The avalanche flow regimes and their pressure on infrastructures

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ABSTRACT

New high-resolution radar measurements performed at the Swiss test site "Vallée de la Sionne" have allowed a reclassification of snow avalanches into 7 different flow regimes. Multiple flow regimes are often simultaneously present in different regions of a single avalanche, and avalanches can change the dominant flow regime as they descend the slope as a result of the entrainment of colder snow at higher altitudes and warmer snow at lower altitudes. 4 of these flow regimes are particularly important for the design of infrastructures impacted by avalanches. These include three dense regimes, namely the cold dense regime characteristic of fast moving dry avalanches, the warm plug and warm shear regimes characteristic of slow moving warm/wet avalanches and one dilute/dense regime, the intermittency regime, characteristic of fully developed powder snow avalanches. Each regime has a distinct impact dynamics, which requires a different modeling approach. The new data suggest that the assumptions underlying current avalanche simulation models and pressure calculation procedures may be too simple. The research community now faces the challenge of developing a better understanding of the physical processes that characterize the individual flow regimes, their transitions, their connection to the snow properties and their interaction with infrastructures.

1. INTRODUCTION

To improve our knowledge on the avalanche dynamics and the interaction between avalanches and structures, impact pressures and other dynamical variables have been measured at the Vallée de la Sionne experimental site (VdlS) in Switzerland since 1998 (Figure 1). In these years of operation we have measured events with an approximate return period of 10-20 years, as well as more frequent events, which may have a return period of one year or less.

In the last years, measurement techniques have considerably improved. Since the winter season 2010-2011, a new radar system, the GEODAR, has measured more than 200 avalanches of all sizes and different flow types (Ash et al., 2014; Köhler et al., 2018a, 2016).

The GEODAR is designed to localise the position of an avalanche with a spatial horizontal resolution of 0.75 m. The radar wavelength is around 5 cm, causing the beam to penetrate the powder cloud and to reflect the dense, basal flow or large snow blocks, underneath. This frequency modulated continuous wave radar is installed inside a shelter and monitors the whole avalanche path (Figure 1 right panel).

Figure 1. The Vallée de la Sionne test site. The left panel shows the obstacle zone and the release area. The right panel shows the measurement setup at the 20 m high pylon and at the 5 m high wedge. The red circle indicates the position of the shelter with the GEODAR radar (Pictures P. Huguenin).

The GEODAR data together with high-resolution measurement of velocity, pressure, density and temperature made on a 20 m high pylon located in the middle of the avalanche path (Figure 1) allow gaining unprecedented details into the avalanche physics both in term of avalanche dynamics and impact with infrastructures. With this contribution we aim to summarise the results of these recent researches.

2. THE NEW AVALANCHE REGIME CLASSIFICATION

In 2014, Steinkogler and colleagues showed that the temperature of the snow entrained along the avalanche path significantly affected the development of the avalanche front velocities at the Vallée de la Sionne test site. A snow temperature warmer than −2 °C could be identified as critical value where large changes in the flow dynamics took place. In 2015, Steinkogler and colleagues confirmed that the reason of this transition was due to snow granulation by mixing snow of varying temperatures and water content in a concrete tumbler. The experiments showed that granules only formed when the snow temperature exceeded about −1°C. No evolution in the granule size was observed at colder temperatures. Depending on the conditions, different granulation regimes were obtained, which were qualitatively classified according to their persistence and size distribution.

This abrupt change in the avalanching snow properties immediately prompted the idea to divide avalanches into two main categories, warm and cold depending on the temperature of the snow and its tendency to granulate (Steinkogler et al., 2015a, b).

In 2018, Köhler and colleagues realized by analysing the measurements from the GEODAR that the radar signals generated by the avalanches could show very different patterns (Figure 2).
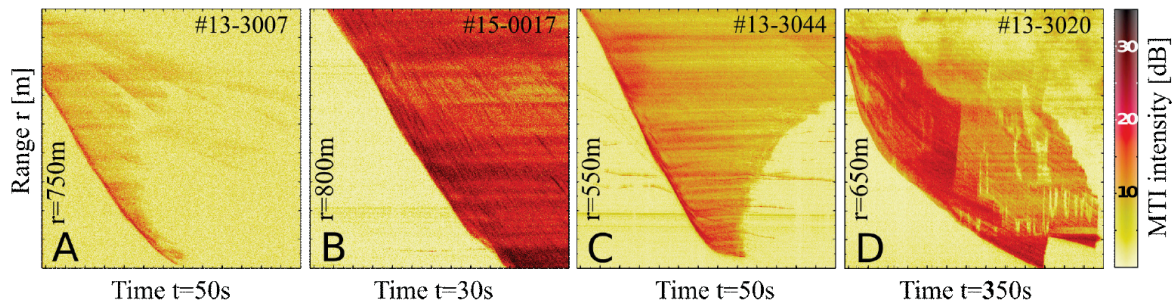
Figure 2. Typical GEODAR data signatures for the avalanche type: A) Cold dense regime, B) Intermittent regime, C) Warm shear regime and D) Warm plug regime. Note: Each panel has a different scale in range and time (Picture from Köhler et al., 2018c).

These differences confirmed the presence of the warm and cold behaviour suggested by Steinkogler et al. (2014), but stressed the need to divide avalanches into more categories, and more specifically into 7 flow regimes (Köhler et al., 2018a):

(1) The warm plug regime occurring when the snow cover temperature is mostly isothermal, $T = 0°C$. These avalanches are characterized by relatively low velocity, but cohesion between granules is large so that snow granules can easily stick together and give rise to large flow depths and flow units, which behave like gliding solid-like blocks.

(2) The warm shear regime occurring at snow temperatures slightly below 0°C. The matrix of the flow is still granular as in the case of the warm plug regime, but the relatively high velocities reached by these flows suggest that the cohesive forces acting between granules are not sufficient to glue particles together into larger units.

(3) The cold dense regime occurring at snow temperatures below -1°C. Their behaviour is similar to the warm shear regime but the snow temperature is lower and the velocity can be higher. Granulation is not expected.

(4) The intermittency flow regime occurring at snow temperature below -1°C. This is typical for the frontal zone of powder snow avalanches and it is characterized by large fluctuations in impact pressure, air pressure, velocity and density. The intermittency is caused by mesoscale coherent structures, i.e. an organized motion of particles, which evolves into the turbulent flow (Sovilla et al., 2018b).

(5) The suspension regime characterizing the motion of the dilute snow cloud in powder snow avalanches.

(6) The sliding slab regime characterizing the initial phase of the avalanche motion when the initial slab start to accelerate and to fragment into snow clods.

(7) The snowball regimes occurring when avalanches contain warm snow can give rise to individual snowballs or snow wheels rolling down the slope.

Particularly relevant for the flow dynamics and the impact pressures are the first 5 flow regimes, namely warm plug, warm shear, cold dense, intermittency and suspension.

2.1 **Flow regimes transitions**

The GEODAR measurements coupled with measurements of avalanche dynamics variables performed at the pylon have further suggested that a single avalanche can be characterized by multiple flow regimes (Köhler et al., 2018a). Powder snow avalanches give the most complex example of flow regime transitions, where all the 5 most relevant regimes may be present at the same time (Sovilla et al., 2015, Köhler et al., 2018a).

At the front region, powder avalanches have an intermittent region, which is characterized by large fluctuations in impact pressure, air pressure and density. Data collected at the VdlS show that the intermittency is caused by mesoscale coherent structures, an organized motion of suspended particles. These structures can have velocities as much as 60% larger than the avalanche front speed and are characterized by an air/particle mixture whose average density can be as high as 20 kg/m^3 (Sovilla et al., 2018b). Each structure can maintain denser snow clusters and single snow granules in suspension for several seconds providing an efficient mechanism for moving superficial cold snow from the snowcover or the dense layer to the powder cloud.

Immediately behind the avalanche front a dense basal flow layer exists. This is formed by direct erosion of the snow cover and by sedimentation of the snow transported by the coherent structures. Toward the avalanche front the dense layer in normally characterized by a cold dense regimes, but toward the tail can transform into a warm shear or warm plug regimes if warmer snow is entrained from deep layers in the snowcover (Sovilla et al., 2015, Köhler et al., 2018b).

Finally, a turbulent suspension cloud of fine particles surrounds the denser regimes.

At the VdlS, the snow cover characteristics control the relative development of the different flow regimes. Indeed, when a lot of snow is cold and cohesionless, powder avalanches tend to develop a large intermittent region that in extreme cases can extend for almost the whole avalanche length. On the contrary, when only a small portion of the snow cover is cold, the intermittent region develops only marginally to give space to a more important basal dense layer. This flow regime balance controls the avalanche dynamics and the pressure the avalanche exerts on infrastructures.

Further, Köhler and colleagues (2018b) also observed from the GEODAR measurements that transitions between dominant avalanche typologies could happen from release to deposition. Indeed, large avalanches may encounter different snow conditions along their track, releasing from a cold snowpack but entraining warm snow at lower altitude. The conclusions of this recent research suggest that many avalanches undergo a transition along the path, thus strongly influencing the avalanche dynamics and the impact with infrastructures in the run-out zone.

3. FLOW REGIMES AND IMPACT PRESSURES

The flow classification presented by Köhler el al. (2018a) appears to be appropriate also to classify pressure measurements at the VdlS. Indeed, 20 years of pressure measurements on a 20 m high pylon show that the warm plug, warm shear, cold shear and intermittency regimes are all relevant in term of impact pressure and thus important for the design of structures (Sovilla et al, 2008, 2010, 2016, 2018a).

The results of a recent investigation (Sovilla et al., 2018a) to estimate which of these regimes is more destructive in terms of impact pressure and bending moment on the pylon of VdlS has surprisingly concluded that the maximum long-lasting bending moment at the pylon was exerted by a warm plug avalanche characterized by relatively low velocity (up to 10ms-1) and large flow depths (up to 7m). Indeed, in spite of the low velocity, warm plug avalanches are able to produce force amplifications on narrow structures as a result of formation of force chains (Sovilla et al., 2010, Sovilla et al., 2016; Kyburz et al., submitted). Furthermore, they exert hydrostatic-like forces that are flow depth dependent, thus these avalanches can become decisive if the flow depth is large.

On the contrary, fast cold dense avalanche, considered so far as the most dangerous in term of structure design, turned out to have a thinner flow depth in comparison to warm plug avalanches, so that their maximum bending moment is small. Nevertheless, cold dense avalanches are still important since they can exert maximum local pressures, which may locally damage the structure and endanger its stability. Further, cold dense avalanches can have longer run out compared to warm avalanches and thus they are decisive for the design of infrastructure, which are located outside the reach of the warmer flow.

In particular, a cold dense regime is particularly important if it is coupled with the intermittency flow regime, as normally happens in the frontal region of large powder snow avalanches. In this case dense snow clusters from the dense layer can be lifted up to significant heights by the coherent structures causing very large forces at large heights above the basal dense layer (Sovilla et al., 2018a). However, these forces are intermittent and last only for a fraction of a second and may rather be dangerous when the resonance frequency of the structure matches the pressure fluctuations (Bartelt et al., 2018).

4. CONCLUSIONS

The measurements performed at the Vallée de la Sionne test site in the last years of operation have shown that the avalanche motions cannot be simply split into the conventional binary definition between dense and powder snow avalanches, which is used today as a basic criteria for avalanche dynamics calculations (Faug et al, 2018), but that more sophisticated criteria are needed. The understanding of the physics explaining the nature and origin of the different flow regimes and their behaviour during the interaction with infrastructures is the next step to improve our modelling tools and pressure calculation procedures.

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