Cold Regions Science and Technology 54 (2008) 176–182

Contents lists available at ScienceDirect

Cold Regions Science and Technology

journal homepage: www.elsevier.com/locate/coldregions

Influence of snowpack layering on human-triggered snow slab avalanche release

Marijke Habermann [a], Jürg Schweizer [a,*], J. Bruce Jamieson [b]

[a] WSL Swiss Federal Institute for Snow and Avalanche Research SLF, Davos, Switzerland
[b] Department of Civil Engineering, Department of Geoscience, University of Calgary, Calgary AB, Canada

ARTICLE INFO

Article history:
Received 30 August 2007
Accepted 22 May 2008

Keywords:
Snow stratigraphy
Snow avalanche
Avalanche formation
Snow stability
Skier triggering
Numerical modeling

ABSTRACT

Dry-snow slab avalanches involve the release of a cohesive slab over an extended plane of weakness. In most fatal avalanches, the triggering of the initial failure occurred by localized rapid near-surface loading by people — followed by fracture propagation. Whereas a limit-equilibrium (LE) approach to snow slope failure only takes into account slab depth, slab density and weak layer strength, it omits properties such as the stiffness of adjacent layers and the fracture propagation process. Nevertheless, LE has been applied with some success to the frequency of skier triggering, suggesting that it is relevant to failure initiation. Since field studies have shown that, for a given slab thickness, stiffer slabs are less likely to be triggered, slab properties influence failure initiation, fracture propagation or both. A highly simplified finite element (FE) model of static skier loading was used to assess the effect of slab and substratum properties on skier-induced stresses in the weak layer. Compared to a uniform slab, the skier-induced stress at the depth of the weak layer varied by a factor of 2 due to layering. In particular, the simplified FE model suggests that while stiffer layers in the slab will reduce the skier-induced stress in the weak layer, stiff layers just below the weak layer can increase the shear stress. These results were incorporated into a modified stability index and compared to stability test results. However, by taking into account snowpack layering the correlation between the modified stability index and stability test results did not improve. While our simulations suggest that less stress penetrates through stiffer slabs and thus fracture initiation is less likely, other studies show that, once initiated, fractures under stiffer slabs have high propagation propensity.

1. Introduction

Dry-snow slab avalanches involve the release of a cohesive slab over an extended plane of weakness (McClung and Schaerer, 2006). Most fatal avalanches are triggered by people (e.g. Schweizer and Lütschg, 2001). Slab release involves fracture initiation followed by fracture propagation (Schweizer et al., 2003). Previous studies showed that the skier skier-induced shear stress in a weak layer under a slab decreases strongly with increasing slab thickness (Föhn, 1987a) and depends on slab layering (Schweizer, 1993). Measurements of the skier's dynamic impact in the snow cover showed the hardness of the slab layers to be the most important variable in respect to penetration of deformation (Camponovo and Schweizer, 1997; Schweizer and Camponovo, 2001; Schweizer et al., 1995). Hardness is assumed to be an analogue for stiffness; the terms are used interchangeably in McClung and Schweizer (1999). Harder slab layers restricted deformation at depth thereby reducing the chance of causing a fracture in the weak layer. Zeidler (2004, p. 172) gives a time series in which a surface crust inhibited skier triggering in a snowpack otherwise favourable to skier triggering. This effect is sometimes called "bridging" (Schweizer and Jamieson, 2003). As snow stiffness (hardness) is also highly temperature dependent, the skier's impact is expected to vary with slab temperature (McClung and Schweizer, 1999).

Before the first measurements of the skier's impact in the snow cover revealed the importance of slab layering, numerical simulations using the finite element method suggested that hard surface layers decrease the skier's impact and that hardness changes might cause stress concentrations at the interface between layers of different hardness (Schweizer, 1993). These simulations considered the elastic response of a layered snowpack to a static surface load which represented the skier. The effect of layering has long been studied for other applications (e.g. Das, 1983), for example, pavement design (Burmister, 1945) and most are based on the solution by Boussinesq (1885) for the stress distribution below a localized load in an elastic half space. Recently, finite element simulations by Jones et al. (2006) suggested that the substratum stiffness also has a substantial effect on the shear stress in the weak layer.

Field studies have shown that harder and deeper slabs are associated with larger (wider) dry-snow slab avalanches (e.g. Jamieson and Johnston, 1992; McClung and Schweizer, 2006). van Herwijnen and Jamieson (2007) found that while the frequency of skier triggering decreased with increasing slab thickness and

* Corresponding author. WSL Swiss Federal Institute for Snow and Avalanche Research SLF, Flüelastrasse 11, CH-7260 Davos Dorf, Switzerland. Tel.: +41 81 4170164; fax: +41 81 4170110.
E-mail address: schweizer@slf.ch (J. Schweizer).

0165-232X/$ – see front matter © 2008 Elsevier B.V. All rights reserved.
doi:10.1016/j.coldregions.2008.05.003

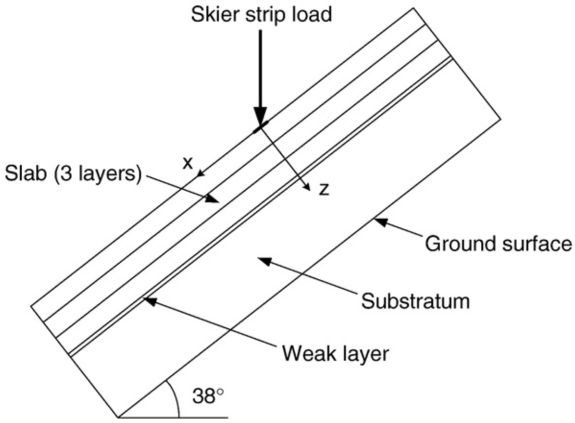

Fig. 1. Geometry of finite element model (not to scale). The model is 10 m long. In the standard geometry, the thicknesses of slab, weak layer and substratum are 0.36 m, 0.005 m and 1 m, respectively.

hardness, the size and width of skier-triggered avalanches increased with increasing slab thickness and hardness. These findings suggest that fracture propagation is favoured by hard and deep slabs. Hence, the slab properties not only influence the transmission of deformation to the weak layer (and hence are relevant to failure initiation) but are also important for fracture propagation. For a given geometry, the energy that is available for crack propagation depends mainly on the material properties of the overlying slab (and potentially on the weak layer collapse height) (Sigrist and Schweizer, 2007; Heierli and Zaiser, 2008).

The skier stability index which has been refined by Jamieson and Johnston (1998) is a limit-equilibrium (LE) approach to snow slope failure. Although it includes the snowpack properties: weak layer strength, slab depth and slab density, it excludes the stiffness of layers above and below the weak layer. As an indicator of failure initiation (but not fracture propagation), it has been applied with some success to the frequency of skier triggering (Föhn, 1987a; Jamieson and Johnston, 1998). The skier stability index has also been implemented in snow cover modeling to predict stability (Giraud and Navarre, 1995; Lehning et al., 2004). Structural instability indicators such as threshold sums (e.g. McCammon and Schweizer, 2002; Schweizer and Jamieson, 2007) have recently been combined with the skier stability index to locate potential weaknesses in simulated snow stratigraphy (Schweizer et al., 2006).

The aim of the present study was to clarify the influence of snowpack layering on the skier-induced shear stress (or deformation) in the weak layer for typical slab and substratum properties, and further incorporate the effect of layering into the skier stability index. Since the skier's impact is highly dynamic and destructive, and the response of the snowpack is non-linear, we initially explored the approach by Haehnel and Shoop (2004). However, a dynamic model would have involved poorly confined dynamic response parameters. Also, we could verify a static linear elastic model for a homogeneous snowpack with an analytical solution, something not feasible for a dynamic finite element model. Further, we wanted to assess a much greater variety of layer properties than Jones et al. (2006) did in their static linear elastic model.

The dynamic loading by a skier involves compaction of the surface layers due to ski penetration leading to energy dissipation. However, in eighteen field measurements by Camponovo and Schweizer (1997), the dynamic stress caused by a skier pushing down on the skis was close to the static analytical solution — provided that the measurement was at least 10 cm below the skis and that ski penetration was taken into account. These measurements were made with a variety of unreported layer properties, which was another reason for this study of the effect of stratigraphy on skier-induced stress.

2. Methods

We used a two-dimensional finite element model of a layered snowpack with slope angle ψ=38° (Jones et al., 2006). Plane strain conditions were assumed. Except for the skier loading, the top surface was stress-free. No displacement was allowed between snowpack and ground. Also, no relative displacement between adjacent snow layers was allowed. The side boundaries were fixed. Snow within a particular layer was homogeneous and isotropic. A linear elastic behaviour was assumed to model the skier's response which seems justified given the rapid loading rate.

The skier was modeled by applying a strip load 0.2 m wide giving a surface stress of 3.9 kPa oriented across the slope on the otherwise stress-free snow surface. Although ski penetration is clearly a factor for the stress penetration into the snowpack, we consider only the snow below the skis as the effective slab depth for the FE model and the analytical model. (Static stress due to the snow above the skis can be added.) We calculated the static shear stress below the skis, $\Delta\tau$, which is the static analogue to the dynamic stress to which snow is very sensitive.

2.1. Model geometry

The 10-m long model geometry included the slab (0.36 m thick in the standard model) consisting of three layers, the weak layer (0.005 m thick in the standard model), and the substratum (1 m thick in all models) (Fig. 1). The layer thicknesses were chosen to represent a typical mid-winter snowpack with a typical slab thickness. The slope perpendicular slab thickness of 0.36 m corresponds to a fracture depth (measured vertically) of about 0.46 m which was found to be the median fracture depth of skier-triggered avalanches (Schweizer and Jamieson, 2001). The slab and weak layer thickness were varied from their values for the standard model (see results below) to check whether the results would depend on the chosen model geometry or can be considered as sufficiently generic.

The model domain was divided into two-dimensional, four-nodded quadrilateral plane strain elements. To save computing time but still get accurate results in the area of the skier loading, the mesh got finer from the ground toward the weak layer and from the up-slope and down-slope ends toward the middle where the load was concentrated. The refined mesh consisted of 120,000 elements. The ANSYS workbench was used to calculate the nodal forces, and stress and strain within each element.

2.2. Material properties

Table 1 summarizes the material property values (Young's modulus E, Poisson's ratio ν and density ρ). Three sets of material properties (soft, medium and hard) corresponding to three layers of varying stiffness (or hardness) were chosen based on data compiled from Mellor (1975) and Shapiro et al. (1997) and previous work by Wilson et al. (1999). A fourth set of material properties described the weak layer. Corresponding to the layer densities, hand hardness indices of Fist (F), Four fingers (4F) and One finger (1F) were assigned (Colbeck et al., 1990). The values in the literature for Poisson's ratio

Table 1
Material properties used in the finite element model

Layer characteristic	Hand hardness index	Density ρ (kg m^{-3})	Young's modulus E (MPa)	Poisson's ratio ν
Soft	F (Fist)	120	0.3	0.25
Medium	4F (Four fingers)	180	1.5	0.25
Hard	1F (One finger)	270	7.5	0.25
Weak layer	F-	100	0.15	0.25

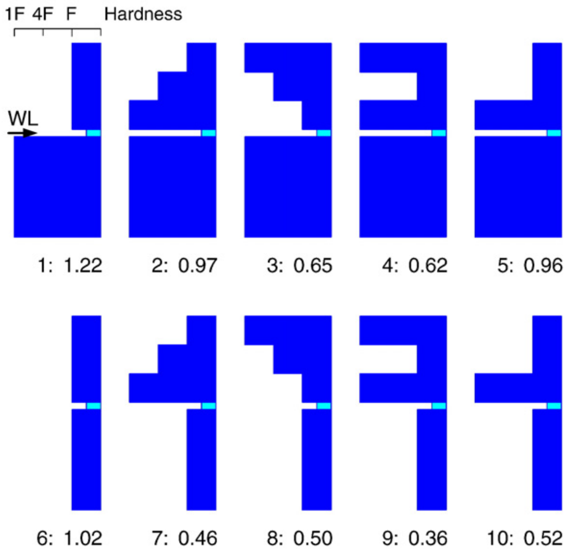

Fig. 2. Schematic of the ten snowpack profiles used for simulation represented as hardness profiles (not to scale). The arrow points to the location of the weak layer (WL). The numbers below denote the profile number and the *k*-value.

vary widely between about 0.15 and 0.4. However, Smith et al. (1971) found that their model results did not vary strongly as a function of Poisson's ratio so we used a uniform value of 0.25 throughout our simulations. The absolute values of, for example, the stiffness are not crucial since we were mainly interested in shear stress which depends on the relative changes in E and ρ. However, we have varied the material properties (see Results below) to check whether results obtained with the chosen model geometry can be considered as sufficiently generic.

2.3. Hardness profiles

Five different typical slab hardness profiles were modeled on either a hard or soft substratum (profiles 1–10) (Fig. 2). The profiles were chosen such that there were hard and soft surface layers as well as hard and/or soft layers just above and/or below the weak layer. Some of the profiles resemble schematic hardness profiles that Schweizer and Wiesinger (2001) proposed to classify snow cover stratigraphy for stability evaluation.

2.4. Comparison of finite element model with analytical solution

Finite element results with uniform material properties were compared to the analytical solution for a strip load (McClung and Schweizer, 1999). The modeled maximum shear stress at a given depth in the snowpack was within 1.7% of the analytical solution. The comparisons were done using both fixed and free upper and lower boundary conditions. There was a difference of less than 3% in the peak shear stress in the weak layer when comparing fixed with free boundary conditions. These errors due to the choice of the boundary conditions were considered negligibly small compared with the uncertainty introduced by the choice of material properties and the simplified loading conditions. The latter errors cannot easily be quantified.

2.5. Analysis

To compare model results that were obtained with different material properties and layering, a k-value was introduced. It is the ratio of the additional shear stress in the weak layer determined by the FEM simulation ($\Delta\tau_{\text{layered}}$) and the maximum additional shear stress obtained by the analytical solution at the same depth for a snowpack with uniform material properties ($\Delta\tau_{\text{uniform}}$):

$$k = \frac{\Delta\tau_{\text{layered}}}{\Delta\tau_{\text{uniform}}}. \qquad (1)$$

The k-value is an index of the effect of snowpack layering on the shear stress in the weak layer. These k-values were calculated for the ten characteristic profiles. The k-values were also used to assess the effect of varying weak layer and slab thicknesses, and for the effect of hard layers such as melt-freeze crusts.

2.6. Field data

To study the effect of slab properties on the skier stability index and in particular of its correlation with the rutschblock stability test score (Föhn, 1987b), a dataset from the Columbia Mountains of western Canada was used. It consisted of 37 snow profiles (including layer density) with rutschblock tests and shear frame measurements for the weak layer that fractured in the corresponding rutschblock test. The shear frame measurements provided the shear strength values (Jamieson and Johnston, 2001) required to calculate the skier stability index Sk_{38} (Jamieson and Johnston, 1998). For each profile a finite element model was built. The Young's modulus was estimated from layer density according to the power law that was fitted by Sigrist (2006):

$$E = A\left(\frac{\rho}{\rho_0}\right)^{2.94} \qquad (2)$$

with A=968 MPa and the density of ice ρ_0=917 kg m^{-3}. This relation gives relatively high values of Young's modulus compared to values from the literature (e.g. Mellor, 1975). However, only relative changes in the elastic modulus from layer to layer were relevant for this study.

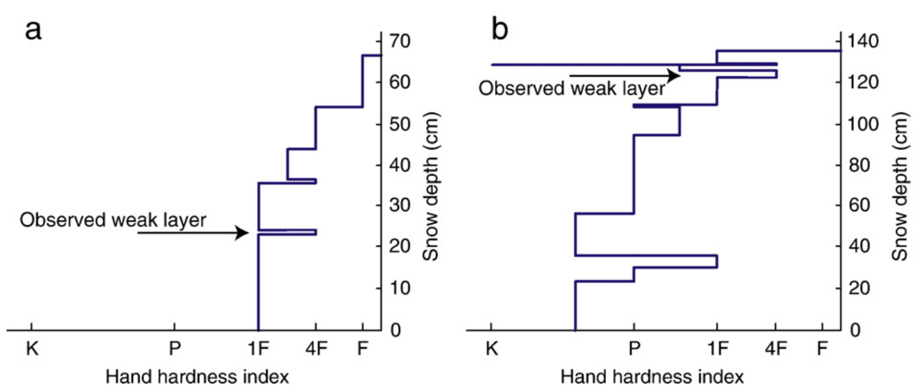

Fig. 3. Examples of snow profiles given as hand hardness profiles. Surface layers penetrated by skis not shown. (a) Profile with increasing slab hardness. (b) Profile with thin, hard layer (crust) above weak layer.

The ski penetration that was measured for each profile was taken into account by building the finite element model without the top layers that were penetrated by the skis, thereby resetting the origin of the model (i.e. the snow surface) to the depth of the ski penetration. Fig. 3 shows two examples of field hardness profiles, one with increasing slab hardness, the other one with a thin, hard layer (crust) above the weak layer. Rutschblock scores were 3 and 6, respectively.

3. Results

Fig. 4 shows the effect of the layering on the additional shear stress compared with the analytical solution for schematic hardness profiles 1 and 10. Profile 1 had a soft slab and a hard substratum, whereas profile 10 had a mostly soft slab but with a hard layer just above the weak layer and a soft substratum. A hard substratum as in profile 1 increased the shear stress in the weak layer ($k=1.2$), whereas a hard layer in the slab reduced it ($k=0.52$) and distributed the stresses over a slightly wider area (Fig. 4a). In Fig. 2 the k-values for all 10 profiles are given. The k-values varied substantially from about 1.2 to 0.4. Except for a soft slab and especially when combined with a hard substratum, the additional shear stress was in most cases less than the value provided by the analytical solution, i.e. $k<1$. The different slab properties resulted in abrupt changes of the additional shear stress, i.e. hardness changes in the slab caused peaks (stress concentrations) in the stress gradient (Fig. 4b).

3.1. Weak layer thickness

To assess whether the chosen model geometry was sufficiently general, the weak layer thickness was varied between 1 mm and 11 mm. The variations in the weak layer thickness had hardly any effect on the k-values in the case of profiles 6–10, each of which had a soft substratum. The k-values for a weak layer thickness of 1 mm were about 0.8% larger than for a weak layer thickness of 5 mm (standard model), and about 1.5% lower for a weak layer thickness of 11 mm. However, for profiles with a hard substratum (profiles 1 to 5) the k-value decreased with increasing weak layer thickness, in particular for profiles 2 and 5, and to some lesser degree for profile 4. In all these profiles the weak layer was sandwiched between two hard layers. If the weak layer was only 1 mm thick, the k-values for profiles 2 and 5 increased to about 1.2, which is approximately 25% higher than the k-value for a 5-mm-thick weak layer. For a 11 mm thick weak layer, the k-value decreased to 0.96, which is about 16% less than for a 5 mm-thick weak layer.

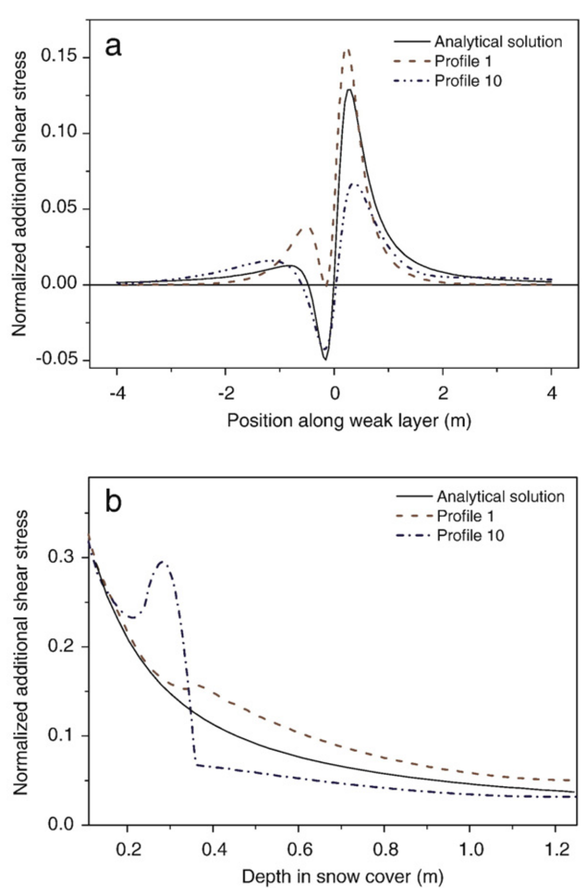

Fig. 4. (a) Additional shear stress along the weak layer and (b) maximum additional shear stress versus depth (normalized to skier load: 3.9 kPa) for profiles 1, 10 and the analytical solution (strip load, uniform material properties).

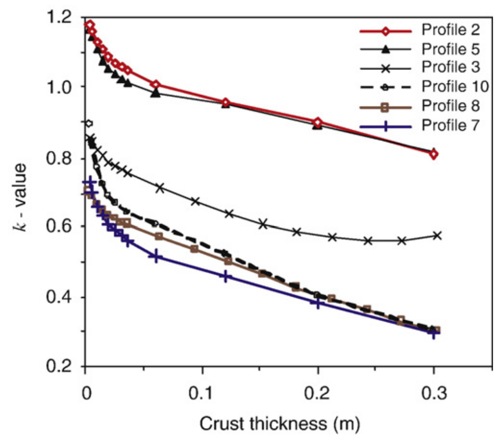

Fig. 5. Variations of the k-value with crust (or hard layer) thickness for profiles 2, 5, 7 and 10 that all had a hard layer just above the weak layer, and profiles 3 and 8 that had hard layer at the surface.

3.2. Slab thickness

The slab thickness (or the weak layer depth) was varied between 0.2 m and 1.2 m, and the thickness of the slab layers were was scaled with the slab thickness. The effect on the k-value was relatively minor. With increasing slab thickness, the k-values tended to decrease slightly — except for profile 2 for which the k-value increased. For profiles 7 and 8, the k-value decreased by about 10%, if the slab thickness was doubled to 0.72 m. When the slab thickness in profile 3 was doubled, the decrease in k was only about 2%. However, for profile 2, doubling the slab thickness increased the k-value by about 14%. The reason for this increase is not fully clear but it seems that with a hard substratum relatively more stress is imparted to the weak layer as the thickness of the soft near-surface layer increases.

3.3. Material properties

Varying the material properties of the slab layers caused changes in the k-values by typically less than the proportional change in slab properties. The density of the slab layers in profiles 2 and 3 was changed by ±20% and consequently the Young's modulus was changed according to the power law relation in Eq. (2). Relative changes in relation to the original k-value varied between 0.1 and 24%. Substantial changes were found if the layer which became harder or softer was either close to the weak layer or it was initially a hard layer close to the surface.

3.4. Crusts

Since crusts (which are modeled as thin, hard layers) play an important role in the avalanche snowpack (Jamieson, 2006), it was studied how the thickness of hard slab layers affects the amount of

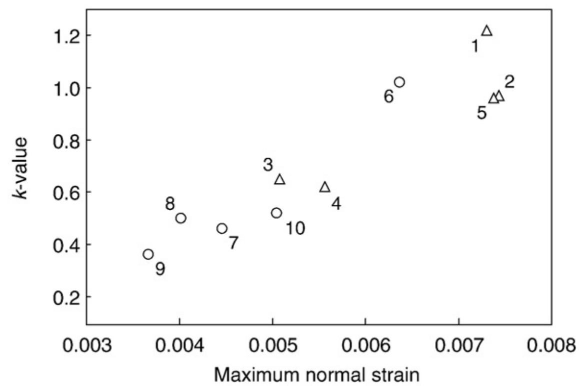

Fig. 6. Maximum normal strain in the weak layer vs. k-value for profiles 1–5 (triangles) and profiles 6–10 (open circles).

stress imparted to the depth of the weak layer. Fig. 5 shows the effect of crust thickness on the k-value. The k-value consistently decreased with increasing crust thickness — regardless of whether the crust was just above the weak layer or at the snow surface. The thinner the crust, the more stress was imparted to the weak layer. However, even when the crust was located just above the weak layer, no stress concentration was observed in the stress profiles (e.g. Fig. 4b) compared to the stress profile for a uniform soft slab. As can be seen in Fig. 5, only for profiles 2 and 5, and only when the crust was thinner than about 5 cm, was the k-value larger than 1. However, even for of the thinnest crust we modeled (3 mm), the k-value was lower than the k-value of 1.22 for profile 1, which had a uniformly soft slab. In general, the decrease in k-value with increasing crust thickness in the slab was attenuated by a hard substratum. The simulations for profiles 7, 8 and 10 showed that with thick hard layers (>20 cm) the material properties of the remaining slab layers became less important — regardless of the position of the hard layer in the slab. Finally, it was found that with a soft substratum the position of the crust within the slab had little influence on the k-value, whereas with a hard substratum the position had a greater effect. The k-values for the profiles in Fig. 5 show that if the hard layer was close to the weak layer (as in profile 2), the k-value was substantially larger than if it was close to the surface (as in profile 3).

3.5. Deformation

In our linear elastic model, stresses and strains are proportional. However, because failure strains are used to characterize failure (Narita, 1980) and as it is essential how much deformation is imparted to the weak layer, we summarize our results in terms of strain. In contrast to the stress, the strain depends on the absolute values of the material properties. Whereas the displacement continuously decreases with increasing depth, despite the changes in material properties, the strain will vary strongly with depth and changes in strain gradient may be found where material properties change. The lower the Young's modulus in a particular layer, the larger the strain. In all ten profiles of our model geometry, significant strain concentrations were found. Those were most prominent with hard layers above or below the weak layer. In Fig. 6 the k-values indicating the amount of stress concentration in the weak layer due to snowpack layering were compared to the maximum normal strain in the weak layer. The maximum normal strain depended on the snowpack layering in a very similar way as the k-values. In general, profiles 1 to 6 caused higher normal strain concentrations than profiles 7 to 10 which all had a soft substratum. These results suggest that slab layering affects normal and shear stress (or strain) in a weak layer in a similar way. Examining shear and normal strain more closely showed that the shear strain was relatively larger than the normal strain for profiles 1 to 6 (i.e. the proportion of shear to normal strain was larger than $\tan\psi$, and even slightly greater than 1 for profiles 1, 3 and 6).

3.6. Skier stability index

We compared the skier stability index Sk_{38} calculated from the field data (not taking into account any slab properties except average slab density and slab thickness) to the index determined with additional shear stress calculated with the FE element model in which the Young's modulus of the layers was based on measured density (Eq. (2)).

In the example with increasing slab hardness (Fig. 3a) the shear stress calculated with the specific FE model increased compared to the analytical solution. Consequently, the skier stability index Sk_{38} decreased from 1.8 to 1.4, which is more consistent with the low rutschblock score of 3 (Jamieson, 1995, p. 178). We note that the upper soft layer would be compacted by the skis — an effect missing from our model. In the second example (Fig. 3b), the shear stress slightly decreased so that the skier stability index Sk_{38} increased from 0.5 to 0.6, which is again a shift in the right direction but still the value of the Sk_{38} is too low compared with the rutschblock score of 6. Considering the 37 profiles, the skier stability index based on the simulations slightly decreased (median index 1.15 compared to 1.35) (Fig. 7). This is surprising, considering slab properties only occasionally resulted in higher values of shear stress in the weak layer. This might be due to

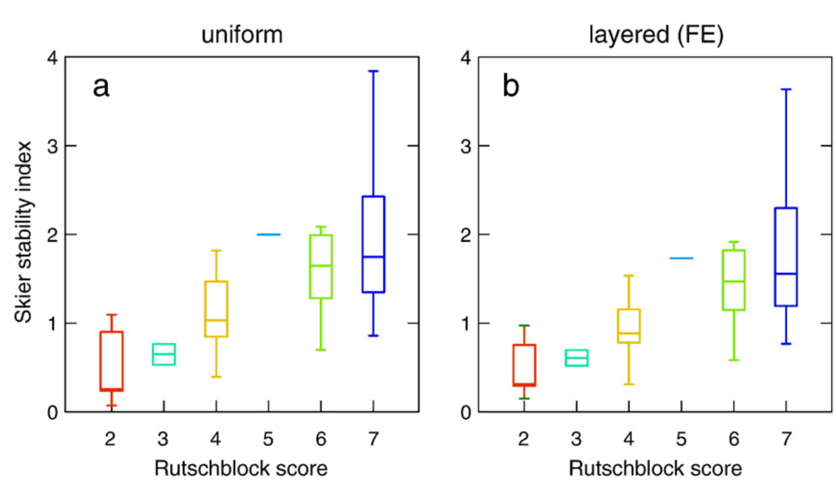

Fig. 7. Skier stability index vs. rutschblock score (N=37): (a) Sk_{38} not taking into account layering, i.e. uniform snow properties, and (b) Sk_{38} determined with additional shear stress calculated with finite element model including layering.

the fact that the dataset included many soft slabs, most with substrata stiffer than the weak layer. Overall, the Spearman (rank) correlation coefficient between the skier stability index that takes into account snowpack layering and the rutschblock score (which implicitly includes layering) only changed from 0.67 to 0.69. As the rutschblock score is only a proxy for triggering probability, the correlation might still improve if the results of skier skier-tested slopes would be considered.

4. Discussion

The simulations suggest that the difference in hardness across the failure interface contributes more to the additional skier-induced stress in the weak layer if a soft weak layer overlies a hard substratum (soft-on-hard) than if a hard layer or crust in the slab overlies the weak layer (hard-on-soft). In other words, crusts above weak layers seem to have less effect on snowpack stability (failure initiation) than crusts below the weak layer. This is partly surprising since Schweizer and Jamieson (2003) found hardness differences across failure interfaces related to snowpack stability but the hardness configuration (soft-on-hard vs. hard-on-soft) did not show up as significant variable separating rather stable from rather unstable profiles. However, Schweizer and Jamieson (2001) found in general a larger hardness difference to the layer below than to the layer above a weak layer. Therefore, we re-analyzed the data used by Schweizer and Jamieson (2007) which was an update of the data used by Schweizer and Jamieson (2003). In fact, if contrasting the hardness difference of stable/unstable profiles separately for soft-on-hard and hard-on-soft layering across the failure interface, the hardness difference was a highly significant variable for soft-on-hard layering ($p<0.0001$, $N=236$) whereas for hard-on-soft layering it was only marginally significant ($p=0.045$, $N=139$). This result confirms similar findings by van Herwijnen and Jamieson (2007). Further, field studies by Savage (2006) and Jamieson et al. (2001) related increased substratum hardness to deep slab avalanches.

Our results suggest that slab properties strongly affect the amount of stress (strain) at the weak layer depth, and hence influence failure initiation. Other studies (Heierli and Zaiser, 2008; Sigrist and Schweizer, 2007; van Herwijnen and Jamieson, 2007) have shown a similarly strong effect of slab properties on fracture propagation. Their findings show that stiffer (denser) and thicker slabs favour fracture propagation, whereas our results suggest that failure initiation is more likely with softer and thinner slabs. Therefore, slab properties seem to influence failure initiation as well as fracture propagation. In terms of stiffness they obviously have opposite effects on failure initiation and fracture propagation. These opposing effects have already been proposed by van Herwijnen and Jamieson (2007) for slab thickness: while thicker slabs generally hinder fracture initiation, they typically favour fracture propagation.

Though we have focused on the skier-induced shear stress in the weak layer below the slab, the additional load by a skier causes in fact a mixed-mode (compression/shear) loading situation. However, as the model results suggest that layering affects normal and shear stress at weak layer depth in a similar way, our findings should be relevant regardless of the type of initial fracture (shear/compression).

Including layering in the stability index did not significantly improve its correlation with the rutschblock score. This is partly attributable to a lack of data from slopes with pronounced hard layers in the slab or at the bed surface (substratum). The data were collected in areas of the Columbia Mountains known for soft snow, i.e. wind stiffened layers and crusts are infrequent between December and March when we collected our data. Further, the bridging effect of stiff slab layers is reduced in rutschblock tests, which involve fully isolated columns of 3 m^2. The effect of bridging would be greater on continuous slabs on open slopes, but we had insufficient data for ski-tested avalanche slopes with strength measurements of the weak layer and density measurements of layers from the surface to the substratum. Furthermore, the lack of improvement might be related to dynamic effects (including snow compaction below skis) which we neglected.

5. Conclusions

A highly simplified 2D finite element model of static skier loading was used to assess the effect of slab and substratum properties on the additional shear stress in the weak layer. The model was compared with results from an analytical solution for a homogeneous snowpack and the model geometry found to be sufficiently generic. Ten typical, strongly simplified profiles of snowpack layering were considered.

The simulations suggest that compared to uniform snowpack properties, the additional skier-induced stress at the depth of the weak layer can vary by a factor of about 2 depending on layering. Hard layers or crusts in the slab always reduced the additional skier-induced stress, even with small crust thickness (3 mm) and even if located just above the weak layer. On the other hand, a hard substratum considerably increased the additional shear stress in the weak layer. Whereas it is uncertain how well the highly simplified model reproduces real conditions including dynamic loading by skiers, these findings are consistent with the field observations of Jamieson et al. (2001), Zeidler (2004) and Savage (2006) and explain why crusts above the weak layer make skier triggering less likely whereas crusts below the weak layer have the opposite effect. Still, the hardness difference across a failure interface remains a relevant structural index of instability. The modeled hardness profiles caused substantial strain concentrations in the weak layer. Based on 37 profiles near rutschblock tests, including the layering in the stability index did not significantly improve the correlation with the rutschblock score. However, rutschblock tests involve isolated blocks and thus underestimate the “bridging” effect of stiff slab layers. Further field data, preferably for skier-tested slopes, need to be analyzed to assess whether the additional information about snowpack layering will improve the skier stability index. In particular, in cases of hard layers in the slab, we expect the stability index to be improved by including slab layering.

Whereas, the simulations suggest that hard layers in the slab decrease the additional skier-induced stress in the weak layer thereby decreasing the probability of triggering (failure initiation), these hard layers may, on the other hand, still be highly relevant for fracture propagation. Hence, while a stiffer (and thicker) slab makes skier-induced fracture initiation less likely, such slabs favour fracture propagation. These opposite effects suggest that there is an optimal (intermediate) slab configuration in terms of thickness and stiffness for skier triggering of dry-snow slab avalanches.

Future attempts to assess the effect of layering on skier-induced stress could include dynamic stresses as well as ski penetration. The latter effect depends on snow compaction under the skis and ski bending, and hence would benefit from 3D modeling.

Acknowledgements

We are grateful for the helpful comments by two anonymous reviewers and by the Editor Garry Timco.

References

Boussinesq, J., 1885. Application des potentiels à l'étude de l'équilibre et du mouvement des solides élastiques. Gauthier-Villars, Paris, France, p. 508.

Burmister, D.M., 1945. The general theory of stresses and displacements in layered systems I, II, III. J. Appl. Phys., 16: 89–96, 126–127, 296–302.

Camponovo, C., Schweizer, J., 1997. Measurements on skier triggering, Proceedings International Snow Science Workshop ISSW 1996, Banff, Alberta, Canada, 6–10 October 1996. Canadian Avalanche Association, Revelstoke BC, Canada, pp. 100–103.

Colbeck, S.C., et al., 1990. The International Classification of Seasonal Snow on the Ground. International Commission on Snow and Ice (ICSI), International Association of Scientific Hydrology, Wallingford, Oxon, U.K., p. 23.

Das, B.M., 1983. Advanced Soil Mechanics. McGraw-Hill, New York, p. 511.
Föhn, P.M.B., 1987a. The stability index and various triggering mechanisms. In: Salm, B., Gubler, H. (Eds.), Symposium at Davos 1986 — Avalanche Formation, Movement and Effects, IAHS Publ., 162. International Association of Hydrological Sciences, Wallingford, Oxfordshire, U.K., pp. 195–214.
Föhn, P.M.B., 1987b. The Rutschblock as a practical tool for slope stability evaluation. In: Salm, B., Gubler, H. (Eds.), Symposium at Davos 1986 — Avalanche Formation, Movement and Effects, IAHS Publ., 162. International Association of Hydrological Sciences, Wallingford, Oxfordshire, U.K., pp. 223–228.
Giraud, G., Navarre, J.P., 1995. MEPRA et le risque de déclenchement accidentel d'avalanches. In: Sivardière, F. (Ed.), Les apports de la recherche scientifique à la sécurité neige, glace et avalanche. Actes de Colloque, Chamonix, 30 mai-3 juin 1995. ANENA, Grenoble, France, pp. 145–150.
Haehnel, R.B., Shoop, S.A., 2004. A macroscale model for low density snow subjected to rapid loading. Cold Reg. Sci. Technol. 40 (3), 193–211.
Heierli, J., Zaiser, M., 2008. Failure initiation in snow stratifications containing weak layers: Nucleation of whumpfs and slab avalanches. Cold Reg. Sci. Technol. 52 (3), 385–400.
Jamieson, J.B., 1995. Avalanche prediction for persistent snow slabs. Ph.D. Thesis, University of Calgary, Calgary AB, Canada, 258 pp.
Jamieson, J.B., 2006. Formation of refrozen snowpack layers and their role in slab avalanche release. Rev. geophys. 44 (2), RG2001. doi:10.1029/2005RG000176.
Jamieson, J.B., Johnston, C.D., 1992. A fracture-arrest model for unconfined dry slab avalanches. Can. Geotech. J. 29, 61–66.
Jamieson, J.B., Johnston, C.D., 1998. Refinements to the stability index for skier-triggered dry slab avalanches. Ann. Glaciol. 26, 296–302.
Jamieson, J.B., Johnston, C.D., 2001. Evaluation of the shear frame test for weak snowpack layers. Ann. Glaciol. 32, 59–68.
Jamieson, B., Geldsetzer, T., Stethem, C., 2001. Forecasting for deep slab avalanches. Cold Reg. Sci. Technol. 33 (2–3), 275–290.
Jones, A.S.T., Jamieson, J.B., Schweizer, J., 2006. The effect of slab and bed surface stiffness on the skier-induced shear stress in weak snowpack layers. In: Gleason, J.A. (Ed.), Proceedings ISSW 2006. International Snow Science Workshop, Telluride CO, U.S.A., 1–6 October 2006, pp. 157–164.
Lehning, M., Fierz, C., Brown, R.L., Jamieson, J.B., 2004. Modeling instability for the snow cover model SNOWPACK. Ann. Glaciol. 38, 331–338.
McCammon, I., Schweizer, J., 2002. A field method for identifying structural weaknesses in the snowpack. In: Stevens, J.R. (Ed.), Proceedings ISSW 2002. International Snow Science Workshop, Penticton BC, Canada, 29 September–4 October 2002. International Snow Science Workshop Canada Inc., BC Ministry of Transportation, Snow Avalanche Programs, Victoria BC, Canada, pp. 477–481.
McClung, D.M., Schaerer, P., 2006. The Avalanche Handbook. The Mountaineers Books, Seattle WA, U.S.A., p. 342.
McClung, D.M., Schweizer, J., 1999. Skier triggering, snow temperatures and the stability index for dry slab avalanche initiation. J. Glaciol. 45 (150), 190–200.
McClung, D.M., Schweizer, J., 2006. Fracture toughness of dry snow slab avalanches from field measurements. J. Geophys. Res. 111 (F4), F04008. doi:10.1029/2005JF000403.
Mellor, M., 1975. A Review of Basic Snow Mechanics, Symposium at Grindelwald 1974 — Snow Mechanics, IAHS Publ., 114. International Association of Hydrological Sciences, Wallingford, Oxfordshire, U.K., pp. 251–291.
Narita, H., 1980. Mechanical behaviour and structure of snow under uniaxial tensile stress. J. Glaciol. 26 (94), 275–282.
Savage, S., 2006. Deep slab avalanche hazard forecasting and mitigation: the South Face at Big Sky Ski Area. In: Gleason, J.A. (Ed.), Proceedings ISSW 2006. International Snow Science Workshop, Telluride CO, U.S.A., 1–6 October 2006, pp. 483–490.
Schweizer, J., 1993. The influence of the layered character of snow cover on the triggering of slab avalanches. Ann. Glaciol. 18, 193–198.
Schweizer, J., Camponovo, C., 2001. The skier's zone of influence in triggering slab avalanches. Ann. Glaciol. 32, 314–320.
Schweizer, J., Jamieson, J.B., 2001. Snow cover properties for skier triggering of avalanches. Cold Reg. Sci. Technol. 33 (2–3), 207–221.
Schweizer, J., Jamieson, J.B., 2003. Snowpack properties for snow profile analysis. Cold Reg. Sci. Technol. 37 (3), 233–241.
Schweizer, J., Jamieson, J.B., 2007. A threshold sum approach to stability evaluation of manual snow profiles. Cold Reg. Sci. Technol. 47 (1–2), 50–59.
Schweizer, J., Lütschg, M., 2001. Characteristics of human-triggered avalanches. Cold Reg. Sci. Technol. 33 (2–3), 147–162.
Schweizer, J., Wiesinger, T., 2001. Snow profile interpretation for stability evaluation. Cold Reg. Sci. Technol. 33 (2–3), 179–188.
Schweizer, J., Schneebeli, M., Fierz, C., Föhn, P.M.B., 1995. Snow mechanics and avalanche formation: field experiments on the dynamic response of the snow cover. Surv. Geophys. 16 (5–6), 621–633.
Schweizer, J., Jamieson, J.B., Schneebeli, M., 2003. Snow avalanche formation. Rev. Geophys. 41 (4), 1016. doi:10.1029/2002RG000123.
Schweizer, J., Bellaire, S., Fierz, C., Lehning, M., Pielmeier, C., 2006. Evaluating and improving the stability predictions of the snow cover model SNOWPACK. Cold Reg. Sci. Technol. 46 (1), 52–59.
Shapiro, L.H., Johnson, J.B., Sturm, M., Blaisdell, G.L., 1997. Snow Mechanics — Review of the State of Knowledge and Applications. Report 97-3, US Army CRREL, Hanover, NH, U.S.A.
Sigrist, C., 2006. Measurement of fracture mechanical properties of snow and application to dry snow slab avalanche release. Ph.D. Thesis, ETH Zurich, Zurich, Switzerland, 139 pp.
Sigrist, C., Schweizer, J., 2007. Critical energy release rates of weak snowpack layers determined in field experiments. Geophys. Res. Lett. 34 (3), L03502. doi:10.1029/2006GL028576.
Smith, F.W., Sommerfeld, R.A., Bailey, R., 1971. Finite element stress analysis of avalanche snowpacks. J. Glaciol. 10 (60), 401–405.
van Herwijnen, A., Jamieson, J.B., 2007. Snowpack properties associated with fracture initiation and propagation resulting in skier-triggered dry snow slab avalanches. Cold Reg. Sci. Technol. 50 (1–3), 13–22.
Wilson, A., Schweizer, J., Johnston, C.D., Jamieson, J.B., 1999. Effects of surface warming of a dry snowpack. Cold Reg. Sci. Technol. 30 (1–3), 59–65.
Zeidler, A., 2004. Forecasting skier-triggered avalanches in the Columbia Mountains of Canada. PhD Thesis, University of Calgary, Calgary AB, Canada, 270 pp.