THOUGHTS ON THE WHY'S AND HOW'S OF SMALL-AVALANCHE EXPERIMENTS

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ABSTRACT: Small avalanche paths (typically 100–300 m long) offer great opportunities for detailed studies of most aspects of avalanche flow except the powder-snow cloud. With impact forces one to two orders of magnitude smaller than in large avalanches, the cost of setting up a test site is correspondingly much lower. At small sites, the initial conditions can be controlled to a large degree, avalanches triggered even if explosives cannot be used, and in some cases direct visual observation of the processes inside the flow is possible. We discuss which fundamental processes in avalanches can be studied in low-budget experiments thanks to recent developments in sensor technology. With small avalanches, detailed post-event studies of the deposits are feasible, including the local mass balance and measuring the dispersion of tracer particles due to shearing and granular temperature.

Keywords: Avalanche experiments, avalanche release, flow regimes, erosion, measurement techniques, data analysis

1. INTRODUCTION – WHY BOTHER ABOUT STUDYING SMALL AVALANCHES?

The development, calibration and validation of advanced numerical avalanche flow models requires much more detailed measurements than just the run-out distance and the velocity, flow depth and impact pressure at one or two points. Moreover, experimental data from diverse types and sizes of avalanches is needed. The two large test sites Ryggfonn in Norway (Gauer and Kristensen, 2016) and Vallée de la Sionne in Switzerland (Sovilla et al., 2008) have been collecting such data for decades, but there is a conspicuous lack of comprehensive data from small avalanches. There have been several small-avalanche experiments (SAEs) in the past half century (see Sec. 2. for a brief summary), but they were either abandoned after a few winters, or did not measure all the variables needed by modern models, or did not succeed in releasing suitable avalanches.

Experiments on snow chutes have been carried out for more than 60 years. In the early days, the emphasis was on impact pressures (Salm, 1964; Nakamura et al., 1987; Sheikh et al., 2008) or velocity and run-out distance (Dent and Lang, 1980). Since the 1980s, new measurement techniques (high-speed film, load plates, photodiode arrays, capacitance sensors, etc.) have been introduced to measure velocity and density profiles and the effective friction coefficient (Dent and Lang, 1980; Nishimura, 1991; Bouchet et al., 2004; Kern et al., 2004; Platzer et al., 2007a,b; Rognon et al., 2008). These experiments have produced valuable results mostly for dense flows (dilute flows in air were studied only by Bozhinskiy and Sukhanov (1998) and Turnbull and McElwaine (2008)), but their results are difficult to apply directly to natural avalanches.

Detailed investigation of the deposits of spontaneous avalanches of different sizes has yielded useful insight into the occurrence of different flow regimes even in small avalanches, the mobility difference between dense and fluidized flows and the dispersion of particles (Issler et al., 2020, 2008) as well as the particle-size distribution (Bartelt and McArdell, 2009). In such cases, however, the release area, volume and flow depth are usually quite uncertain and the velocity can at best be inferred indirectly from observed superelevation in winding paths (Issler et al., 2008; Issler, 2020).

At small test sites, one can combine the strengths of chute experiments and observations on spontaneous avalanches while circumventing to a large degree their respective limitations. Here, we discuss three main points: First, recent developments in sensor technology make it possible to set up comprehensive experiments and probe the fundamental mechanisms of avalanche flow at relatively low cost. Second, there are promising and simple methods for enhancing the probability of triggering avalanches with a controlled size. Third, detailed post-event field work is feasible at small sites and should be given high priority. We emphasize, however, that small avalanche test sites are not a replacement for, but a complement to, the large sites Vallée de la Sionne and Ryggfonn because the formation and properties of the suspension layer ("powder-snow cloud") can be studied only in sufficiently large and fast avalanches, and information on the scaling behavior of avalanche flow is of great value (Gauer, 2018).

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Figure 1: A glide avalanche recorded by a webcam at Hijiori.

Figure 2: Small wet-snow avalanche artificially released at Mizuno-no-sawa, Niseko on 2017-03-25.

2. SMALL AVALANCHE EXPERIMENTS IN THE PAST AND PRESENT

In the late 1970s, Dent and Lang (1980) used natural terrain near the Bridger Bowl ski area in Montana for setting up two fairly large snow chutes, with a release volume up to 2.7 m^3. Two notable features were (i) the lining of the acceleration zone with polyethylene sheets to attain high velocities and (ii) a glass window at the beginning of the run-out segment to obtain velocity profiles by tracking snow particles between frames of film recordings. Gubler et al. (1986) tested their novel radar devices on small slopes in the early 1980s and obtained relevant results about the velocity distribution in these flows; they did not, however, apply other measurement techniques.

Several small test sites using natural terrain deserve mention:

The site Revolving Door near the Bridger Bowl ski area, Montana was used in the 1990s (Dent et al., 1998). Its most unique feature was a protected shed with a window, along which the avalanches flowed. Instrumentation included a flow-depth sensor, a load plate measuring shear and normal stress, a vertical array of six pairs of small light-emitting diode (LED)/photosensor compounds mounted in the shed wall, and four capacitance sensors at different distances from the running surface for estimating the instantaneous avalanche density profile.

At Arabba (Italian Dolomites), a 600 m long and strongly channelized path descending from Monte Pizzac was equipped with masts carrying several piezo-electric load cells and flow height sensors; this allowed calculating the mean front velocity between masts (Sommavilla and Sovilla, 1998). In the winter 1997/1998, Sovilla et al. (2001) reconstructed the mass balance along the path for four avalanches by digging and analyzing 20–40 cross-sectional snow pits. This was only feasible because the channel is narrow. Like Revolving Door, the Monte Pizzac site was closed down before its potential was exhausted.

There is only one report on experiments in the Tianshan mountains in China in the mid-1990s (Abe et al., 1999). The path had a drop height of some 200 m and a length of about 300 m. From time-lapse photographs, the front velocity was inferred. At different heights on a pylon, pressure sensors were mounted in pairs 0.5 m apart in the flow direction and 0.2 m in the normal direction. By cross-correlating their signals, the velocity profile could also be estimated.

In the early 2010s, impact measurements and entrainment studies were carried out in a 200 m long and about 30 m wide path on Seehore, Val d'Aosta (Italy) (Barbero et al., 2013; Maggioni et al., 2019). The extent of the avalanche and the local mass balance were measured by comparing surface scans before and after an avalanche event. Bovet et al. (2013) developed a simple device and method (termed the straw test) for obtaining both the erosion and deposition depths at selected points.

In Japan, two sites in maritime and sub-arctic climate, respectively, have been in operation in recent years: A small slope at Hijiori, Yamagata prefecture (Fig. 1) is continuously monitored with an automated weather station, seismometers and webcams. The latter are used to determine the front velocity of avalanches, while the release volume and deposit distribution are inferred from UAV surveys before and after an event. The data presently serve to calibrate relatively simple dynamical avalanche models under Japanese conditions and to test methods for probabilistic hazard mapping.

In Niseko, southwest Hokkaido, experiments on two slopes (Mizuno-no-sawa and above the Moiwa bowl, Fig. 2) were started in 2016 in cooperation with the ski resort staff (Nishimura et al., 2018). At Mizuno-no-sawa, explosives can be used, but at Moiwa avalanche release is attempted by pushing snow masses over a terrain edge with a snow groomer. A wide variety of portable instruments (stationary and UAV-borne video, seismometers, pulsed Doppler radar, a thermal camera, inertial measurement units as active tracers) have been utilized. However, numerous constraints due to the resort operations and the lock-down during the COVID-19 pandemic have hampered the success so far.

In summary, SAEs have made important contributions to our understanding of avalanche dynamics, but none of the sites that were or are being used have exhausted their full potential. The reasons for this seem to be very different: lack of long-term support, limited ambitions, departure of key personnel, too many logistic constraints, etc.

3. WHAT TO MEASURE, AND HOW TO DO IT?

The selection of sensors for an SAE depends on the main focus of the experiments, the budget, local regulations, and topographic constraints. Here, we list our current—highly subjective—assessment of which quantities are most useful in the development of different types of models and which sensors are most suitable for these purposes.

Standard global measurements. Several standard characteristics of an event like the release area and volume, run-out distance and deposit distribution do not generate new insight when considered in isolation. They are nevertheless necessary for meaningful back-calculations and put significant constraints on continuum models or DEM (discrete-element method) approaches. Measurements from many avalanches in the same path can be used in statistical analyses (Gauer and Kristensen, 2016; Fischer et al., 2020). These avalanche properties can be measured easily with modern techniques like high-resolution mapping before and after the event from a drone. When combined with sufficiently many measurements of density profiles in the deposit area, the local mass balance can be reconstructed, as pioneered by Sovilla et al. (2001).

Velocity. Calibration even of simple two-parameter flow models requires velocity data along the path. The cheapest way to achieve this is by extracting the front velocity from video footing; McElwaine (2006) gives useful suggestions for the entire process. However, pulsed Doppler radar provides aggregated velocity spectra within each range gate (with a length of 10–20 m in current systems), giving valuable insight into the interior dynamics of the flow. Such instruments have become portable and relatively affordable in recent years. More advanced systems with very high resolution like GEODAR (Ash et al., 2014) can reveal surges in the flow or indicate flow-regime transitions (Köhler et al., 2018), but they are not commercially available and require stationary installation in a protective shed and a stable power supply.

There are two aspects of snow avalanche flow—flow-regime changes and erosion/deposition—that most models in practical use do not incorporate explicitly through the model equations but that nevertheless must be accounted for when calibrating the empirical parameters of these models. More advanced flow models include evolution equations for the flow density or the entrainment/deposition rate, but the fundamental mechanisms of these processes are still poorly understood so that heuristic arguments and speculative assumptions abound in the proposed process models.

Density. Several flow properties play a fundamental role in both flow-regime changes and entrainment/deposition: the density ρ, the deformation rate D_{ij}, the shear and normal stresses σ_{ij}, and the (shear) strength of the snow cover, τ_c. The latter must be measured manually at representative locations near the path at the time of an experiment. In principle, the depth-averaged density of the flow, $\bar{\rho}$, can be measured with a load cell flush with the ground, but unpredictable bridging effects may produce spurious results. Capacitance sensors measuring the local density have been used in avalanche research since the 1990s (Nishimura, 1991; Louge et al., 1998; Dent et al., 1998) but have not been adopted universally because their signals depend not only on the density of the snow but also on the particle size and shape and the water content. With suitable on-site calibration, useful results should nevertheless be obtainable in many situations. Extracting the snow density from microwave scattering using traditional frequency-modulated continuous-wave (FMCW) radar (Gubler and Hiller, 1984) is plagued by similar ambiguities, but Pasian et al. (2019) proposed and demonstrated a one-emitter-two-receivers (1E2R) configuration that can resolve them at least for relatively dry snow. It should be worthwhile to test this concept in a chute with granular materials and snow because such an instrument would measure the flow depth and the erosion/deposition rate as well.

Velocity profiles and shear rate. Measuring velocity inside the flow using the Doppler effect with ultrasound or microwaves is probably not practical because of impedance mismatch (ultrasound) or cost and size (Doppler radar). Instead, one must rely on cross-correlating signal fluctuations between two sensors placed a suitable distance from each other in the mean flow direction. This has been put in practice with vertically stacked arrays of pairs of LED–photodiode sensors, e.g. (Nishimura et al.,

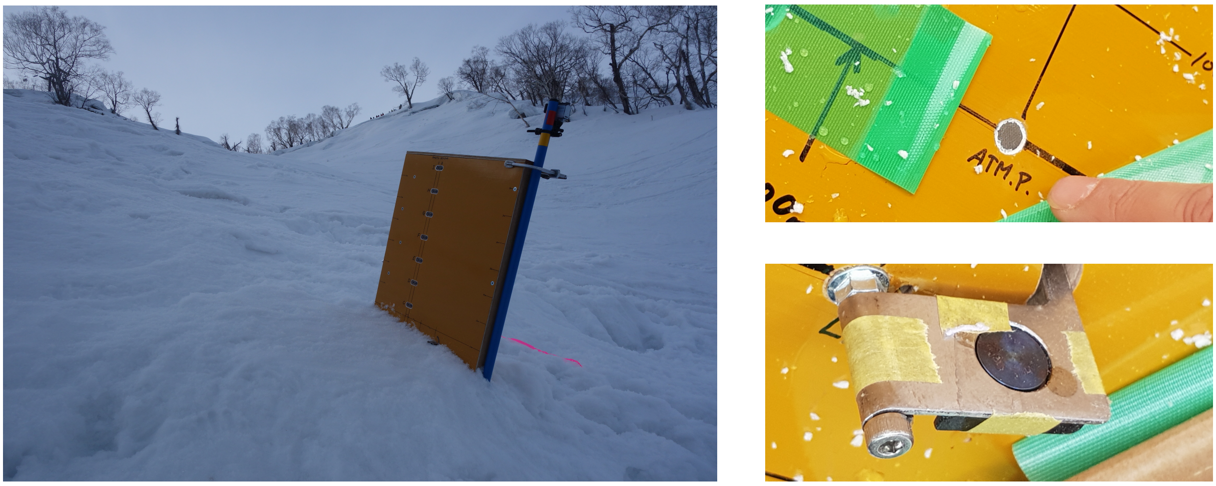

Figure 3: Experimental mobile multi-sensor board measuring velocity profiles, total load and pore-air pressure, constructed for the experiments at Niseko, Japan. **a**) Board provisionally fixed in the snow cover with a steel pole, with seven pairs of LED–photodiode packages visible. On the other side, the pore-pressure sensor (**b**) is covered by a fine metal mesh to prevent snow grains from entering the duct. At the same height, the load cell measuring total overburden is mounted on a swivel arm so it can adjust to the attack angle of the flow (**c**).

1993; Dent et al., 1998), see Fig. 3.a, with pairs of impact or air-pressure sensors (Nishimura et al., 1993), pairs of capacitance sensors and also two FMCW radars (Gubler et al., 1986). Among them, the LED–photodiode sensors are cheapest and arguably most reliable, but they measure only velocity (and velocity fluctuations); McElwaine (2006, Secs. 5 and 6) discusses relevant error sources.

With LED–photodiode sensors, velocity fluctuations in the flow direction can also be measured. With density measurements and additional assumptions about the isotropy of this random motion, the granular temperature and its contribution to fluidizing the flow can be estimated. This is of importance for directly testing DEM models and the balance of random kinetic energy (granular temperature) used in RAMMS::EXTENDED (Buser and Bartelt, 2015).

Stresses. As mentioned above, the bed-normal load and shear stress can, in principle, be measured with a 3-component load plate installed flush with the ground or—as at Revolving Door—with a glide plane prepared beforehand, but both placements have significant drawbacks. An alternative set-up, devised for the SAEs at Niseko, measures the normal stress σ_n perpendicular to the flow direction at a fixed height above the ground (Fig. 3.c). If this yet untested design is found to work satisfactorily, the load cell can be supplemented with a sensor recording the shear stress. Combining this device with LED–photodiode arrays and a density estimate, one can determine the effective friction coefficient $\mu(I)$ as a function of the non-dimensional shear rate $I = \dot{\gamma}/\sqrt{\sigma_n/\rho}$ and study the the rheology of flowing snow in detail.

Pore-air pressure. Pore air from the snow cover, escaping through the avalanche body when pressurized under the weight of the avalanche, has been suggested as a potentially important factor for fluidization and low friction in some dry-snow avalanches (Issler, 2017). To test this hypothesis, the pore pressure inside the avalanche must be measured together with the total normal stress at the same location. A prototype sensor combination is awaiting laboratory and field tests (Figs. 3.b,c).

Entrainment and deposition rates. The instantaneous erosion or deposition rate at a given location can, in principle, be obtained from densely spaced LED–photodiode sensors, but a large number of sensors is needed. An FMCW radar system buried in the path or suspended above it may have comparable or better spatial resolution than an LED–photodiode array and coarser yet sufficient temporal resolution.

To gain a better understanding of the process for testing DEM models and developing entrainment formulas for depth-averaged continuum models, it would be very valuable if a sufficiently large longitudinal section ($0.5{\times}0.3\,\mathrm{m}^2$ or larger) comprising the snow cover and lower part of the avalanche could be observed visually, as was done in a chute with granular materials (Barbolini et al., 2005). In a portable instrument support structure like in Fig. 3.a, a high-speed video camera system can easily be integrated, but it remains to be seen whether one can achieve sub-millimeter resolution and frame rates above $200\,\mathrm{s}^{-1}$ at reasonable cost.

Particle trajectories. DEM models make predictions about the trajectories of snow clods that were released initially or entrained along the path. The travel distance of passive tracers like larch or mountain pine cones, twigs, bark or small stones can be measured if they are identified in the deposit. If the particles were initially close to each other, their spatial distribution in the deposit contains information about dispersion and velocity fluctuations in the avalanche. Active tracers record or transmit their instantaneous location, velocity and acceleration and thus provide detailed information about the collision forces between particles in an avalanche, see e.g. (Neuhauser et al., 2023; Winkler et al., 2024), which is useful not only for DEM models but also for advanced continuum models.

4. WHAT TO DO BEFORE AN EXPERIMENT?

Perhaps the decisive preparation step is choosing the most suitable test site. However, this choice depends on so many circumstances that little of general value can be said except that avalanche conditions must occur frequently, easy and safe accessibility before, during and after an avalanche event is essential. Moreover, even though wet-snow avalanches have become an increasing practical concern in view of a warming climate, a test site where dry-snow avalanches can be studied during early and high winter is scientifically more interesting than one with only wet-snow avalanches.

The day before a forecast substantial snowfall is a crucial period for setting up an experiment, provided the snow cover stability allows safe working in the path. Depending on the set-up of the site, key activities can be (i) determining safe observation points and instructing the participants about safety measures, (ii) preparing the prospective release area to enhance triggering probability, (iii) installing mobile sensors that either are suspended above the track or mounted in the path, (iv) place a first layer of active and/or passive tracers, and (v) survey the old-snow depth with LiDAR. If the experiment involves tracers are and safety safety considerations allow it, one can place additional (distinguishable) tracers at different heights in the new-snow layer.

More often than not, experiments fail because no avalanche can be released, especially if explosives cannot be used for legal reasons. There are, however, a few methods to increase the chances of success that may be worth trying. Ski patrols in Switzerland have often released avalanches at a slope-break by jumping on the steep part from above, secured with a rope. A safer and possibly more effective method is pushing, shaking or loading the new snow with a snow groomer. Another way may be creating a pulse of excess pore pressure by rapidly pressing air or water through hoses laid out on the surface of the old-snow cover. A highly effective variant of this is using thermite charges in or below the new snow (Yamamoto et al., 2007). Thermite is a mixture of a metal powder like aluminum and a metal oxide like Fe_2O_3 with a highly exothermal reaction when ignited; it can rapidly vaporize a quantity of water in which it is embedded and thus create high pressure.

In typical release areas, the ratio of the fracture areas along the circumference of the slab and along the weak layer is of the order $r \sim 6HL/(2L^2) = 3H/L$, where H is the fracture depth and it is assumed that the avalanche width is about twice its length, L. Hence, r and thus the importance of slab support from the surrounding snow cover increases with decreasing avalanche size. To increase the chances of triggering, one may eliminate these forces by cutting out the desired slab, first along its sides and then along the crown line. In some cases, it may be easier to delimit the desired release area *before* the snowfall starts by setting face boards (as used on construction sites) vertically into the snow cover, forming three sides of a trapezoid.

A highly promising method for reducing the shear strength of the weak layer or interface between the new and old snow consists in covering the old-snow surface with geotextiles (Glover et al., 2021). This method can very well be combined with the face boards mentioned above. The most suitable fabric type and surface roughness will depend on the size of the release area, its steepness, the expected snowfall and temperature. Acquiring this knowledge will require some experimentation.

5. POST-EVENT FIELD WORK

After a successful avalanche release, the subsequent field work may take up to several days, especially if passive tracers have to be collected. Needless to say that the residual avalanche hazard must be monitored and managed continually throughout the entire work period.

To supplement the surface models obtained from LiDAR surveys before and after the event, snow pits in strategically selected points are needed to distinguish between the residual, compacted snow cover, the eroded part of the new snow, and snow deposited by the avalanche. The thicknesses and mean densities of these three components are necessary for obtaining the correct mass balance, as shown by Sovilla et al. (2001). Without this, one cannot even determine the sign of the mass balance of the avalanche in a given cross-section in some cases. Often, one candistinguish the residual snow cover from the deposits visually or with the fingers or a brush, but where this is difficult, one may spray a mixture of writing ink and 2-propanol alcohol on a clean pit face and warm it gently with a

Figure 4: Visualization of the deposit texture by spraying an ink–alcohol mixture onto the vertical face of a snow pit and warming it lightly with a camping-stove burner.

camping stove (H. Gubler, personal communication, 2004). However, this technique must be practiced sufficiently beforehand (Fig. 4).

Recognizing the different layers and their changing properties along the avalanche path is also crucial for distinguishing parts of the deposit stemming from the dense or the fluidized flow regime. Sometimes, the boundaries of the dense-flow deposits are clearly recognizable, in other cases there is a gradual transition. Obtaining quantitative information on the typical particle sizes and densities, the run-out distance and—in the case of channelized paths with pronounced turns—the superelevation of the two flow regimes along the path is extremely valuable for testing advanced flow models describing flow-regime transitions. Interestingly, the fluidized regime can be attained even in quite small avalanches, and terrain features can sometimes be used to estimate the minimum velocity of the fluidized front and the maximum velocity of the dense core (Issler et al., 2008, Figs. 2 and 3). Some models suggest that the snow properties play a decisive role in the fluidization process (Issler and Gauer, 2008; Vera Valero et al., 2015). One should therefore relate these results of the post-event field work with the properties of the undisturbed snow cover and the temperatures measured with a thermal camera, if available.

In very short avalanche paths, constraints on the rarely studied break-up process of the slab may also be obtained from video recordings in some cases. Such data can be compared to the predictions of advanced 3D models that simulate both the release process and the details of the avalanche motion (Gaume et al., 2019).

6. DISCUSSION

We firmly believe that SAEs hold great promise, in part because many aspects of avalanche dynamics can be studied in more detail than in large avalanches, and in part because the investment costs for SAEs are much smaller. Chances are high that a deeper understanding can be gained of (i) the rheology of avalanching snow and its dependence on the snow properties and temperature, (ii) the mechanisms responsible for fluidization and inordinately long run-out, and (iii) the interaction between the bed and the flow. A wide range of low- or moderate-cost sensors can be applied, and there are promising methods for increasing the chances for releasing avalanches even if explosives cannot be used. Moreover, SAEs offer aspiring avalanche researchers a great opportunity for gaining experience in experimental work and a more profound understanding of the physics challenges in the numerical modeling of avalanches.

Designing SAEs requires a wide range of considerations, and many compromises must be made due to the specific financial, logistic and topographic boundary conditions. Nevertheless, experience from past SAEs reveals a few guiding principles that we believe should be followed as much as possible:

- Preferably, sites should be chosen where both dry-snow and wet-snow avalanches occur.
- When planning an SAE, a minimum set of scientific questions that one wishes to answer should be formulated as a basis for the set-up of the SAE and the choice of sensors.
- Various methods for increasing the chances of triggering an avalanche should be tested and improved systematically. Similarly, some novel experimental techniques should be developed further.
- Much experience and collaboration is needed to run comprehensive experiments successfully. Hence, SAEs should be planned with a long time horizon to maximize the scientific gains. An international collaboration with a wide range of complementary competence and skills is advantageous. It will also be more resilient against fluctuations in funding and personnel.

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