GRANULATION OF SNOW: EXPERIMENTS AND DISCRETE ELEMENT MODELING

Walter Steinkogler[1,2*], Johan Gaume[1], Henning Löwe[1], Betty Sovilla[1] and Michael Lehning[1,2]

[1] WSL Institute for Snow and Avalanche Research SLF, Davos Dorf, Switzerland
[2] CRYOS, School of Architecture, Civil and Environmental Engineering, EPFL, Lausanne, Switzerland

ABSTRACT: The flow dynamics of snow avalanches can strongly differ for individual avalanches even if the release conditions are similar. The development of different flow regimes, e.g. whether a plug flow or a sheared flow is formed, strongly depends on the snow properties in the avalanche. Depending on whether the avalanche was dry, moist or wet, typical granular structures and size distributions can be observed in the deposition zone. These are then often interpreted as indirect indicators of the internal flow dynamics of an avalanche. In order to understand under which circumstances granules form, we used a concrete tumbler to examine the granulation, the generic name for particle size enlargement, of snow with different properties. Our experiments show that granulation of snow only occurred when a snow temperature of -1°C was exceeded. No granule formation could be observed below this temperature threshold. To better understand the physical processes involved in the granule formation, cohesive discrete element simulations were performed, allowing to correctly reproduce the size distributions of granules as measured in the tumbler and in real-scale avalanches. The results of this paper confirm recent studies that the snow temperature plays a crucial role on granulation and thus on the flow dynamics of avalanches since it may strongly change the structure of the flowing snow. This investigation provides a first step for more complex and real-scale modeling of flowing cohesive avalanches and shows that granulation has the potential to link snow cover properties with avalanche dynamics.

KEYWORDS: Granulation of snow, temperature, tumbler experiment, discrete element simulation.

1. INTRODUCTION

A sheared and fluid-like layer, a plug flow or a dilute suspended powder cloud are flow behaviors which can often be observed in snow avalanches (Gauer et al., 2008). Often these different regimes coexist at the same time at different locations inside an avalanche (Sovilla et al., 2008). Due to its flow dynamical characteristics, the dense core of snow avalanches is often approximated as a granular flow (Roche et al., 2011). Yet, a comprehensive understanding of the conditions that define the particle size distribution and their properties and the consequent influence on flow dynamics of avalanches is still lacking.

Recent studies show that the properties of the snow entrained by an avalanche during its downward motion, especially snow temperature, significantly affect flow dynamics (Naaim et al., 2013; Steinkogler et al., 2013), mostly by changing the granular structure of the flow. The relation between particle size distribution and mobility of a granular flow, i.e. its ability to move faster and further, has been shown in multiple studies on mono- and bi-disperse materials (Moro et al., 2010; GDR MiDi, 2004). However, the link between snow cover properties and a certain size distribution was never quantified.

Up to now, very few investigations exist (Nohguchi et al., 1997; Turnbull, 2011) which address the granulation of snow, i.e. the generic name for particle size enlargement (Walker, 2007). For other disciplines, extensive research on granulation processes (Pietsch, 2003) and the characterization on the granule properties and size distributions took place in the last five decades (Ennis et al., 1991). Rotating drums are a common experimental setup to conduct this research. For numerical studies on cohesive powder flows in rotating drums generally the discrete element method (Cundall and Strack, 1979) is applied. Yet, these studies mainly focus on the mixing behavior (Chaudhuri et al., 2006) rather than the evolution of granule sizes. To our knowledge, DE modeling has never been used to model granulation effects in snow avalanches which are often described using cohesionless granular materials (Faug et al., 2009).

It is the aim of the present paper to describe relevant snow parameters and thresholds that control the size and properties of granules for different types of snow that formed in a rotating tumbler by ways of laboratory experiments (Section 2.1) and numerical simulations (Section 2.2). We then compare those results to measurements in the deposition of real-scale avalanches

---

* *Corresponding author address:* W. Steinkogler
WSL Institute for Snow and Avalanche Research SLF,
Davos, Switzerland; tel: +41 81 417 03 75
email: steinkogler@slf.ch

(Section 3). Section 4 discusses characteristics of the different granule classes and practical applications of the results.

2. METHODS

2.1 Experimental setting

To investigate the granulation potential of different snow types a standard, unmodified concrete tumbler (Fig. 1) was used. Two blades inside acted as mixing elements and the tumbler rotates with a constant velocity.

Snow of different types, e.g. new snow particles, with different properties, e.g. temperature, was used for the experiments. A regular snow profile following the guidelines of Fierz et al. (2009) was conducted before every experiment to assess the initial conditions of the investigated snow (temperature, density, grain shape, grain size, moisture content, hardness). Subsequently a defined volume of snow layers with similar properties was shoveled into the tumbler.

Fig. 1: Granules in motion in rotating tumbler. One (of the two) mixing blades can be seen at lower left corner.

The tumbler was stopped at regular intervals, e.g. every 5 minutes, and the properties of the snow or the formed granules were measured. Snow temperature was measured with a digital thermometer and snow densities of the granules or fine material in the tumbler were measured with a 100 cm^3 snow shovel and a digital scale. The liquid water content (LWC) was visually estimated by using a 8x magnification glass to identify water and squeezing the snow by hand. An LWC classification was then assigned according to Fierz et al. (2009). Grain shape and size were identified by using a crystal card and a magnifying glass.

2.2 Discrete Element (DE) Modeling

To assess mechanical quantities such as stresses, displacements, shear rates at each point within the sample a discrete element (DE) modeling approach is used. Such a complete spatial picture is impossible to achieve experimentally. We apply DE simulations to characterize the link between the macroscopic behavior of dense cohesive granular materials and micro-mechanical properties of the grains to further investigate the granulation processes of snow. The inter-particle strength (tensile and shear) and a sintering parameter for the bond creation are accounted for in a cohesive contact law. Finally, the size distribution acquired from the DE simulations are compared to that obtained from the rotating tumbler experiments and real-scale avalanches.

3. Results

A strong dependency of granulation on snow temperature could be observed. As soon as a temperature of $-1°C$ was reached, granulation occurred very rapidly (colored markers in Fig. 2). No persistent granules could be observed (gray circles in Fig. 2) below the threshold of $-1°C$, even though multiple experiments were run for an extensive duration of more than 100 minutes.

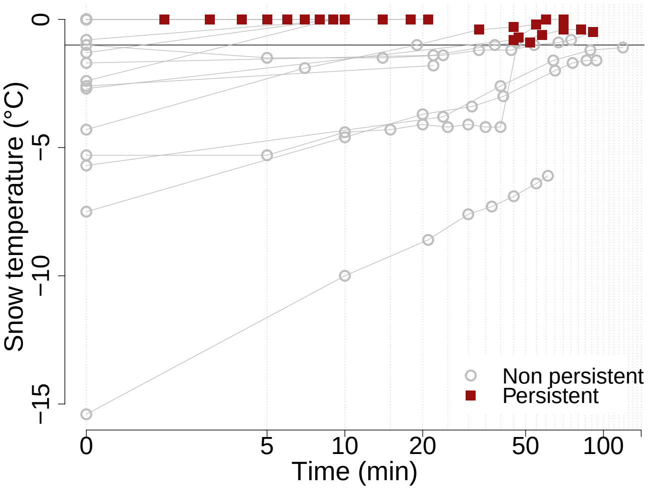

Fig. 2: Snow temperature measurements for all individual experiments (gray lines) and time of each measurement (gray and colored markers) and for persistent-moist granules (colored squares).

Water could neither be recognized by eye nor by magnification (Fierz et al., 2009) for persistent-moist granules yet the snow showed a distinct tendency to stick together. Liquid water was only observed for persistent-wet granules (not shown). Most experiments with non persistent granules occurred in dry snow conditions. Even though many persistent-moist experiments were at or close to $0°C$ they never reached the *wet* class. Persistent-wet granulation only occurred if the initial snow was already wet or water was added to the tumbler.

3.1 Granulation classification

The conducted tumbler experiments allowed to identify different granule classes which are defined by their persistency and the snow properties of the granules inside the tumbler:

Non persistent granules fragmented upon collisions and always occurred for experiments with snow temperatures below $-1°C$.

Fig. 3: Persistent-moist granules that formed inside the tumbler.

Persistent-moist granules formed for snow temperatures warmer than $-1°C$, were very hard and even resisted direct impacts on the mixing blades.

Persistent-wet granules were softer and deformed upon impacts. The snow was at $0°C$, liquid water could be observed and the snow had a clear tendency to stick together. Yet, the formed granules had a low persistency and often broke apart again.

Videos of the experiments for the main granulation regimes (non-persistent, persistent-moist, persistent-wet) helped to qualitatively visualize the granulation process and are available on request.

3.2 Numerical results

The conducted DE simulations allow to discuss the different, observed granulation classes (Section 3.1) and relevant snow parameters in more detail with respect to the determining physical processes of cohesion and sintering. Figure 4 shows an example of a DE model simulation for persistent-moist granules (individual granules are indicated with different colors).

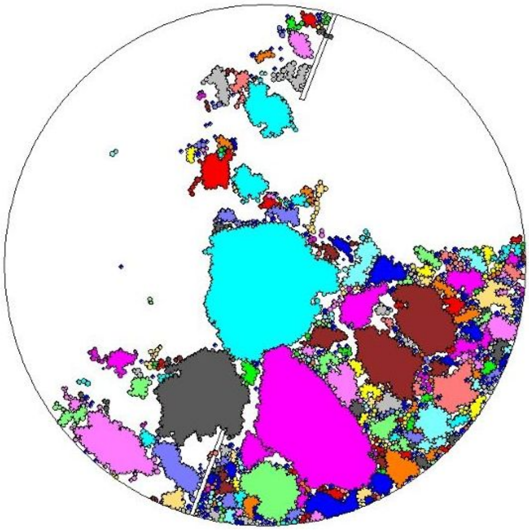

Fig. 4: DE model simulation of persistent-moist granules.

3.3 Granule size distribution

Fig. 5 compares the granule size distributions of a persistent-moist tumbler experiments (violet filled circles), the corresponding DE simulation (violet line) and a distribution as observed in avalanche deposits (green triangles). The granule size showed a typical log-normal distribution (Bartelt and McArdell, 2009), although with a shift towards smaller granule sizes compared to real-scale avalanches and the DE model results are in good agreement with the measurements. The artificially small tumbler size and the computational domain may limit the growth of larger granules in experiments and simulations.

4. DISCUSSION and CONCLUSIONS

The observed variety in granule sizes and properties can have a direct influence on flow dynamics and is therefore relevant for practical applications. The granulation process can influence flow dynamics in two possible ways: by changing the size distribution of the flowing particles and by a change of their properties.

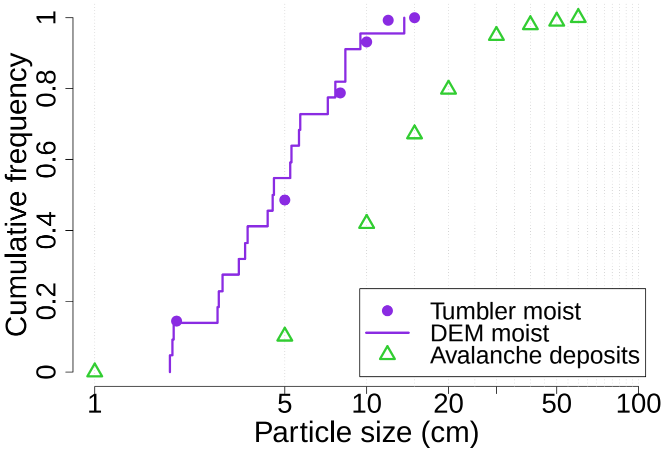

Fig. 5: Granule size distributions conducted for a persistent-moist tumbler experiment (violet filled circles), a DE simulations (violet line) and in the deposition area of an artificially released avalanche (green triangles).

The significant effect of size distribution on flow dynamics has been shown in several studies (Moro et al., 2010; Andreotti et al., 2013). The presented results demonstrate that the granule size distribution (Fig. 5) inside an avalanche is determined by the snow cover properties. For avalanches consisting of cold snow, i.e. $<-1°C$, a fine-grained structure with non-persistent granules can be expected. The granular structures that are often observed in the deposition zone of these avalanches are likely to be fragments of the eroded snow cover and are not expected to have formed due to granulation. Contrary, for avalanches consisting of warm snow, i.e. $>-1°C$ and possibly containing liquid water, only persistent granules are expected.

The different properties of the granules can significantly influence the flow regime of an avalanche and define if a plug flow, i.e. typically found in warm avalanches, or a sheared flow, i.e. cold avalanches, will form (Kern et al., 2010; Sovilla et al., 2008). Our results indicates that large values of cohesion and sintering acting between granules, i.e. when the snow temperature exceeds $-1°C$, enhances the resistance of particle to shear. This is in agreement with other granular experiments (Rognon et al., 2008). Also the energy dissipation upon collisions between granules was observed to be very different for the individual granule types.

For future developments in avalanche dynamics models and also the accurate forecasting of avalanche run-out by practitioners it is therefore essential to take snow cover properties into account.

ACKNOWLEDGEMENTS

Funding for this research has been provided through the Interreg project STRADA by the following partners: Amt für Wald Graubünden, Etat du Valais, ARPA Lombardia, ARPA Piemonte, Valle d'Aosta, Regione Lombardia. The authors would like to thank all the people who helped gathering the data during the field.

REFERENCES

Andreotti, B., Y. Forterre, and O. Pouliquen, 2013: *Granular Media* (1st ed.). Cambridge University Press.

Bartelt, P., and B.W. McArdell, 2009: Granulometric investigations of snow avalanches. *Journal of Glaciology*, **55**, 829–833.

Chaudhuri, B., A. Mehrotra, F.J. Muzzio, and M.S. Tomassone, 2006: Cohesive effects in powder mixing in a tumbling blender. *Powder Technology*, **165**, 105–114.

Cundall, P.A., and O.D. Strack, 1979: A discrete numerical model for granular assemblies. *Geotechnique*, **29**, 47–65.

Ennis, B., B.J., G. Tardos, G., and R. Pfeffer, 1991: A microlevel-based characterization of granulation phenomena. *Powder Technology*, **65**, 257–272.

Faug, T., R. Beguin, and B. Chanut, 2009: Mean steady granular force on a wall overflowed by free-surface gravity-driven dense flows. *Physical Review E*, **80**.

Fierz, C., R. Armstrong, Y. Durand, P. Etchevers, E. Greene, D. McClung, K. Nishimura, P. Satyawali, and S. Sokratov, 2009: The international classification for seasonal snow on the ground. *IHP-VII Technical Documents in Hydrology*, **83**.

Gauer, P., D. Issler, K. Lied, K. Kristensen, and F. Sandersen, 2008: On snow avalanche flow regimes: inferences from observations and measurements. In: *Proceedings, International Snow Science Workshop ISSW 2008, Whistler, Canada*.

GDR MiDi, 2004: On dense granular flows. *Eur. Phys. J. E*, **14**, 341–365.

Kern, M.A., P.A. Bartelt, and B. Sovilla, 2010: Velocity profile inversion in dense avalanche flow. *Annals of Glaciology*, **51**, 27–31.

Moro, F., T. Faug, H. Bellot, and F. Ousset, 2010: Large mobility of dry snow avalanches: Insights from small-scale laboratory tests on granular avalanches of bidisperse materials. *Cold Regions Science and Technology*, **62**, 55 – 66.

Naaim, M., Y. Durand, N. Eckert, and G. Chambon, 2013: Dense avalanche friction coefficients: influence of physical properties of snow. *Journal of Glaciology*, **59**, 771–782.

Nohguchi, Y., T. Kobayasi, K. Iwanami, K. Nishimura, and A. Sato, 1997: Granulation of snow. In: *Snow engineering: Recent Advances*.

Pietsch, W., 2003: An interdisciplinary approach to size enlargement by agglomeration. *Powder Technology*, **130**, 8 – 13.

Roche, O., M. Attali, A. Mangeney, and A. Lucas, 2011: On the run-out distance of geophysical gravitational flows: Insight from fluidized granular collapse experiments. *Earth and Planetary Science Letters*, **311**, 375–385.

Rognon, P., J.N. Roux, M. Naaim, and F. Chevoir, 2008: Dense flows of cohesive granular materials. *Journal of Fluid Mechanics*, **596**, 21–47.

Sovilla, B., M. Schaer, M. Kern, and P. Bartelt, 2008: Impact pressures and flow regimes in dense snow avalanches observed at the vallee de la sionne test site. *Journal of Geophysical Research: Earth Surface*, **113**.

Steinkogler, W., B. Sovilla, and M. Lehning, 2013: Influence of snow cover properties on avalanche dynamics. *Cold Regions Science and Technology*, **97**, 121–131.

Turnbull, B., 2011: Scaling laws for melting ice avalanches. *Physical review letters*, **107**, 258001.

Walker, G.M., 2007: Chapter 4 drum granulation processes. In: *Granulation*, M. H. A.D. Salman and J. Seville (Eds.), Volume 11, pp. 219–254. Elsevier Science B.V.