling state is strongly dependent upon an adequate material characterization. To date an extensive variation exists in the constitutive properties used to study snow response. Most analyses are based upon linear constitutive equations, and time dependence expressed by a deformation or strain rate term (viscous response). In setting up a buckling model, it would appear that refinement in the constitutive law to account for more than one rate dependence can be treated. In constitutive law modeling to date, a linear viscoelastic model of low density snow has been reported by Shinojima (1967); however, in the absence of stress relaxation considerations, the model is based upon long-term fluid behavior. Results by Yosida (1966) and in tests conducted by the authors (Brown et al. 1972b), long-term solid material residual is observed, in that complete stress relaxation under constant deformation does not occur. An additional complication report by Shinojima (1967) is that the linear form of the constitutive equations is different for each type of loading investigated, which included simple tension, compression, and torsion. Thus, different material coefficients should be used depending upon local stress conditions. However, this form of material nonlinearity should not be a primary factor in formulating a buckling criterion. The existence of a weakened sublayer, which is generally recognized as a necessary condition for slope instability, results in incomplete stress transfer to the slope bed surface and a transmittal and intensification of bearing stress downslope. Thus, the toe region material is in a state of compression, which simplifies the requirements on the constitutive representation.

The nonlinearity noted by Shinojima (1967) in transition from a compression to a tension state is reflected also in his reported values of Poisson's ratio. In tension the Poissonic effect approaches that of an equivoluminal material, whereas in compression the Poissonic effect is small. This difference in material behavior under different types of loading is attributable to the skeleton crystal structure of snow, in which both volumetric and distortional deformation mechanisms act. This is markedly different from typical viscoelastic modeling assumptions, but should be accounted for in setting up a viscoelastic model of snow.

What is perhaps the greatest impediment to a simple constitutive representation of snow is the fact that snow behaves strongly nonlinearily to changes in deformation rates, loading sequences, etc. Yosida (1966) indicates a strong nonlinear relationship between normal stress and low strain rates in simple compression tests of snow columns. Application to analysis of buckling can be handled by equivalent linearization of the constitutive model in the standard method of treating material nonlinearity.

The behavior of snow is complicated by its dependence on a number of items, which includes temperature, density, and state of metamorphism. The state of metamorphism, as indicated by Yosida (1966) can be characterized in terms of the thermal history and stress history of the material. These considerations therefore make the complete thermomechanical characterization of snow an extremely difficult task to undertake. However, this approach of characterizing snow is probably not necessary for making a comprehensive analysis of the problem of buckle mode growth. It is quite possible, as indicated by Yosida (1966), that a large portion of the snow slab may be metamorphically stabilized during the months of January through March, and that the timewise variation of the material properties may be negligible. If this is the case, the material aging characteristics and thermal history effects may be neglected in formulating the material constitutive equations, which must necessarily be nonlinear. However, since the stress distribution in the downslope region of an imperfection zone in the slab is compressive, the use of equivalent linear constitutive equations can be considered a valid simplication. However, more research needs to be done to verify if this can be done. Some questions pertaining to this which must be answered are: first, the extent to which one simplified constitutive equation can be utilized to represent the entire slab (that is, the effect of density variation and the percentage of the slab which does stabilize metamorphically), and, second, the correlation between stabilization of metamorphosis and macroscopic material properties.

In summary, the key to the analytic treatment of the buckling question is a refined model of the constitutive representation coupled with simplifying assumptions on the range of parameters based upon the physical conditions of the slab buckling phenomonen.

Physical Characteristics of Snow Slab Buckling

Two buckling geometries can occur. One is buckling of the surface layer of the snowpack while supported by a bed surface cushion. This requires either an interstitial weak layer (as from water percolation or material stratification), or a metamorphized basal layer (as from formation of depth hoar). Perla (1971) determined from examination of a number of postavalanche slopes that in 65 percent of the cases depth hoar was in evidence. Admitting the mechanism of long-term buckling, the wave shape of a typical buckling mode induces local regions of bearing stress intensification on the basal layer of depth hoar. This overstress enhances the brittle fracture and collapse of the depth hoar matrix, and, thus, is a plausible mechanism as an initial triggering source.

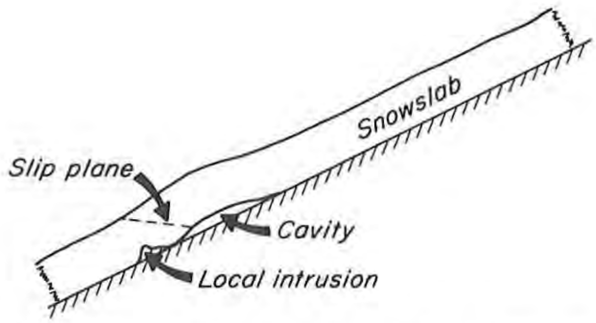

Figure 1. Geometric and stress intensification configuration due to local slab buckling.

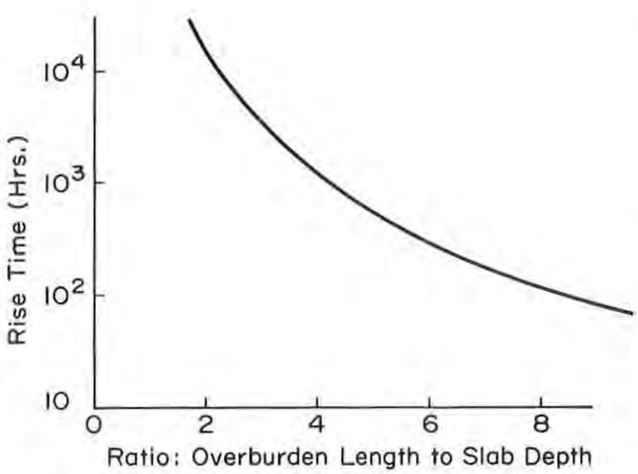

Figure 2. Rise time versus relative overburden length for specified initial imperfection amplitude to wave length ratio of 0.05.

The second buckling geometry is the formation of a buckling pattern of the entire slab, which implies cavity formation at the bed surface. Two alternatives exist here, that either the cavity exists and buckling follows, or that the tendency for buckling produces the cavity. Whichever is the case, the formation of a buckle lobe in the toe region produces a geometric and stress intensification configuration that enhances the formation of a slip plane (fig. 1). Alternately, the feasibility of a buckling mechanism "locking" a slope must also be examined.

To examine the question of whether or not buckle formation is physically possible in snow slabs, (1) snow columns were tested in compression, and (2) the material coefficients determined were used in a buckling analysis. Snow columns of nominal length 20 cm, and specific weight 0.39 gm/cm^3 were tested at -10° C at constant deformation rates up to 0.005 cm/min. The load-deformation data were fit by a linear three-element viscoelastic solid model, and a buckling analysis procedure was followed (Lang et al. 1973). Results of the computations are shown in figure 2. The interpretation is that for a given length of bed-surface imperfection having an initial amplitude 0.05 of its length, the curve shown is the boundary between growth and subsidence of the imperfection. The abscissa is the factor indicating the number of equivalent lengths of imperfection that must be bearing onto the imperfection zone to yield a corresponding rise time for an order-of-magnitude change in the amplitude of the imperfection. Thus, for an imperfection of length, ℓ, snow of equivalent length 4ℓ must bear onto the imperfection zone in order that the amplitude of imperfection increase by a factor of ten in 10^3 hrs or approximately 41 days. Thus, even though the snow specific weight is high and the test temperature is low for midalpine snowpack (both factors, if adjusted accordingly, decrease the time for amplitude growth), a reasonable estimate of a buckling mechanism is obtained.

To further define whether or not subsurface imperfections can form, a snow slope in the Bridger mountain range north of Bozeman, Montana, having a history of avalanche activity, was selected. A 40-meter-long trench was dug along the nominal 40° slope approximately one-third of the distance in from the left flank of the snowpack, which terminates into tree and rock outcrops on both flanks and at the crown. Void imperfections were found (fig. 3), which encompassed 40 percent of the 40-meter length. All voids were easily distinguishable, the largest having an amplitude of approximately 12 cm, and all voids extended under the snowpack indicating the exposed section probably was typical. Approximately 5 meters from the crown region tree outcrop a crack 20 meters in length and 0.3 meter in maximum separation ran parallel to the outcrop. The existence of this crack indicates that the particular slope was in a state of glide. However, the significant fact is that the void formation mechanism was more pronounced than snowpack settlement, which would cause subsidence of the voids. Thus, it is probable that slope creep rate relative to snowpack settlement rate is an important parameter on whether voids form or not. Once voids develop, any weakened subsurface condition that would result in incomplete shear stress transfer to the bed surface would reinforce void growth.

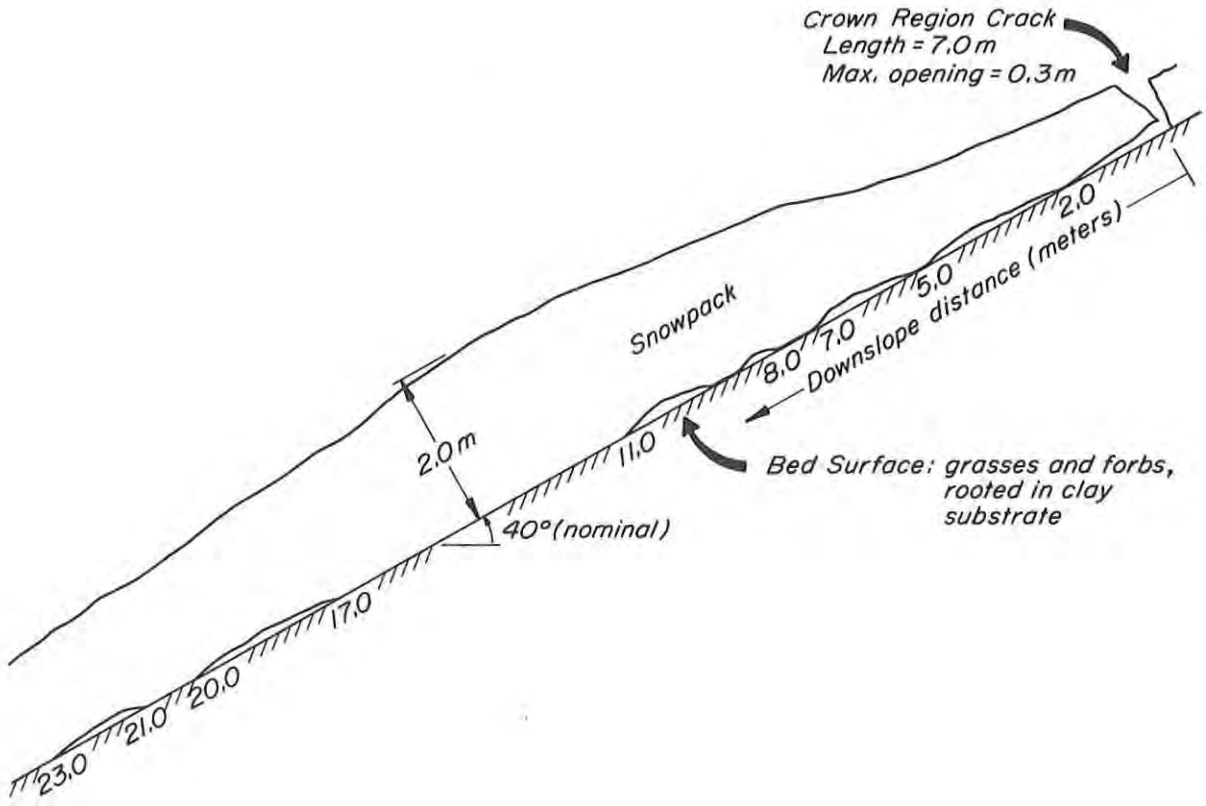

Figure 3. Slope cross section showing base lift-off, Bridger Range, Montana, January 19, 1972.

Final consideration is here given to a geometric profile described by Perla (1971). He indicates that the flank fracture profile of an avalanche zone has the shape of a sawtooth in a majority of cases. The sawtooth slants downslope, and conforms exactly to what would be predicted if a buckle wave with a downslope sagging central region were present immediately preceding avalanche release. Although the flank regions are influenced strongly by edge intrusions of rocks, trees, etc., if regular dimensions can be ascribed to the sawtooth pattern, this might relate directly to dominant buckling mode dimensions. Perla reports no data of this type, and the authors find none available in the literature.

Conclusion

Based upon the initial evidence concerning slab buckling, it appears that the possibility of a buckling state developing in avalanche-sensitive slopes must be considered. Using a simplified analytical model and nominal material properties, the times computed for buckle mode growth are at least of the same order as times associated with the avalanche phenomenon. The possibility exists for void formation and growth, depending upon the relative rates of snowpack settlement and slope-parallel creep, coupled with the necessity of a structurally weakened basal-plane zone. Also, evidence may exist on the flank region fracture profile that may correlate with dominant mode buckling pending further study and data acquisition.

Since buckling is a structural phenomenon extending into the toe region of the slope, physical measurement of void formation and buckle mode growth is difficult. Evidence of buckling from surface measurements is probably inconclusive because of wind transport of material that would obliterate long-term geometry changes. Thus, advanced *in situ* techniques such as acoustic emission monitoring, or slope modeling techniques, may be required to further assess the toe region influence on avalanche release.

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