# AVALANCHE HAZARD ASSESSMENT: THE PROBABILISTIC VS. ANALYTICAL APPROACH – THE WELL-CHERISHED DICHOTOMY

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ABSTRACT: Assessing avalanche risk in the backcountry is a challenging task. First and foremost since avalanche hazard cannot be accurately determined: We do not know snow stability in space and time with sufficient accuracy. Therefore, it is not surprising that many approaches have been suggested for assessing avalanche hazard when travelling in the backcountry – ever since the first educational avalanche book has been published. Given the uncertainty due to the insufficiently known stability of the snowpack, most approaches rely on experience, comparing contributory factors of avalanche formation to avalanche occurrence. They were developed from rules of thumb to quantitative statistical analyses, to the present machine learning models. For backcountry travelers, the era of the probabilistic approaches started with the advent of Munter's reduction method – and variants thereof derived subsequently. These methods were promoted in contrast to what was termed the analytical approach which essentially involves assessing and weighing the contributory factors to avalanche formation. Obviously, these terms – probabilistic and analytical – are ill-posed, since any approach can only describe the hazard with a relative probability. We suggest leaving the dichotomy behind, describing the approaches as *knowledge-based* and *rule-based*, and moving forward toward a comprehensive risk assessment. The latter implies combining estimates of release probability *and* consequences, taking into account adequate risk reduction measures, and finally assessing the risk. Such a primarily knowledge-based approach considers simple and relevant observations for both estimating the release probability and the consequences, and builds on our present understanding of avalanched release.

KEYWORDS: avalanche danger, risk assessment, decision-making, backcountry touring

## 1. INTRODUCTION

Assessing the avalanche danger is doubtless a key application of snow and avalanche research, and many methods were developed, still exist, and are applied to this day. No one of the methods can reliably predict avalanche danger since we do not know snow stability in space and time with sufficient accuracy. Before diving into the various methods, defining the scale of consideration is imperative. Scale issues are notorious for causing misunderstandings. We do not consider the regional scale which the avalanche bulletin addresses (i.e. avalanche forecasting), nor the basin scale which we cover during a day of backcountry travel, but the slope scale where we need to make decisions on whether, and if so, how to engage on a particular slope. Therefore, according to Schweizer et al. (2023), we deal with slope stability evaluation, or in other words with the probability of an avalanche occurring (avalanche release probability, or slope (in)stability). If this release probability, the hazard on that slope, is multiplied with the potential consequences we face if being caught, we obtain the risk we expose ourselves to (risk = hazard × consequences).

On a particular slope, a dry-snow slab avalanche occurs if (1) an initial failure forms in a weak layer below a slab, or a crack is triggered, (2) that crack will start propagating and (3) does so across the whole slope, and (4) the slab is released, disintegrates and slides down the slope (Schweizer et al., 2016).

Slope stability evaluation, therefore, implies answering five questions: (1) Does an unfavorable snowpack stratigraphy exist, i.e. a cohesive slab on top of a weak layer? (2) Can a failure be initiated in the weak layer? (3) Will the slab support crack propagation in the weak layer? (4) Does this unfavorable stratigraphy exist across the slope (variability)? (5) Is the slope steep enough for the slab to slide? (Harvey et al., 2023). While the last question is easy to answer, for the first four, we need to know the stability of the snowpack on that slope. As this is not the case, we have to make an informed guess on the release probability, mostly based on simple observations. Essentially, we estimate a probability, in any case a small number, to take a final, often binary decision: to go or not to go.

Now, to estimate this very probability, many different methods have been developed. For an

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overview of decision-making frameworks, the reader is referred to Landrø et al. (2020b) who describe ten “widely-used” decision-making frameworks. They also classify the frameworks concerning the decision-making process in probabilistic and analytical. Eight of ten frameworks were from the probabilistic family, one was classified as analytical (SSD; Kronthaler et al., 2013), and the Avaluator 2.0 (Haegeli, 2010) was considered as a mixture of probabilistic and analytical approach. We will not review all of them but describe some of the cornerstones of the different approaches. The probabilistic approaches rely partly on statistics of avalanche occurrence and often combine two well-known rules of thumb: *the steeper the more dangerous and the higher the danger level, the more dangerous*. The analytical approaches weigh the contributory factors to avalanche formation. This is the method used by all forecasting services, however, for evaluation at the regional scale – and as repeatedly shown also the most widely used method by backcountry travelers (e.g., Landrø et al., 2020a; Mersch et al., 2007). At the regional scale, for avalanche forecasting, the task of weighing the various contributory factors can now be (partly) outsourced to machine learning models (e.g., Hendrick et al., 2023; Pérez-Guillén et al., 2022). A third approach, which we will not go into further, would be a fully deterministic evaluation based on avalanche mechanics modeling in space and time.

This contribution aims to demonstrate the similarities and differences of the various approaches and suggests that a knowledge-based approach for risk assessment (considering hazard *and* consequences) is feasible, for amateur recreationists and professionals alike.

## 2. HISTORICAL PERSPECTIVE

To understand some of the not-so-obvious developments and terms used, it is useful to take a brief look back at selected developments over the last five decades.

Historically, the probabilistic approach, the original reduction method, was introduced to counter the failure of one of the previous methods, in retrospect called analytical, which included a rather overstretched decision framework based on the rutschkeil (a formerly used stability test related to the rutschblock). This rutschkeil-based approach, propagated particularly by Munter (1979) until about 1990, was essentially rule-based; it related stability scores to the “go/no go” decision. Subsequently, after some fatal false-positive predictions, Munter switched to the probabilistic approach in about 1992, abandoning his former method for slope-scale decision-making (Munter, 1997). Anything related to snow cover observations was considered superseded due to the variable nature of the snow cover. The result of the switch, or better the learning, was that now two


Figure 1: An illustrative example of how the dichotomy was cultivated (from Behr and Mersch, 2018; © Sojer).

approaches were emphasized and contrasted with each other: presented as right and wrong. Over the following decades, this dichotomy was further cultivated (e.g., Figure 1), at least in (the German-speaking parts of) the Alps, and to this day, the debate is still nurtured. While these historical developments are now obsolete, they at least explain why the analytical approach is seen as inherently linked to snow cover observations. Finally, we wish to make it clear that we appreciate many seminal contributions by the Swiss mountain guide Werner Munter which are part of today's basic curriculum (Harvey et al., 2018b).

## 3. "ANALYTICAL" APPROACH

While in the context of the dichotomy the analytical approach was confined to snow cover observations (Figure 1), we consider the assessment of so-called contributory factors to avalanche formation (Perla, 1970) as the core of any method of hazard evaluation whether at the regional or the slope-scale. The more the contributory factors are related to the avalanche formation process, the more they are relevant. For instance, air temperature is in most cases not directly related, whumpf sounds, on the other hand, are clearly linked to snow instability (McClung and Schaerer, 2006). Contributory factors can be related to avalanche occurrence, as originally done, e.g., by Perla (1970) to derive a probability of occurrence for given thresholds. For instance, Mayer et al. (2023) showed for their dataset that the probability of natural avalanches was larger than 50 % if the 3-day sum of new snow height was larger than about 60 cm. Or, the observation of shooting cracks increased the odds of an avalanche by a factor of 4 (Schweizer et al., 2021).

In short, analyzing contributory factors reveals probabilities. These probabilities are either absolute if analyzed for a specific dataset or, in most cases, relative, i.e. either high, low, or somewhere in-between. In senso stricto, analytical would imply that there is an equation describing avalanche occurrence that we can solve analytically, i.e. calculate the exact solution. However, as we know, the exact time and location of an avalanche release cannot be determined, but there are of course times when and locations where avalanches are more frequent. In conclusion, whatever is called analytical is in fact probabilistic.

Hence, instead of analytical, we suggest using the term *knowledge-based*. The knowledge-based approach has traditionally been seen as an approach for experts (e.g., McCammon and Hägeli, 2007). However, Landrø et al. (2022) question this and suggest that a knowledge-based approach is suited for amateur recreationists since their study results suggest that amateurs do well understand the relevance of important contributory factors.

## 4. PROBABILISTIC APPROACHES

Times when and locations where avalanches are more frequent, are at the very core of the probabilistic approaches. Moreover, they typically include clear recommendations or travel advice following a traffic light approach (yellow, orange, red). In other words, there are quantitative thresholds, above which, for instance, travel is not recommended. These thresholds and related recommendations for a specific behavior are nothing more than rules. In fact, McCammon and Hägeli (2007) who compared the effectiveness of five decision-making frameworks, called the probabilistic approaches algorithmic, rule-based decision aids for slope-scale avalanche prediction. Given this rule-based nature, they can easily be implemented in the form of algorithms (Schmudlach et al., 2018). While in the past, the probabilistic methods were, at least initially, qualitatively derived from accident statistics, now also the non-events can be considered by using GPS tracks from backcountry touring community portals (Winkler et al., 2021).

A well-known issue with the probabilistic methods is that they are intended for slope-scale evaluation but rely on the avalanche bulletin which forecasts avalanche activity for a region. It is clear that, on average, the release probability at the slope scale increases with increasing danger level. However, on a particular slope and for a given danger level, the danger level represents a first guess at best, since the danger level summarizes a certain frequency distribution of snow stability (and expected avalanche size) (Techel et al., 2020), while the stability of the specific slope remains unknown. The original reduction method suggested a risk calculation without explicitly addressing consequences. The risk term is still often used in connection with probabilistic approaches which, however, as is particularly evident in the case of the graphical reduction method, provide an estimate of the danger; the consequences cannot be substituted by the slope angle Still, this initial estimate of the release probability is considered useful, despite the scale mismatch, in the absence of other pertinent information, for instance when traveling the first day after a storm.

Winkler et al. (2021) suggested that the hazard potential strongly increases from one danger level to the next higher which makes it unlikely that a simple compensation with the slope angle (in steps of 5 degrees) is appropriate. This can of course be rectified with more sophisticated algorithms integrated into platforms that support trip planning (Degraeuwe et al., 2024).

As above, we suggest a more appropriate term for the so far mainly called probabilistic approaches: *rule-based* – following (McCammon and Hägeli, 2007).

## 5. RISK ASSESSMENT

Most approaches, analytical and probabilistic alike, provide only one of the risk elements, namely the hazard, and ignore the other, equally important element, namely the consequences. The state-of-the-art approach for slope evaluation is risk-based: by combining estimates of release probability and consequences, the risk for a particular crux (slope) is assessed, taking into account adequate risk reduction measures (Harvey et al., 2018a; Reuter and Semmel, 2018).

These decision frameworks build on our present understanding of avalanche formation and integrate different approaches while focusing on crucial observations at cruxes. They are primarily knowledge-based and include different levels of complexity and time required to evaluate the hazard. In most cases, a combination of simple indicators such as hazard locations, signs of instability, and tracks is sufficient to estimate the release probability. Here, also the danger level or the result of the graphical reduction method are considered. If the situation is still unclear after considering the avalanche problem type, answering four questions that derive from avalanche formation may help to narrow down the hazard estimate (Harvey et al., 2024). Assessing the consequences is straightforward by answering another four questions that derive from accident statistics. For instance, avalanche size and fracture depth are related to accident severity (e.g., Schweizer and Lütschg, 2001).

As shown by Landrø et al. (2022), simple observations such as signs of instability, slope incline, avalanche size, and terrain traps are correctly rated by experts and recreationists alike, suggesting that knowledge-based approaches such as the risk assessment framework described above may well be feasible in avalanche education. Considering hazard *and* consequences echoes the popular expression in avalanche education of "*When the snowpack is the problem, terrain is the answer*" (e.g., Landrø et al., 2022) and emphasizes the high relevance of terrain choices in avalanche risk management.

## 6. SUMMARY

Slope stability evaluation, the assessment of avalanche release probability, has for decades been framed as either probabilistic or analytical, at least in the European Alps. The two approaches were often presented as contrasting. However, there have always been views that they were complementary rather than contrasting (e.g., Wassermann, 1999). Also, it is clear that the analytical approach is far from being confined to digging holes in snow but instead is equivalent to a knowledge-based approach applicable to any sort of observation related to avalanche formation. Local observations such as recent skiing activity, signs of instability, local variation in snow cover, and safe or unsafe terrain features can easily be interpreted by amateurs and professionals alike. In the absence of observations, and in particular during trip planning, the danger level or reduction methods can serve as prior for slope stability evaluation – despite the obvious scale mismatch.

As we have seen, all the approaches, knowledge-based and rule-based alike, can at best provide a relative probability (of avalanche release). One of the few differences noted is that some methods yield specific recommendations based on thresholds. Almost all approaches as listed in Landrø et al. (2020a), except e.g. for the Avaluator, do not explicitly consider the seriousness of terrain. Terrain, however, is crucial for assessing the consequences if caught in an avalanche. Therefore, focusing on risk (= hazard $\times$ consequences) appears to be the right approach for slope evaluation. By combining estimates of release probability and consequences, risk is assessed, taking into account adequate risk reduction measures. This risk approach is a good example of a decision framework that builds on our present understanding of avalanche formation and integrates different approaches while focusing on crucial observations at cruxes.

Given the minor conceptual differences, it seems about time to leave the dichotomy in avalanche hazard evaluation at the slope scale behind and move forward to a truly risk-based assessment supported by automated algorithmic tools. Still, we keep in mind that so far none of the methods, which we suggest calling either knowledge-based or rule-based, will provide an accurate yes or no result, but an estimate of the relative hazard or risk.

Decision-making in avalanche terrain can have fatal consequences. However, there is no one-size-fits-all method that is always correct – since we deal with making predictions for a complex system. Uncertainty is inherent. Fortunately, avalanches are rare events, high times and locations can be predicted, and at most times, the risk can be managed with reasonable confidence when traveling in the backcountry.

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