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Editorial

On recent advances in avalanche research

1. Introduction

Every second year, formally since 1982, the International Snow Science Workshop (ISSW) attracts a large number of snow and avalanche professionals from across the world. The motto of the ISSW is “A merging of theory with practice”. Academic researchers meet ski patrollers, public avalanche forecasters, avalanche safety consultants, mountain guides, to name a few groups from the vast attendance, share their findings and experience – and challenge each other.

The 2016 ISSW was held in Breckenridge (U.S.A.) from 3 to 7 October 2016 and again facilitated the interdisciplinary exchange of ideas and experiences between snow science researchers and practitioners in an exemplary way. Close to 1100 participants from 21 countries flocked to the little mountain town in Colorado and for five days engaged in exchange – more in the spirit of a workshop than a formal conference.

During the oral and poster sessions of the conference, a total of 279 contributions were presented covering a wide range of topics including snowpack structure, variability and metamorphism; instrumentation and measurements; avalanche release; wet snow and wet-snow avalanches; avalanche hazard assessment; avalanche forecasting; human factors and risk management; avalanche education; avalanche accidents and rescue. Together with the proceedings of previous ISSWs, all of the contributions presented at the 2016 ISSW are available online at http://arc.lib.montana.edu/snow-science. This Special Issue compiles eight papers that cover the many aspects of applied avalanche research. Some of these papers represent recent innovative work and tackle some of today's most challenging topics in avalanche control.

2. Avalanche release

The topic attracting most interest in recent years is avalanche release. Our understanding of how dry-snow slab avalanches release has much improved over the last decade, not least due to a number of detailed laboratory studies, but primarily due to theoretical and modeling studies. Since the publication of the anticrack model by Heierli et al. (2008) a debate developed over the question how weak layers fail and consequently how slab avalanches release: in shear or collapse. The shear model dates back to at least the pioneering work by McClung (1979), whereas collapse refers to the anticrack model more recently put forward.

The anticrack model assumes an opposite mode I crack, where the magnitude of the displacement field is equal but opposite to a classical tensile mode I crack. This fracture mode is only physically possible for collapsible structures, which weak snow layers clearly are – given their high porosity and strongly anisotropic microstructure (e.g., Walters and Adams, 2014; Reiweger et al., 2015). The anticrack model correctly considers – among other things – the mixed mode loading conditions, the collapsible nature of weak layers and allows quantitatively evaluating propagation saw test (PST) results (e.g., van Herwijnen et al., 2016b). However, a rather counterintuitive result of the anticrack model was the finding that the critical length for a self-propagating crack is almost independent of slope angle. Triggering by localized rapid surface loading by e.g. skiers from flat terrain often accompanied by a characteristic whumpf sound is well known (Seligman, 1936), in other words artificial triggering is possible at any slope angle. However, the probability of occurrence of natural slab avalanches clearly increases with increasing slope angle; moreover, on slopes below 30° avalanches are rarely observed (van Herwijnen and Heierli, 2009).

Based on discrete element modeling of a PST (Gaume et al., 2015), Gaume et al. (2017b) recently suggested a new model for evaluating the critical crack length by reconciling the shear- and collapse-based approaches. They take into account the complex interplay between slab elasticity and the mechanical behavior of the weak layer including its structural collapse. Their model reproduces crack propagation on flat terrain, but also the decrease of the critical length with increasing slope angle. The formulation of the critical crack length can be incorporated into numerical snow cover models as long as the mechanical parameters can be derived from layer properties, in particular layer thickness and density. This allows, for instance, following the temporal evolution of crack propagation propensity for a specific weak layer, which can otherwise only be done by intensive field campaigns (Calonne et al., 2016; Schweizer et al., 2016b).

Gaume and Reuter (2017 - in this issue) apply the new model by Gaume et al. (2017b) for the case of skier triggering. Considering that failure initiation and crack propagation are the key processes in dry-snow slab avalanche release and need both to be addressed for stability evaluation (e.g., Reuter et al., 2015a), they combine the classical skier stability index and the critical crack length. For a given weak layer, the critical crack length is compared to the size of the area where the skier-induced stress exceeds the shear strength of the weak layer. As the slab layering affects the skier stress (Habermann et al., 2008; Schweizer, 1993) as well as the crack length (Schweizer et al., 2011) they perform FE simulations to evaluate the skier stress as well as the bulk modulus of the slab required for calculating the crack length.

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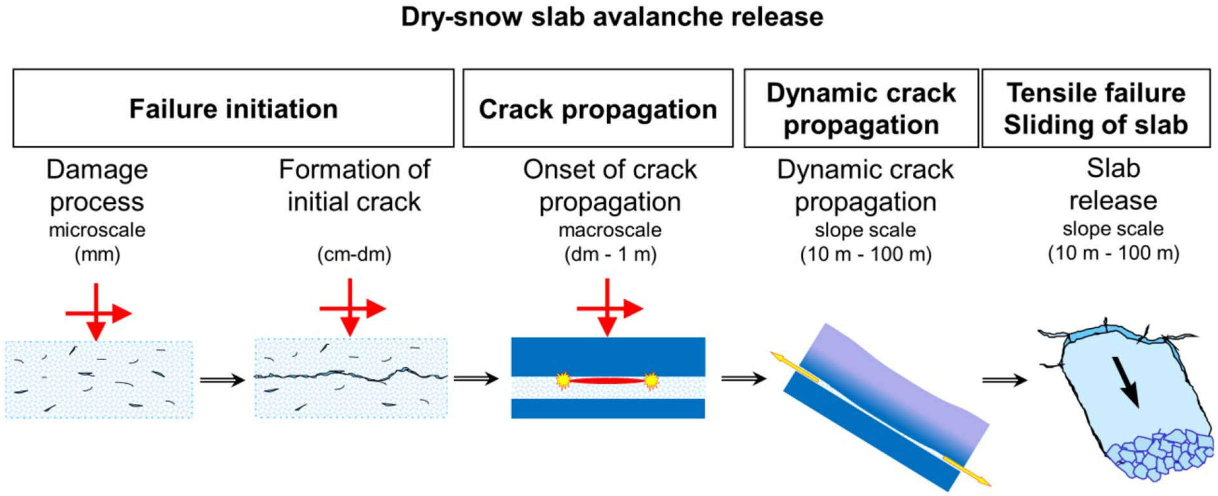

Fig. 1. Conceptual model of dry-snow slab avalanche release including the four stages of (i) failure initiation in a weak layer underlying a cohesive snow slab, (ii) the onset of crack propagation, (iii) dynamic crack propagation through the weak layer across the slope, and (iv) tensile slab failure arrests the propagating crack in the weak layer, followed by sliding of the slab; red arrows indicate mixed-mode loading (adapted from Schweizer et al., 2003a). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The collapse is the consequence of weak layer failure, not to be misinterpreted as (compressive) failure mode, and may play an important role in dynamic crack propagation, i.e. the stage of slab release when the crack rapidly propagates across the slope. While analyzing a large dataset of PSTs van Herwijnen et al. (2016a) found that full propagation to the far end of the column was associated with large collapse height and high crack speed. These results suggest that both weak layer collapse height and crack propagation speed are relevant parameters for dynamic crack propagation, hence influencing how far a crack propagates and eventually controlling avalanche size.

While the new model by Gaume et al. (2017b) reiterates the importance of shear stresses, the actual failure mode within the complex microstructure of snow is largely unknown as pointed out by Schweizer and Jamieson (2008). Even under macroscopic compressive loading large tensile and shear stresses may exist in the ice matrix, and vice versa for macroscopic tensile loading (Hagenmuller et al., 2014). In fact, recently Gaume et al. (2017a) studied the failure behavior of a granular systems of sticky hard spheres and found that the bonds between the particles failed mostly due to due to tension or bending rather than shear or twisting.

A more detailed summary of recent developments in avalanche formation is provided by Schweizer et al. (2016a). They also provide an update of the conceptual model of slab release (Fig. 1). They suggest slab avalanches to result from a sequence of fracture processes including (i) failure initiation in a weak layer underlying a cohesive snow slab, (ii) the onset of crack propagation, (iii) dynamic crack propagation through the weak layer across the slope, and (iv) tensile failure through the slab causing crack arrest in the weak layer, followed by sliding of the slab.

3. Hazard assessment and avalanche forecasting

Avalanche hazard assessment can be understood in two ways. On one hand, it deals with assessing the avalanche hazard at hand, i.e. the probability of release in the current situation, for example by performing snow instability tests (e.g., Schweizer and Jamieson, 2010). On the other hand it involves assessing the runout and impact of possible avalanches, typically based on a few scenarios with varying initial and boundary conditions (e.g., Bründl and Margreth, 2015; Eckert et al., 2010).

Avalanche hazard assessment is particularly challenging if a deeply buried, persistent weak layer is present in the snowpack (Jamieson et al., 2001). These avalanches are difficult to trigger, yet when they release they tend to propagate far and can result in large and destructive avalanches. Various studies have explored the difference in meteorological conditions prior to days with deep slab avalanches compared to conditions prior to days without deep slab avalanches (e.g., Conlan et al., 2014). Their triggering is often associated with increasing air temperature, i.e. a warming trend. Whether the warming trend is directly related to the release is at least questionable, given that effects of warming on the snowpack are subtle (Reuter and Schweizer, 2012). Warming may contribute to slab release at best in areas of shallow snowpack. Conlan and Jamieson (2017 - in this issue) do not only consider the weather conditions prior to release at the elevation of typical starting zones, but also snowpack conditions for the preceding week and recent avalanche observations. Based on these three elements they developed a decision support tool to aid in forecasting the probability of deep slab avalanches. The tool includes 12 questions based on numerical thresholds determined statistically; they have to be answered with yes or no. If more than 8 questions are answered with yes, natural deep slab avalanches are likely.

Instead of considering the weather conditions prior to release, Marienthal et al. (2015) looked into the meteorological conditions during weak layer formation over the early months of seasons with deep slab avalanches compared to those meteorological conditions during seasons without deep slab avalanches. They found – among other things – that seasons with deep slab avalanches had drier than average early seasons than seasons without deep slab avalanches. This finding suggests that the shallow early winter snowpack may often be subject to large temperature gradients resulting in persistent layers of faceted crystals and depth hoar. Still, forecasting deep persistent slab avalanches remains to be very challenging, not the least as readily available snow properties often only partly reflect the fracture processes needed to describe snow instability (e.g., Reuter et al., 2015b). Hence, tools such as developed by Conlan and Jamieson (2017 - in this issue) do not reduce the need for a conservative approach to travel, work and recreation in avalanche terrain.

A similarly challenging problem is assessing the hazard of wet-snow avalanches. Forecasting this type of avalanches is difficult since their release depends on the complex interaction between snow stratigraphy and water flow within the snowpack. Water ponding at discontinuities and preferential flow, which is particularly prominent when a dry snowpack is wetted the first time, are among the main difficulties for predicting whether the infiltration of water will substantially weaken an already existing instability. Recent laboratory studies have quantified the coupling between liquid water movement in snow and wet-snow metamorphism, which causes much faster grain growth rates than observed during dry-snow metamorphism (Avanzi et al., 2017). The speed of water infiltration into the snowpack clearly depends on preferential flow and capillary barriers (Avanzi et al., 2016). These two processes can be represented in numerical snow cover models if the water transport is described by the Richards equation (Wever et al., 2014). This also allows improving wet-snow avalanche prediction as suggested by Wever et al. (2016). They found a volumetric liquid water content of 5–6% locally within the snow cover to be a better predictor for wet-snow avalanche activity compared to other methods such as the daily mean air temperature. Alternatively, Mitterer et al. (2013) considered the average liquid water content of the entire snow cover, as simulated by the SNOWPACK model (Lehning et al., 1999). They suggested that the onset of wet-snow avalanching starts when an average volumetric liquid water content of 3% is reached, and introduced a corresponding index (LWC_{index}). These model developments were partly triggered by improved observational methods, most notably upward looking ground penetration radars (e.g., Mitterer et al., 2011; Schmid et al., 2014).

The LWC_{index} approach was further employed by Bellaire et al. (2017 - in this issue). They forced the 1-D physically based snow cover model SNOWPACK with data from the high-resolution numerical weather prediction (NWP) model COSMO and investigated whether forecasting regional patterns of the onset of wet-snow avalanche activity was feasible. Even in forecast mode the index predicted the onset of wet-snow avalanche activity with a probability of detection of 80%; however, the false alarm rate was high too.

Of course, driving a snow cover model with NWP data is not new (e.g., Bellaire et al., 2011; Vernay et al., 2015; Vionnet et al., 2016), but validation of model output represents a challenge, in particular with respect to parameters related to snow instability. Observations on number, size and type of avalanches are best suited to validate model predictions, since recent avalanching provides direct evidence of snow instability. However, these data are often rare and inaccurate not the least due to limited visibility during storms. For the remote detection of avalanches several ground-based techniques exist such as radar (Kogelnig et al., 2014; Meier et al., 2016), infrasonic sensors (e.g., Marchetti et al., 2015; Thüring et al., 2015) and seismic sensors (e.g., Suriñach et al., 2005; van Herwijnen et al., 2016c).

Air-borne remote sensing techniques are in principal also well suited to monitor avalanche activity (Eckerstorfer et al., 2016), but near-real time monitoring seems more difficult to achieve than, for example, with seismic methods (Heck et al., 2017). Eckerstorfer et al. (2017 - in this issue) manually identified, using a change detection method, avalanche debris in Sentinel-1 images from Northern Norway and obtained an avalanche catalogue for two winters. They then used these data to – among other things – validate public avalanche forecasts. However, for their dataset there was no correlation between avalanche activity and forecasted avalanche danger level. Still, the avalanche activity was highest when the avalanche danger level ‘Considerable’ (level 3 out of 5) was issued. Moreover, the comparison was useful to detect and analyse outliers of either under- or over-estimating the danger level.

Given the disadvantages of avalanche occurrence data for forecast verification, Techel and Schweizer (2017 - in this issue) compared local avalanche danger level estimates (nowcasts) to regional avalanche danger level as forecast in the public bulletin (forecasts) – despite an obvious lack of objectivity and independence between the two data sources. They first analysed how often two local nowcasts by experienced professional from the same region agreed and found a disagreement rate of 22%. This clearly shows the difficulty of assessing the avalanche situation, and describing it with a single danger level – not the least since the avalanche danger cannot be measured (but is estimated on an ordinal scale). Based on almost 10′000 individual ratings, they found an agreement rate of 76% between local nowcasts and regional forecast. The forecast was biased towards over-forecasting (higher danger levels), in time and space. This level of accuracy is typical for regional avalanche forecasts (Schweizer et al., 2003b). Their findings suggest that local danger level estimates represent useful data in the forecasting process.

Avalanche hazard assessment, on the other hand, is the basis for elaborating hazard maps and consequently land-use planning. Whereas in Switzerland hazard mapping with regard to extreme snow avalanches has long been completed, new hazards occasionally arise often in relation to climate warming induced changes in the high mountain cryosphere. Margreth et al. (2017 - in this issue) assess the hazard caused by ice avalanches from a hanging glacier on the Eiger west face in the Bernese Alps (Switzerland). Ice avalanches are particularly dangerous in winter when they entrain snow or even trigger secondary snow avalanches. Consequently, a combined snow/ice avalanche has a greater mass, a more distinct powder part and a longer runout. Based on 2-D avalanche simulations (Bartelt et al., 2016) the hazard for the nearby train station and ski area was assessed and a safety concept was developed. This includes an early warning and alarm system to minimize the closure times for the railway and ski area. The hanging glacier is monitored with an interferometric radar system (inSAR) to detect the acceleration of the ice motion and a Doppler radar to detect falling ice and avalanches (e.g., Meier et al., 2016).

4. Avalanche control

In the case of ice avalanches, Faillettaz et al. (2011) found monitoring very useful for prediction, whereas artificial triggering is not an option – unlike for snow avalanches. The artificial release of snow avalanches is nowadays a key measure in avalanche mitigation. It is relatively cheap compared to engineering works such as e.g. constructing a snow shed to protect a road. To trigger an avalanche artificially, an explosion is caused by igniting either solid (or liquid) explosives or a gas mixture, either propane-oxygen or hydrogen-oxygen. The avalanche is triggered by the impact of the pressure wave onto the snowpack. Most studies investigated the effect of solid explosives. Simioni et al. (2017 - in this issue) are to first to focus on the effect of a directed gas explosion. They measured air pressure at the snow surface and accelerations within the snowpack at three distances from the point of explosion. Their setup was similar to the one used before for solid explosives (e.g., Binger and Miller, 2016; Simioni et al., 2015). The experimental gas exploder they used was partly different from an operational Gazex®, but allowed to best possibly mimic the directed impact. Apart from the reduced lateral impact, they found no significant differences between the impact of solid explosives and the impact due to a gas explosion. In both cases, for example, the air pressure distinctly decreased with increasing distance from the point of explosion following a power law with an exponent of about -1.7. Their findings suggest that the efficiency of artificial release (in terms of long-range effect) might rather be related to the propensity for crack propagation at the time of triggering rather than the relatively minor impact at large distances (~80–100 m) from the point of explosion.

5. Avalanche statistics

Recording avalanche events is of great relevance for avalanche forecasting, but also model validation. In many countries extensive databases exist, but data are usually only complete for fatal avalanches. These statistics allow detecting long-term trends and may provide hints on the efficiency of mitigation measures (Techel et al., 2016). Höller (2017 - in this issue) analysed avalanche accidents and particularly avalanche fatalities, which occurred during the last 70 years in Austria. He found few trends, in particular when considering the last 20 years. The number of fatalities stayed about the same, as did the proportion of off-piste skiers among the recreational fatalities, i.e. about 30%. On the other hand, considering the 70 years, there was a clear trend towards fewer fatalities due to so-called catastrophic avalanches that affect people in settlements. During the first half of the study period (1946–1947 to 1980–1981) the proportion of avalanche fatalities due to catastrophic avalanches was about 40%, whereas it was less than 10% in the more recent period. This trend was observed for all Alpine countries and is clearly the consequence of successful implementation of avalanche mitigation measures (Techel et al., 2016).

6. Concluding remarks

The papers included in this special issue nicely illustrate the breadth of research currently being conducted in applied avalanche research. Many of these studies have been triggered by recent developments in either modeling techniques or observational methods. It will be interesting to see how quickly and successfully these new methods will become operational standards in avalanche hazard assessment. This in particular applies to tools derived from our newly advanced understanding of avalanche release, remote sensing techniques (ground-based or air-borne) and the coupling of numerical weather prediction models with snowpack models. The latter model chain can be extended to calculations of avalanche impact and runout, and allows in principal assessing the avalanche hazard due to large avalanches based on currently prevailing snow and weather conditions – also called dynamic hazard mapping and recently tackled for wet-snow avalanche by Vera Valero et al. (2016).

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