SURFACE WARMING OF A DRY SNOWPACK INCREASES SKIER-INDUCED STRESS AND STRAIN MAGNITUDES IN DEEPER WEAK LAYERS

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ABSTRACT: Changes in air temperature, and hence snow temperature, influence snow stability for skiers. This paper studies how warming in the top 20 cm of a hard 'spring' like snowpack and a softer 'mid-winter' like snowpack influence the stresses and strains due to a skier load in weak layers 30 cm and 50 cm below the surface. The temperature effects are studied using a finite element model to predict how the load is transferred through a layered snowpack. The results show that the warming front does not have extend into the weak layer to have an effect. As the stiffness of the top slab is reduced, the peak stress and peak strain increase in the weak layers. The 30 cm weak layer was more effected by the skier load than the 50 cm layer with an increase in shear stress of 8% in the mid-winter snowpack model and 51% in the spring snowpack model. A model of a real snowpack with a surface wind slab again subject to a skier load showed an increase in shear stress of 32% when a weak layer was present at 22 cm and the top 19 cm was warmed. The increase in stress and strain in the weak layer in all models support the argument that there will be increase in the likelihood of skier-induced avalanche after warming.

Key Words: Snow Stability, Avalanche Triggering, Snow Thermal Effects.

1. INTRODUCTION

Avalanche control workers and backcountry recreationists report increased dry slab avalanche activity when the air temperature increases. This effect should be interpreted in terms of dry slab release which begins with the failure in a weak layer underlying the comparatively stronger and stiffer layers of the snow slab (e.g. Perla and LaChapelle, 1970; McClung, 1987). In the longer term, warming trends are associated with faster rounding and sintering of grains and reduced temperature gradients, resulting in increased stability if the slab load remains constant (McClung and Schweizer, 1997). It would therefore appear that the processes associated with warming might proceed in two phases: initial destabilization when first warmed followed by a gradual increase in stability as exposure to warm temperatures continues.

McClung (1979, 1981, 1984, 1987) proposed that warming could contribute to instability by reducing the stiffness of the slab overlaying the weak layer and consequently increasing strain in the weak layer. More recently, McClung (1996) argued that warming and reducing the stiffness of the upper portion of the slab would reduce the work of fracture of the slab-weak layer combination and thereby promote instability for natural avalanches. McClung and Schweizer (1997) used a similar argument for skier-triggered dry slab avalanches

Following previous work (Singh, 1980; Curtis and Smith 1974; Schweizer, 1993; Smith, 1972; Jamieson, 1995) a finite element model for a multi-layered snowpack was developed. There were two primary objectives:

1. To show how only warming and resultant loss of stiffness of the top layer of the slab can increase the stress and strain in a weak layer and consequently reduce stability for skier-triggered avalanches. This approach, which uses four stiffness profiles and two weak layer depths, gives results which augment the analytical studies of the effect of warming on the stability of homogeneous slabs by McClung (1996) and McClung and Schweizer (1997).
2. To model a real multi-layered snowpack and examine the effects of warming. The profile chosen for this part of the analysis was a wind slab overlying a buried surface hoar layer. The experienced observers were surprised when they could not skier-trigger the wind slab. The profile was taken while the slab temperature was at –15°C and it is assumed that the surface 19 cm of wind slab warmed to -5°C for the purpose of this analysis.

The first case provides a range of solutions to the warming condition while the second case examines a specific case that occurred during field observations.

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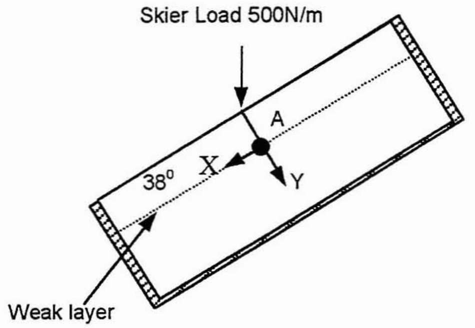

Figure 1. Schematic of the finite element model. The two dimensional model contained 170,000 degrees of freedom, was fixed at the constrained boundaries (hashed lines). There was a 500 N/m line skier load applied to the model. Weak layers were modelled at 30 cm and 50 cm. The x and y coordinate system are shown on the figure. Point A shows the origin used for the presentation of the results.

Table 1 Material properties used in the finite element model (Mellor, 1975; Shapiro et al., 1997).

Snow Condition	Hand Hardness	Stiffness MPa	Poisson's Ratio
Soft	F	0.25	0.25
Medium	4F	1	0.25
Hard	1F	4	0.25
Warm Wind Slab	1F+	5	0.25
Very Hard	P	10	0.25

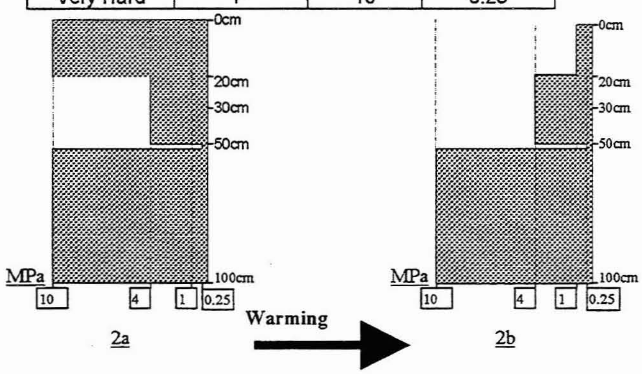

Figure 2a and 2b. Stiffness Profile for Spring Snow Conditions with a Weak Layer at 50cm

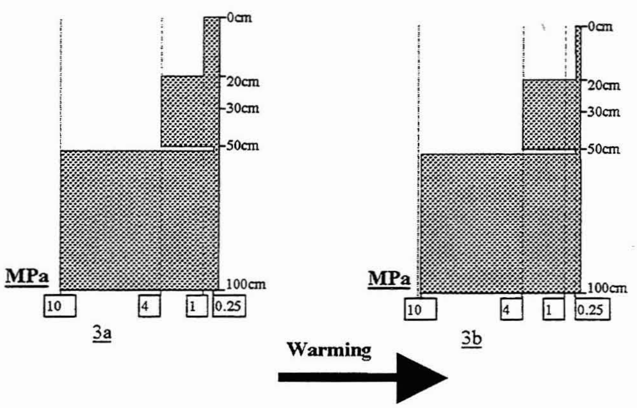

Figure 3a and 3b. Stiffness Profile for Mid-Winter Snow Conditions with a Weak Layer at 50cm

2. METHODS

The model was a 6 m long snowpack, 1 m deep on a 38° slope with a weak layer 0.5 cm thick at 30 cm or 50 cm below the surface. All dimensions were measured in the xy plane as shown in Figure 1. Only one weak layer was studied at a time. The model had 170,000 degrees of freedom comprising two dimensional, eight-noded, quadrilateral plane strain elements. The assumptions in this analysis included:

1) Since the snow was loaded quickly by a skier (a strain rate greater than 10^{-4} s^{-1}) the use of a linear elastic model was considered appropriate.

2) Weak layers have lower moduli than adjacent snow layers.

3) The top 20 cm of snow was homogeneous and of constant density before and after warming.

4) Plane strain and plane stress adequately describes a three-dimensional snowpack (e.g. Smith, 1972; Föhn, 1987; Schweizer, 1993). The two dimensional assumption has the advantage of being computationally simpler, but obviously can loose three-dimensional effects such as boundary effects from the sides.

5) The skier load was applied far from the fixed boundaries. As such, the boundary conditions would not effect the results beneath the skier load.

A spring-like snowpack was modelled in which the top 20 cm was stiff. In this case, a marked reduction in stiffness was modelled due to warming. Also a mid-winter-like snowpack was modelled in which the top 20 cm was relatively soft. A smaller reduction in stiffness due to warming was modelled. The stiffness and density profiles shown in Figures 2-5 were used to define the material properties for each analysis leading to a total of eight material models. A 500 N/m skier line load orientated across the slope was applied to the eight 'spring' and 'mid-winter' snow profiles. The boundaries of the snow were assumed encastre (fixed) except for the top surface that was left free to deform.

The finite element model was developed and then verified by comparing it with an ideal homogeneous elastic solution (Föhn, 1987) to ensure that there were no significant errors. Further analyses were performed assuming plane stress, and to test for boundary effects by removing the restraints at the ends of the slope. The models were developed using PATRAN (McNeal Schwindler Corp. Costa Mesa C.A.) and analyzed using ABAQUS (Hibbit, Karlson and Sorrenson, Rhide Island, N.Y.) the analyses were performed on a Silicon Graphics Origin 2000 (Silicon Graphics, Calgary, Alta.).

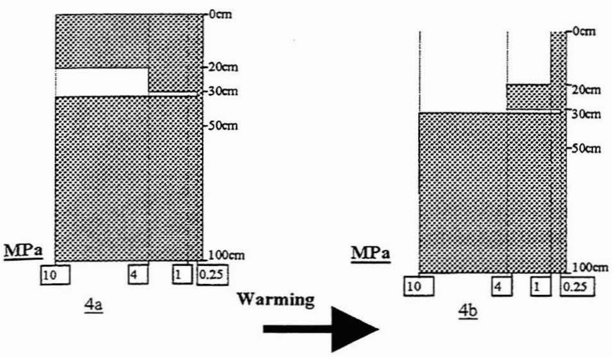

Figure 4a and 4b. Stiffness Profile for Spring Snow Conditions with a Weak Layer at 30cm

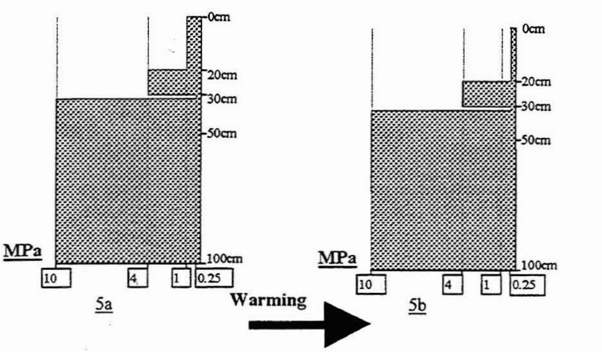

Figure 5a and 5b. Stiffness Profile for Mid-Winter Snow Conditions with a Weak Layer at 30cm

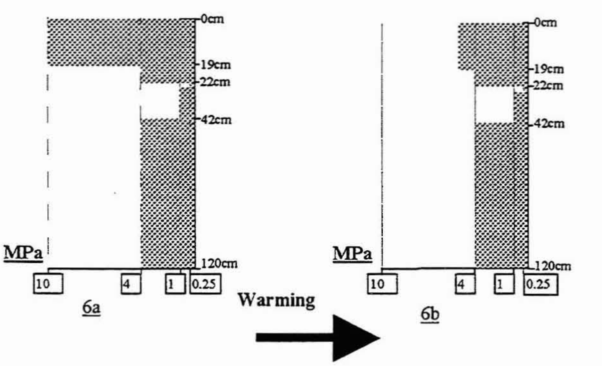

Figure 6a and 6b. Stiffness Profile for a Wind Slab with a Weak Layer at 22cm

In the first case of the spring and mid-winter snowpack models, material properties were chosen to study the effects of temperature change. The snow profiles represented spring and mid-winter snow conditions before and after warming. Typical values of Young's modulus (stiffness) and Poisson's ratio where chosen from Mellor (1975) and Shapiro et al. (1997) (Table 1). The stiffness profiles are shown in Figures 2 to 5. Considering each in turn, a weak layer at 50 cm with a spring snowpack (Figures 2a and 2b) and with a mid-winter snowpack (Figures 3a and 3b). The profiles for the weak layer at 30 cm with a spring snowpack are shown in Figures 4a and 4b and for the mid-winter snowpack in Figures 5a and 5b. For the analysis it was assumed that an increase in temperature reduced the stiffness of the top 20 cm of the snowpack, all other material properties, boundary conditions and loads remained constant. In the spring profiles, the refrozen top 20 cm of snow were assumed to warm and change in stiffness from 10 MPa (Figures 2a and 4a) to 1M Pa (Figures 2b and 4b). For the mid-winter profiles, the top 20 cm changed from 1 MPa (Figure 3a and 5a) to 0.25 MPa (Figures 3b and 5b).

The realistic profile (wind slab) is shown in Figure 6. There is a stiff wind slab to a depth of 19 cm and the weak layer is located down 22 cm. The model's boundary conditions and loads were the same as in previous analyses. The warming front was assumed to propagate the snow to a depth of 19 cm, reducing the stiffness of the whole wind slab. The other material properties remained constant (Table 1.). As a result of warming the stiffness was changed from 10 MPa to 5 MPa a reduction of 50 %. This change is in accordance with experimental data collected by Schweizer (1998) for a temperature change from –15°C to –5°C.

3. RESULTS

Before considering individual loading cases, the boundary conditions and finite element model were verified. Shear stresses and the distance to the peaks stress from the skier load from the homogeneous finite element model were compared with an analytical solution (Föhn, 1987). In both cases, the finite element solution tended to predict slightly larger shear stresses. The difference at depth y= 30 cm were in the order of 2.5 % for the peak stress, the maximum occurring at x=21 cm from the skier load for both the analytical and finite element solutions. At y=50 cm, the location of the peak shear stress in the numerical model was offset by about 2 cm compared to the analytical solution. The maximum shear stress occurring at x=33 cm for the finite element solution and x=35 cm for the analytical solution. The difference in peak stress at y=50 cm was less than 2 %. These differences were not considered significant.

When the plane stress and plane strain solutions were compared the maximum difference in shear stress beneath the skier load was in the order of 2 %. The end boundary conditions (fixed and free) were also compared. There was a difference of 2 % in the peak shear stress between

Table 2. Changes in peak shear stress as a result of warming for the spring and mid-winter snowpack models

Snow Pack	% Change in shear stress (30 cm weak layer)	% Change in shear stress (50 cm weak layer)	Change (Pa) in shear stress (30 cm weak layer)	Change (Pa) in shear stress (50 cm weak layer)
Spring	51 %	37 %	140	70
Mid-winter	8 %	6 %	30	10

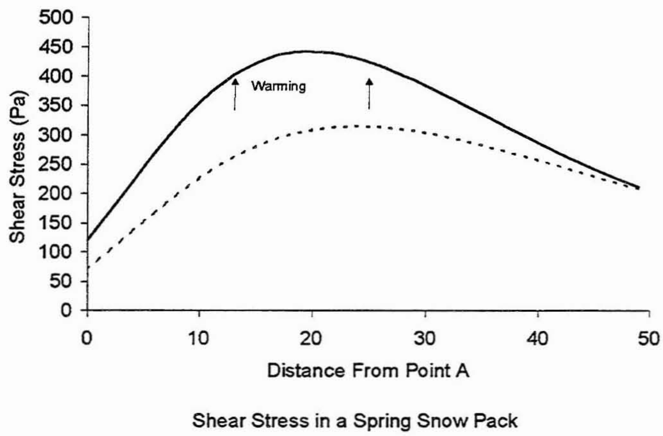

Figure 7. The shear stresses due to a skier for a weak layer at 30 cm before and after warming for a spring snowpack.

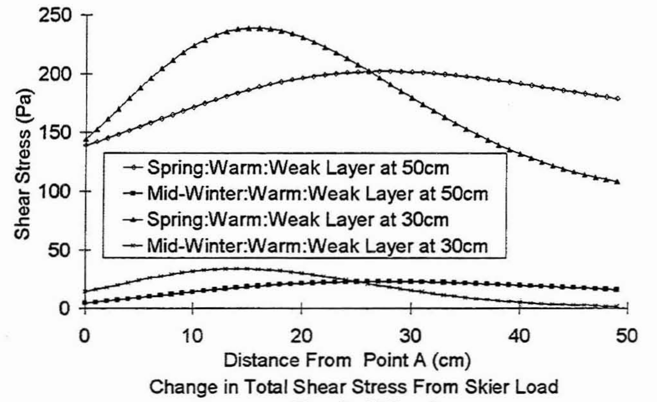

Figure 8. Change in shear stress due to a skier as a result of the snow changing from cold to warm: weak layers at 30 cm and 50 cm in spring and mid-winter snowpacks.

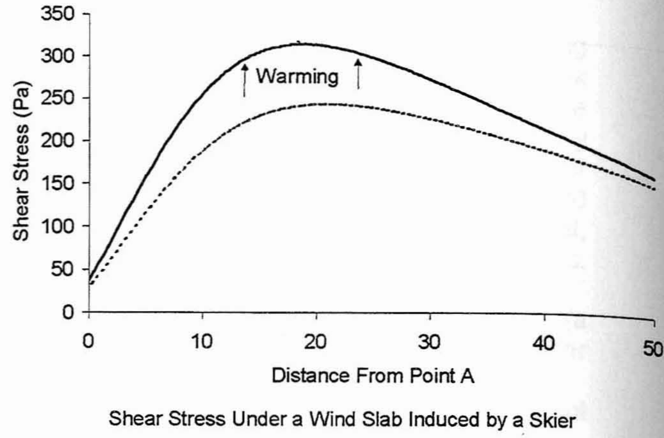

Figure 9. Shear stress before and after warming due to a skier for the wind slab profile.

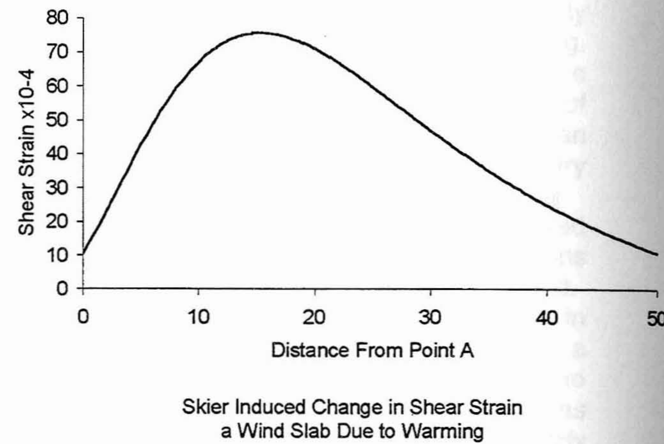

Figure 10. Change in shear strain due a skier for the wind slab profile

the plane stress, plane strain, fixed end and the free end conditions. When compared with the variability of the material properties (Mellor 1975), these errors were considered sufficiently small to be ignored. In accordance with previous studies (Föhn, 1987; Schweizer, 1993; Smith, 1972), the plane strain results are presented.

The typical shear stress distribution associated with a skier load is shown in Figure 7. As the slab softens (i.e., warms) the stress becomes more concentrated below the skis, i.e., the peak stress moves towards point A (Figures 1 and 7). This result is in accordance with numerical and experimental results by Schweizer (1993) and Camponovo and Schweizer (1997).

Skier loads caused a greater change in shear stress in the weak layer at 30 cm than at 50 cm for both models due to the general decrease of the skier stress with increasing depth (Table 2). The increase in peak shear stresses for all the warm snow conditions ranged from 6 to 51% with the spring snow showing the most changes. The change in stresses induced by the skier were much higher (140 vs. 70 Pa) in the spring snow pack. In mid-winter snow the same trend was observed but the stress were lower i.e., the skier caused a larger change in shear stress at 30 cm than at 50 cm (Figure 8). The results that the skier shear stress $\propto 1/h$ (where h is the depth beneath the skis) are again consistent with previous models, (e.g. Föhn, 1987).

The realistic profile (wind slab) showed an increase in shear stress in the weak layer as the snow warmed (Figure 9). The shear stress increased from 235 Pa to 310 Pa, an increase of 32 %. The peak stress occurred at X=16 cm down slope from point A. The change in shear strain for the wind slab profile and skier load is shown in Figure 10. The behaviour shown was typical for all models. In the wind slab case the shear strain change was at a maximum 16cm from point A with an increase in strain of 0.7%.

4. DISCUSSION

The object of this study was to determine the change in the skier-induced shear stress in weak layers of a snowpack as the uppermost snow layer was warmed. In order to determine the shear stresses, finite element models were developed to which a skier load was applied. The results showed that as the top of the snowpack was warmed, there was an increase in stress and strain within the weak layers. Upon warming the snowpacks representing 'spring' and 'mid-winter', a skier load increased the shear stress of the weak layer at 30 cm more than in weak layers at 50 cm (Table 2). These results are consistent with the work of McClung (1996) and McClung and Schweizer (1997).

The increasing stress due to warming is further supported by the results from the analysis of the realistic profile (wind slab) where again an increase in shear stress was observed in the weak layer as the snow warms. Since experienced observers thought that the slab was close to failure prior to warming, and the shear stresses induced by a skier would be transmitted more easily to the weak layers after warming, it is likely that this slab would have produced a skier-triggered avalanche.

This study showed that warming, when associated with a reduction in stiffness of the upper snowpack, plays a role in increasing shear stress in weak layers of a snowpack. As the stiffness of the upper layers was reduced while the load remained the same the strain increased. For the snowpack to remain a continuum, the softened snow, which was now straining more, transferred its strain to the layers below, therefore increasing stress and strains in deeper layers. This increase in stress and strain may cause failure within the weak layers and consequently avalanche activity.

In the current study, after the top 19-20 cm of snow was warmed, skier loads increased the stress in all the weak layers. Hence, these results suggest that skier-triggered slab failure is more likely after warming.

In conclusion, even if warming effects do not extend as deep as weak layers themselves, this study shows that there is increase in shear stress in the weak layers as a result of warming. If stability is rated low to moderate this increase could be large enough to induce shear failure. Thus, warming may increase the likelihood of skier triggered avalanches, even if weak layers are not warmed.

5. ACKNOWLEDGEMENTS

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