Effect of Snow Temperatures on Skier Triggering of Dry Slab Avalanches

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ABSTRACT

Field observations and experience show that snow temperatures can have a strong influence on dry snow slab instability. Experience shows that there are two general categories of important competing effects: 1. metamorphism (depending on temperature, temperature gradient and other snow properties) and creep; 2. mechanical properties (excluding metamorphism effects) including snow stiffness (hardness), fracture propagation potential (failure toughness) and strength. There are two general features which separate these categories: 1. they may operate on different time scales and 2. for a given snow temperature they usually operate in opposite directions with respect to stability. For example, warmer snow temperatures imply faster bond formation due to metamorphism in a potential weak layer thereby increasing stability but warmer temperatures in the weak layer also decrease snow stiffness, failure toughness and strength.

TEMPERATURE EFFECTS

McClung (1995, 1996) described the effects of snow temperature on hardness, failure toughness and strength. Figure 1 shows a schematic of the effects and definitions of the terms based on experimental results from slow, direct, simple shear tests on alpine snow. The important effects are: 1. stiffness (hardness) is highly temperature dependent. The increase in stiffness is about 100 % as the temperature decreases from -2 °C to -15 °C. This is the most important temperature dependent property of alpine snow. The stiffness is defined as the initial resistance to deformation and this property is closely related to hardness as determined with the hand hardness test in the field. 2. Failure toughness defined as the work input needed to fail the material (reach a peak on the stress-strain curve) is temperature dependent. It is equivalent to the area under the stress-strain curve when the peak is reached. The failure toughness typically increases by about 20-40 % as the temperature decreases from -2 °C to -15 °C. 3. Failure strength (defined as peak on the stress-strain curve) increases with decreasing temperature. Over the range -2 °C to -15 °C, we estimate that the strength increases by about 25 %. We are somewhat uncertain about this latter value due to scatter in our shear testing results (McClung, 1977; Schweizer, 1996): natural strength variations in a layer are similar to the effects of temperature on strength.

EFFECTS OF SNOW TEMPERATURES ON DRY SNOW SLAB RELEASE

In order to understand the effects of snow temperatures on mechanical properties and the mechanics of dry snow slab release, it is convenient to divide the temperature effects into two categories based on two time scales: immediate and delayed. In Table I the effects are divided according to these time scales and the properties and their usual effects on stability are summarized.

Note that strength changes by changes in the mechanical properties could also be affected immediately but our laboratory data suggest (McClung, 1995, 1996) that imme-

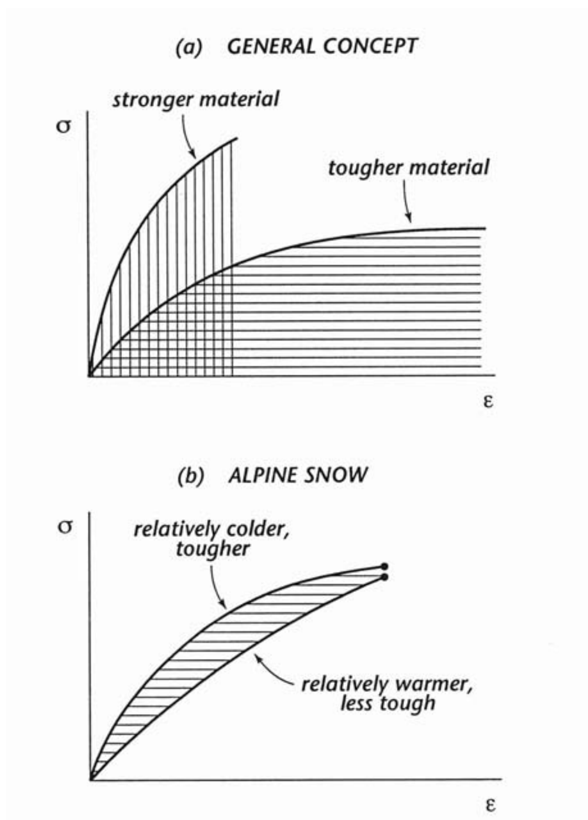

Figure 1: (a) Definitions of strength and toughness in terms of stress (σ) strain (ε) curves. Strength is defined by the peak on the stress-strain curve. Toughness is defined as the area under the stress-strain curve until a peak is reached. Stiffness is defined as the initial slope of the stress-strain curve. (b) Schematic of stress-strain curves for alpine snow of two different temperatures: strength, toughness and stiffness decrease with increasing temperature.

Snow Temperature Effects According to Time Required and Relation to Stability

Immediate Effects: No Time Required

1) Stiffness or Hardness: Warming decreases stiffness significantly; stability decreased

2) Failure Toughness: Warming decreases failure toughness; stability decreased

3) Strength: Warming decreases strength slightly; stability decreased

Delayed Effects: Time Required

1) Bond Formation (Metamorphism): Warming increases bond formation rate and strength; stability increased

2) Creep: Warming increases creep rates, causing settlement, densification, increased strength and hardness; stability increased

3) Temperature Gradient: Warming usually causes decreased temperature gradient with crystal form changes and increased strength; stability increased

Summary: For warming, immediate effects promote instability; delayed effects promote stability. Under warming, instability is likely to come from immediate not delayed effects. Strength effects may be immediate (decrease) or delayed (time dependent with increase) under warming with the greatest strength changes being delayed.

Table 1: Snow temperature effects according to time and stability

diate temperature dependence of strength is not highly significant in shear testing.

What emerges is that, significant strength increases by metamorphism require considerable time to take place for a buried weak layer that is warmed. Thus, except for new snow instabilities, such strength changes are usually slow. Similarly, except for new snow instability (where densification is rapid), creep and its effects on hardness also require considerable time for significant changes.

On the other hand, snow stiffness (hardness), and failure toughness are affected immediately. It is these properties which are most affected when air temperatures change to affect surface layers which overly weak layers. It is also these properties that are of primary concern for skier triggering since they can rapidly decrease the snow stability when buried weak layers are present. Furthermore, of the three, snow hardness is the most significantly affected by changing snow temperatures (as opposed to failure toughness or strength).

Perhaps the most significant result from Table I is that the immediate effects promote instability and the delayed effects promote stability under warming. Therefore, in the following sections we will emphasize the immediate effects since for skier triggering the concern is most often with the present instability and its variations.

SNOW SLAB MECHANICS

The key to understanding slab avalanche release involves considering both the slab and the weak layer, not in isolation, but as interactive, dependent elements. Furthermore, it is much more useful to think about the problem in terms of deformation instead of stresses (e.g. calculation of a stability index) particularly when skier triggering is considered.

Immediate effects

Consider first, the slab release problem in relation to changes in snow temperatures, for example by warming air temperatures. Initially, warming will affect the slab only (it is assumed the weak layer has not yet felt the effects) and the hardness of the slab is reduced. For this scenario, it has been shown (McClung, 1996) that stability is reduced as slab stiffness is decreased even though the weak layer is unaffected by temperature changes. The primary reason is that condition for fracture propagation in the weak layer contains the slab stiffness (or modulus) and reduced stiffness implies energetically easier propagation. The analysis (McClung, 1996) shows that snow slab stability can be importantly reduced by warming snow temperatures in the slab without the weak layer being affected by the warming. Since snow stiffness (hardness) is highly temperature dependent, the effect is probably the most important temperature effect for skier triggering.

Now if, in addition, warmer temperatures later reach the weak layer, failure toughness and strength are reduced implying reduced stability since less work is required during deformation to achieve failure and the failure strength is reduced. All three effects (reduced stiffness in the slab and weak layer stiffness and reduced failure toughness and strength) can work together to reduce stability in this case.

Delayed effects

Warming the slab initially will increase the creep rate which will slowly increase the slab density and hardness. By the logic above, stability will slowly increase. In addition, metamorphism rates will increase causing bond formation, hardness and strength increases. Also, surface warming usually reduces the overall snowpack temperature gradient to slow or stop formation of facets or depth hoar to increase stability.

SKIER TRIGGERING AND SNOW TEMPERATURES

Consider now the case of skier triggering with the immediate effects of snow temperatures on stiffness, failure toughness and strength. When a skier moves over a snowpack a dynamic load is imparted to the snow cover and the stresses penetrate through the entire depth of the snow cover (Föhn, 1987). In order to fail snow in a weak layer, a skier will have to impart significant deformation to that weak layer. It is not possible to fail snow (or any other material) without significant deformation even if stresses are very high.

Measurements of snow deformation imparted by skiers (Schweizer et al. 1995a,b) show that the most important variable with respect to the penetration of significant deformation is the snow hardness. Harder layers permit less deformation at depth than softer layers thereby making the chance of failure less. Furthermore, by the argument above, snow hardness is strongly temperature dependent. Figure 2 shows schematics of slab hardness variations and the relation to skier triggering derived from the results of Schweizer et al. (1995a).

Combining the results above, increasing snow temperatures can immediately decrease snow slab stability importantly in two ways when a skier is present: 1. by decreasing stiffness of surface (slab) layers significant deformation may penetrate deeper in the snow cover to increase weak layer deformation and allow easier failure (more deformation) and propagation and 2. if warming temperatures later reach the weak layer, failure toughness and strength are reduced allowing easier failure. Of these two effects, we consider the first to be the most important, particularly since a person on skis is directly in contact with the surface layers. Furthermore, surface layers are subject to great variations in temperature and snow hardness is affected immediately. Therefore, one can expect the stability to vary greatly when conditions are right depending on the hardness of the surface layers and their fluctuating temperatures. For example, on a cold morning or northerly aspect when surface layers are cold and hard, deformation under skis will not penetrate as deep and as effectively as later on or at other places if surface layers are warmer. Furthermore, the effect on stability is immediate: there is no requirement for delayed effects such as metamorphism or creep (settlement) effects to take place.

STABILITY TESTS

The results above have important implications about interpretations of stability tests in particular the Rutschblock test. Stability tests provide some of the most important data elements with respect to evaluation of instability in the snow cover (McClung and Schaerer, 1993). They should be used as much as possible to collect information to evaluate potential sources of instability. Below we briefly discuss some of the tests and the related effects of snow temperatures and hardness.

Rutschblock test

The Rutschblock test is often favoured because it results in loading the snowpack by a skier and the sample size is large. The test includes the effects of the slab properties and is directly related to snow stability. It implicitly tests the surface layer hardness and its propensity for deformation penetration. - However, the extrapolation is actually very complex. To do the extrapolation it is of particular importance to consider the slab properties, including the hardness structure of the slab, which can vary considerably not only spatially but also rapidly in time as layer temperatures change. For example, it is possible to go from a condition indicating stability to one of instability as surface layers warm to allow deeper penetration of deformation and hence easier failure and propagation. For the extrapolation it is therefore important to complete the test with a snow profile and follow and quickly assess the slab properties (hardness of surface layers) at different locations and over time.

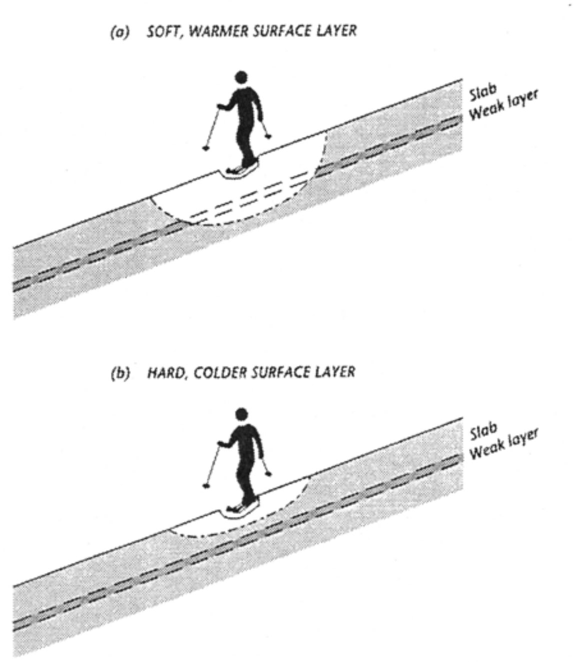

Figure 2: Schematic of influence (not to scale) of deformation imparted by a skier (a) for soft, warm slab properties (b) for hard, cold slab properties. In (a) deformation penetrates deeper whereas in (b) deformation does not penetrate as deep.

The Rutschblock test gives an indication of the weak layer strength only if the deformation penetrates deep enough with enough spatial extent to fail snow in a weak layer. We expect that in slightly consolidated low density snow layers (deep ski penetration) the deformation penetration is poor and the Rutschblock test may not be indicate potential instability. In conclusion, the interpretation of the Rutschblock test result is complicated and one expects highly variable results depending on both, hardness variations of the surface layers and strength variations of the weak layer. Such highly variable results have been amply demonstrated (Föhn, 1989). At a given location, the Rutschblock test is a very good test but extrapolation to other locations is uncertain and might be risky, e.g. if surface hardness conditions change by temperature or wind packing variations.

If no indication of instability results from a test, one is left with the question: Have I measured deformation propensity or is the weak layer strength such that failure is unlikely? Preferred locations for Rutschblock tests are those with soft, but well consolidated surface layers to ensure that deformation has the best chance to penetrate deeply to give an indication of instability. Unconsolidated soft snow at the surface will attenuate deformation to reduce effective penetration of deformation.

Shovel shear test

The shovel shear test also has its limitations (for example small sample size and more qualitative loading). However, the shovel shear test gives a qualitative estimate of weak layer strength as well as and indication of the quality of the shear plane formed. As it does not test the slab properties it is simpler to interpret, but the information needed is incomplete. Since the shovel shear test is essentially independent of slab properties one must to use other information such as hardness variations to complete an evaluation of instability.

Shear frame test

The interpretation of the shear frame test is similar to the shovel shear test: it tests true variations in weak layer strength. The results are more quantitative than for the shovel shear test. With either the shear frame or the shovel shear several tests must be done to get consistent results. When the shear frame measurements are combined with the normal load to give a non-dimensional stability index the results are independent of slab properties including temperature and hardness. Analysis of instability for skier triggering should include the slab properties. Again, the key to understanding snow slab stability is to concentrate on deformation, rather than stress, and the interpretation of the slab and weak layer properties together in a coupled mechanical system.

SUMMARY

The effects of snow temperatures on snow slab instability may be divided into two categories: 1. immediate influences which promote *instability* under warming including reduced snow stiffness (or hardness), failure toughness and strength with no time delays; 2. delayed effects such as metamorphism and creep which promote *stability* under warming with time required to produce the changes.

- In order to include the effects of snow temperature in an analysis of instability, one must seek out information about snow hardness and one must think about the problem in regard to deformation rather than an analysis of stresses. Conventional stability evaluation, for example, calculation of a strength to load ratio will not contain much of the important information about temperature dependence (or snow hardness) and instability.
- For skier triggering, the most important immediate influence of snow temperatures is the decrease of hardness of the surface layers under warming. Secondary effects are decreases of failure toughness and strength if the weak layer is warmed. Hardness estimates (e.g. the hand hardness test) implicitly include snow temperature effects.
- The Rutschblock test has the advantage that it implicitly includes snow temperatures and slab hardness effects in an analysis of instability whereas tests like the shovel shear test or the shear frame test do not. The drawback is that another source of variation is included that has to be considered for extrapolation: the test results depend heavily on the surface layer stiffness. It is proposed to perform Rutschblock tests at places with relatively rather soft than hard surface layers for comparison and extrapolation.
- The advantage of the shovel test and shear frame test is they contain direct information about strength and quality of weak layer failures and, therefore, their interpretation is less complicated than the Rutschblock test. However, they do not contain the most important information about snow temperatures and hardness and, therefore, supplementary information about the slab properties must be sought. We propose that to complete any stability test, observations of hardness variations be made (e.g. with a profile), otherwise the information gained by the tests is too limited and cannot be easily be used for extrapolation.

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