WHEN TO DIG? THOUGHTS ON ESTIMATING SLOPE STABILITY

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ABSTRACT: Information about the snow cover stability is crucial for avalanche forecasting and for winter backcountry recreation. For a reliable estimation of snow cover stability at all levels of stability and over terrain many stability tests would be required. These tests are time consuming and therefore not practical for backcountry recreationists. Sampling strategy becomes important if spatial variability is considered as a key component of avalanche release. A recently proposed sampling strategy for slope stability estimation allows one to estimate the slope stability with a maximum of four compression tests. However, since backcountry recreationists as well as avalanche professionals during recreation rarely perform stability tests, we wade into this important and controversial question: to dig or not to dig? We review and discuss sampling strategies and methods from the perspective of experienced and less experienced recreationists. Factors were identified which increase or decrease the value of snow cover observations – which require digging – for recreationists in order to estimate the snow cover stability. These factors include experience level, local observations – which do not require digging – from previous days and the current day, ability to interpret observations over terrain and across spatial scales as well as cumulative knowledge of the snowpack. In conclusion, the question is not "To dig or not to dig?", but "When to dig?" – the latter question we try to answer.

1. INTRODUCTION

Snow stability depends on the type of layering of the seasonal mountain snow cover, which is typically unknown prior to investigation. These investigations usually include methods that require digging, e.g. snow profiles or stability tests, and methods that do not require digging, e.g. observing signs of instability such as whumpfs (e.g. Schweizer and Jamieson, 2010). In addition, the seasonal mountain snow cover is spatially variable. Spatial variability of the snow cover is mainly caused by the interaction of wind and radiation with terrain. As slab and weak layer properties vary over terrain so does snow stability. Therefore, the avalanche formation process is strongly influenced by spatial variability of snow cover properties (Schweizer et al., 2008). All these factors show the challenge of estimating snow cover stability even for experienced observers skilled in site selection.

Snow cover investigations are crucial for avalanche professionals and avalanche warning services to estimate snow stability. However, it is impossible to derive a fully reliable estimate of the snow cover stability with common field observations in a reasonable time for the area of a drainage or even a slope. This is due to the fact that a) site selection strongly influences the results, b) all available test methods are semi-quantitative point observations with unknown test errors, and (in consequence) c) extrapolation of the results is challenging depending on a), b) and the amount of spatial variability present.

Nevertheless, properly interpreted snow cover observations, e.g. snow profiles, stability test, and signs of instability, can provide valuable information for assessing snow stability, at least under certain conditions. This has been shown over and again (e.g. Schweizer and Jamieson, 2010), despite occasional prediction failures. The question really is – as we cannot reliably determine snow stability – whether we can at least a) substantially reduce the uncertainty of our estimate in an efficient manner and b) assess the uncertainty of the stability estimate to adapt the sampling procedure if necessary.

Schweizer and Jamieson (2010) have recently analyzed the pros and cons of different stability tests. They considered the compression test (CT; Jamieson, 1999), the rutschblock test (RB; Föhn, 1987), the propagation saw test (PST; Gauthier and Jamieson, 2008), the extended column test (ECT; Simenhois and Birkeland, 2006) as well as observations, which require no digging (Jamieson

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et al., 2009). The support (area tested) is different for all test methods ranging from 0.09 m^2 for the compression test to 3 m^2 for the rutschblock test. The support of the compression test is too small to capture fracture propagation propensity, but can be used to estimate the propensity of failure initiation. The compression test is quick to perform and usable by advanced recreationists to identify weak layers and assess their strength. van Herwijnen and Jamieson (2007) showed that the fracture character is related to the fracture propagation propensity. The other tests (RB, ECT, PST) fracture a larger area, which seems large enough to capture the fracture propagation propensity. Schweizer and Jamieson (2010) reported that these tests can classify slopes into stability classes of stable and unstable with an accuracy of 70-90% higher than the compression test or the threshold sum approach (Schweizer and Jamieson, 2007). They inferred that even an experienced forecaster might misclassify stability in at least 5-10% of the cases.

If spatial variability at the slope scale is considered to be a key factor for avalanche formation the sampling strategy as well as the site selection becomes crucial for slope stability estimation. The site at which a snow profile or stability test is performed should be representative for slopes of similar aspect and elevation. Experience is required for site selection and the ability to interpret these results over terrain and across spatial scales.

The critical length, i.e. the length a failure has to reach before it becomes a self-propagating fracture for avalanche release, is assumed to be in the range of 0.1 – 10 m (e.g. Schweizer et al., 2003), but probably rather on the order of the slab thickness as also indicated by PST results. Birkeland and Chabot (2006) proposed to perform a second stability test beyond the correlation length (which is however not known) and choose the least stable result. Jamieson and Johnston (1993) as well as Schweizer et al. (2008) proposed at least 10 m between two stability tests. Schweizer and Bellaire (2010) tested the proposal whether two tests about 10-15 m apart are better than one. They compared the results of two spatially distributed compression test pairs, i.e. score and fracture character and compared the results within a pair as well as the results between the two pairs. In general, they found that the fracture character was less variable than the score within pairs as well as between pairs, i.e. similar in 75% of the cases. The compression test scores of a pair were similar in 61% of the cases and in 59% between the pairs. Furthermore, they classified the compression test results into three stability classes of 'poor', 'fair' and 'good' stability based on the compression test score and found, if the first pair showed consistent 'poor' stability in two thirds of the cases the second pair indicated 'poor' stability, too. That means if the first pair indicates instability, a second pair of tests about 10 m apart is not required, as rather uniform weak and slab layer conditions at this scale can be assumed. On the other hand, if the first pair indicates 'fair' stability, a second pair can be helpful to reduce false stable predictions.

In the following, we will put the findings by Schweizer and Bellaire (2010) into the realm of practical stability evaluation during a day of recreation – a process most often done with the shovel rarely leaving the pack. First, we present definitions of spatial variability, a representative site and the experience level of recreationists, which are used for further discussion. Afterwards we will discuss and relate sampling strategies and the degree of experience to spatial variability and the avalanche formation process.

2. DEFINITIONS

In this section we define spatial variability, signs of instability, representative site and the experience level of recreationists in the context of our contribution. In addition, a possible definition of slope stability is given. These definitions are preliminary.

2.1 Spatial variability and scale

- The variation of a physical property when measured at different locations over terrain. The distance between measurement locations determines the scale of variation. The term spatial variability should always be accompanied by a scale (i.e. a finite distance, area or volume).
- The correlation length, also known as the range is the distance up to which the physical property tends to be similar. The correlation length has to be related to the investigated area and the relevant processes related to the physical property at this scale.
- The spatial structure of a physical property can be described by linear and non-linear trends. For a linear trend the difference between measurements increases the further apart they are. The correlation length can describe a non-linear trend.

2.2 *Signs of instability*

- Whumpfs
- Shooting cracks
- Recent slab avalanche activity on nearby slopes
- Triggering a slab avalanche, including ski-cutting

2.3 *Representative site*

- The site should not be affected by avalanches, trees or tracks.
- The snow depth should be rather uniform and an average for similar slopes and the region. Snow depth should be below average or at average when new to an area.

2.4 *Recreationists' experience level*

We define two groups of recreationists:

Basic skills (L1, see Figure 1a)

- Know the basics about the avalanche formation process.
- Can identify signs of instability.
- Follow basic rules of safe backcountry travel.

Advanced skills (L2, see Figure 1a)

- Are able to perform and interpret snow profiles as well as all common snow cover tests, i.e. CT or RB.
- Have the experience to select a representative site.
- Are experienced in backcountry travelling and are skilled in route selection.

2.5 *Stability classification*

An avalanche release is likely if the snow cover conditions favour failure initiation as well as fracture propagation (e.g. Schweizer et al., 2003a). Therefore we suggest classifying slope stability based on these two processes in stability classes of 'poor', 'fair' and 'good'. The following classification is not part of the Canadian Observation Guidelines and Recording Standards (CAA, 2007) or the American Snow Weather and Avalanche Observation Guide (Greene et al., 2010).

- 'poor': Failure initiation *and* fracture propagation are likely. Since considerable experience is required for route selection, inexperienced recreationists should avoid avalanche terrain.
- 'fair': Either failure initiation *or* fracture propagation is unlikely. A potential for fracture propagation is more critical (closer to poor stability) than potential for failure initiation. Experience is required for route selection to substantially reduce the risk.
- 'good': Failure initiation *and* fracture propagation are unlikely. Normal caution (Haegeli, 2010) is recommended.

3. ESTIMATING SLOPE STABILITY

We suggest a decision tree for estimating slope stability based on the knowledge about the snow cover, the experience level and observations, which require digging or not (Figure 1). For this preliminary decision tree we chose the compression test and estimate slope stability based on fracture character and score.

The knowledge about the present snow cover conditions derived from, e.g. the bulletin, previous personal observations in the area or verbal information from experienced persons seems to be of primary importance for decision making. Signs of instability during recreation, such as whumpfs, shooting cracks and recent avalanches, indicate 'poor' snow cover stability. A whumpf is caused by the collapse of a weak layer. This implies a) a failure was initiated and b) this failure became a self-propagating fracture. In other words, without digging and knowledge about the snow cover one can identify the two main processes as well as the potential of an avalanche release.

If a widespread (basin scale) and active (unstable) weak layer in the area exists and signs of instability are observed, 'poor' snow cover stability can be assumed and no digging is required (Figure 1a). In addition, it is most likely that stability tests performed at representative sites will indicate instability, too. In the absence of signs of instability the snow cover conditions can be considered as mostly 'fair'.

The experience level of a recreationist is of particular importance for snow cover stability estimation. Schweizer et al. (2003b) as well as Bakermans et al. (2010) found that regional to local stability cannot reliably be estimated based on test results from a single pit. Furthermore, they pointed out that only experienced observers, skilled in site selection, can estimate stability with a few tests. Therefore, we recommend performing stability tests, i.e. digging, only if the recreationist has the experience to select a representative site and is able to interpret the results. That means, recreationists with basic knowledge (L1 in Figure 1a) should follow the advice of the bulletin if no signs of instability were observed, since the avalanche danger can range from Low to Considerable. Recreationists with basic knowledge should be cautious in route selection since absence of signs of instability does not necessarily indicate ‘good’ stability (Schweizer, 2010). Recreationists with advanced knowledge might wish to perform stability tests to narrow down the level of stability (see Figure 1b for details). In the absence of a widespread, active weak layer and of signs of instability snowpack stability can be considered as ‘good’ and no digging is required. If signs of instability are observed, rather ‘poor’ conditions can be assumed and digging is also not required.

If nothing is known about the snow cover layering and signs of instability were observed the snow cover stability can be assumed as ‘poor’ and no digging is required. As mentioned above only advanced recreationists should perform stability tests since such tests require experience in site selection as well as interpreting the results. Recreationist with basic knowledge (L1) should again follow the advice in the bulletin in the absence of signs of instability since the snow cover stability can range from ‘poor’ to ‘good’.

Schweizer and Jamieson (2010) showed that some stability tests (RB, PST, ECT) performed better in estimating stability than others. Since even experienced recreationists rarely perform time-consuming stability tests (e.g the rutschblock test) we identify a strategy for performing compression tests (Figure 1b) and suggest interpreting the results as follows.

If the compression test shows a sudden fracture and a low score and the weak layer is a persistent, prominent weak layer, e.g. surface hoar or depth hoar, below cohesive slab layers the snow cover stability in the view of failure initiation and fracture propagation can be rated as 'poor' and a second test on the same slope is not required. This is supported by the fact that several studies at the slope scale showed that the fracture character is less variable than the score (e.g. Schweizer and Bellaire, 2010 – 75%). Therefore, it is likely that additional compression tests performed on the same slope would show similar results and hence indicate instability. Also, we have found instability, and that's what we are looking for (targeted sampling) (McClung, 2002). In addition, this is in alignment with the ‘three-part model’ for an avalanche release (strength-energy-structure) introduced by McCammon and Sharaf (2005). A low score indicates low strength of the weak layer. Weak layers below cohesive slab layers showing sudden fractures are related to higher fracture propagation propensity.

A second compression test, at least 10 m from the first, is recommended if the first test does not show either a sudden fracture, a low score or a non-persistent weak layer below cohesive slab layers.

The slope stability, or the propensity of failure initiation and fracture propagation, can be estimated based on the results of both tests. Non-sudden fractures and high scores indicate that the probability of both failure initiation and fracture propagation is low and hence stability might be rated as 'good'. This is supported by the fact that Schweizer and Bellaire (2010) found no combination of compression test pairs rated as 'good' and 'poor' on the same slope. The fracture propagation propensity should be rated as more critical in view of avalanche release than the failure initiation. If the second test shows also a sudden fracture, fracture propagation is likely. In combination with low scores, i.e. initiation is also possible, snow stability can be rated as 'poor'. Even with intermediate to high scores, stability should be considered as critical since initiation might be possible at a shallower spot on the same slope. ‘Fair’ conditions can be assumed if both tests showed either consistent non-sudden fractures or high scores.

4. OTHER OBSERVATIONS

Spatial variability of snow cover properties affects the avalanche formation process. As a matter of fact, the variation of especially weak layer and slab layer properties is not visible and can only be quantified by intensive and time consuming snow cover investigations. However, the snow surface can give some hints on spatial variability.

Spatial variability is mainly caused by the interaction of wind and radiation with terrain. Weak layers are often formed at the snow surface, e.g. surface hoar or near surface faceting. Therefore, the observation of the snow cover surface becomes of particular importance since the surface might be the next weak layer (cumulative knowledge). Observations of the snow cover surface, prior to storm events, can help to estimate spatial variability (Schweizer et al., 2008). For example, if a surface hoar was formed prior to a storm the following question can help to assess the regional snow cover stability. Did it form

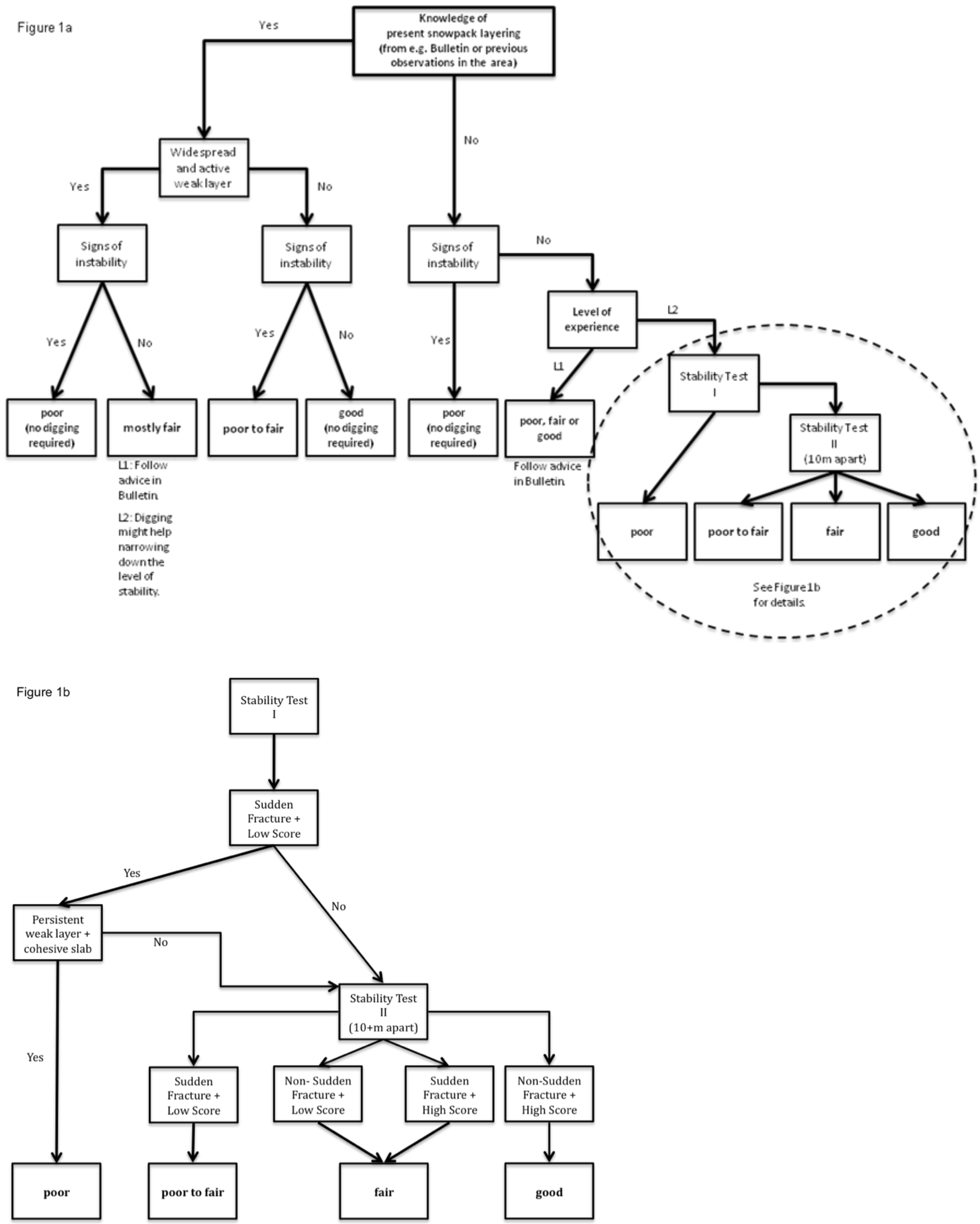

Figure 1: (a) Decision tree for slope stability estimation depending on the personal knowledge about current conditions in the area of backcountry travelling, signs of instability, recreationist's experience level (L1 and L2) and stability test results (compression test score and fracture character). Snow cover stability is classified into three stability classes of 'poor', 'fair' and 'good'. (b) Detailed tree for the interpretation of stability test results (dashed circle in Figure 1a).

uniformly over the entire area and at all elevations (i.e. widespread)? Or did it only form on specific aspects and/or in specific elevation bands? Such cumulative knowledge of prior snow cover observations in combination with current observations decreases the value of snow cover investigations, which require digging.

5. CONCLUSIONS

We suggested a preliminary decision tree for slope stability estimation based on recreationists' knowledge about the snow cover layering, observations of signs of instability and level of experience.

No digging is required if signs of instability are observed during backcountry travelling and/or the recreationist knows that a widespread and active weak layer exists. In the absence of signs of instability and if nothing is known about the existence of a widespread and active weak layer, only very experienced recreationists should perform stability tests, i.e. dig, to independently estimate stability. In addition, no digging is required if stable snow cover conditions can be assumed (based on prior knowledge). Recreationists with basic knowledge should follow the advice given in the bulletin in absence of signs of instability. The extent of digging can be decreased if stability test results and weak layer properties are taken into account.

In conclusion, the proposed procedure suggests that digging is only recommended for very experienced recreationists under specific conditions. In most cases digging is not required. Nevertheless, snow cover observations – performed and interpreted correctly – can contribute to informed decision making in avalanche terrain, especially if little or nothing is known about the snowpack conditions and stable conditions cannot be assumed.

The proposed decision tree is based on the compression test, which is known to underestimate stability. Nevertheless, the compression test is quick to perform and widely used by avalanche professionals and uncertainty can be reduced if a) both fracture score and character are considered and b) more than one test is performed in a pit and on a slope. Other tests like the ECT – also quick to perform – can also be used for slope stability estimation, but the interpretation of different stability tests for slope stability estimation is beyond the scope of this paper.

The proposed decision tree is rather focused on old snow conditions. Different decision trees and procedures might apply for new snow and wet snow conditions (Jamieson et al., 2010).

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