BEYOND DENSE Flow AVALANCHES (bDFA) – RESEARCH PROJECT WITHIN THE AUSTRIAN ACADEMY OF SCIENCES RESEARCH PROGRAMM
EARTH SYSTEM SCIENCES (ESS)

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<table>
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<th><strong>Final Report:</strong></th>
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<td><strong>bDFA – beyond dense flow avalanches</strong></td>
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<tr>
<td>Quantifying the destructive reach of snow avalanches beyond the dense flow regime</td>
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<tr>
<td><strong>Duration of project:</strong> 1.4.2015 to 31.3.2017 prolonged to 31.7.2018</td>
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<td><strong>Reporting period:</strong> 1.4.2017 to 31.7.2018</td>
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<td><strong>Project team (in alphabetic order):</strong></td>
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<tr>
<td>1 BFW Austrian Research Centre for Forests, Department of Natural Hazards</td>
</tr>
<tr>
<td>2 IGT Institute of Infrastructure, Division of Geotechnical and Tunnel Engineering, University of Innsbruck</td>
</tr>
<tr>
<td>3 IOG Institute of Geography, University of Innsbruck</td>
</tr>
<tr>
<td>4 SLF WSL Institute for Snow and Avalanche Research SLF</td>
</tr>
<tr>
<td><strong>Associated partner:</strong></td>
</tr>
<tr>
<td>5 WLV Austrian Avalanche and Torrent Control, Department Snow and Avalanches</td>
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</tbody>
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Abstract

The final report summarizes
- primarily the progress that has been achieved during the second project year (April 1, 2017 to July 31, 2018) of the ESS project bDFA – beyond dense flow avalanches (Quantifying the destructive reach of snow avalanches beyond the dense flow regime)
- and highlights the major achievements that have been gained during the entire project period April 1, 2017 to July 31, 2018.

The project aims at the analysis and improvement of avalanche simulation tools, primarily of the Swiss tool RAMMS::AVALANCHE and the Austrian tool SamosAT.

At first, damage back-calculations of documented events and a damage catalogue have been completed. Additional data have been investigated on damages of avalanche gullies and on the recent avalanche disaster in Farindola, Italy. Furthermore, the expert interview conducted in the first project year was completed and evaluated. In total 51 participants from various countries have participated. Major results are about to be published. Progresses could be achieved at the Vallee de la Sionne test site. Here, the installation of pressure sensors was completed and in cooperation with the Ruhr-Universität Bochum (RUB) a novel radar system has been developed to measure snow concentration and density in powder snow clouds. First measurements of artificially released avalanches could be made. Findings within the second project period suggest that the flow variable – pressure relation represents the he missing link between current bDFA models and impact pressures and therefore bDFA damages. Therefore, three-dimensional Eulerian multiphase fluid dynamic simulations with OpenFOAM have been performed and a unified framework for snow avalanches has been established. The finalization of Back-calculations of avalanches from Switzerland and Austria has been realized within the second and third project year. Therefore, 9 avalanches from both countries have been simulated using RAMMS and SamosAT. Because of a new version release of SamosAT, the calibration of an adjusted parameter has been pushed forward and implemented in a preliminary form. Further a comparison between the two simulation tools has been initiated. Finally, vulnerability functions describing the aversive effects of powder snow avalanches on massive constructed buildings as they are typical for the Alpine region have been derived. The basis of that work is a wide investigation of documented damage events in Tirol. An approach that relates classified damages to monetary values.
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1 Introduction

The project proposal 'bDFA – beyond dense flow avalanches (Quantifying the destructive reach of snow avalanches beyond the dense flow regime)' was submitted to the Earth System Science (ESS) research program of the Austrian Academy of Sciences in April 2014. On October 13, 2014, the research contract was signed. Facing the signed contract the project period as well as the deadlines for submission of the project report have been changed as shown in Table 1. The changes have been approved by the funding authority ÖAW with the confirmation email from January 1, 2015.

| Table 1: Approved changes of deadlines for the submission of the project reports |
|-------------------------|-------------------------|-------------------------|
| 1. Interim report       | October 31, 2015        | March 31, 2016          |
| 2. Interim report       | October 31, 2016        | March 31, 2017          |
| 3. Final report         | October 13, 2017        | March 31, 2018          |

In section 2 the progress of each workpackage for the reporting period (April 1, 2017 to August 31, 2018) and the entire project period are shown.

1.1 Objectives and research question

A long-standing problem in avalanche science is to quantify the destructive potential of the air-blast that arises from snow avalanche motion. This problem is especially difficult to solve because the air blast extends beyond the reach of the dense flowing core. Hence, the main goal of the project bDFA is to test, extend and apply existing dense/powder avalanche dynamics models to predict the destructive force of avalanches beyond the dense flow regime.

Subsequently the following research questions are formulated for the project bDFA:

- How does a long-term full-scale monitoring have to be set up to support modellers with the essential physical information to improve numerical snow avalanche simulation models or to introduce a new bDFA model or bDFA model component?
- How does the general model improvement / development have to look like to fulfil the requirements coming from the practice and from full-scale test site measurements?
- Which socio-economic effects are to be expected from these numerical snow avalanche model improvements/developments with particular consideration of transdisciplinary approaches?
1.2 Workpackages, project structure and budget

Table 2: Workpackages and time plan for the entire project and responsible partners

<table>
<thead>
<tr>
<th>WP</th>
<th>Description</th>
<th>Year 1</th>
<th>Year 2</th>
<th>Year 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>WP00 IOG</td>
<td>Project management</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>WP01 IGT</td>
<td>Acquisition of bDFA data and damage categorization</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>WP02 SLF</td>
<td>Analysis of experimental bDFA field data</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>WP03 BFW</td>
<td>Computational bDFA simulation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>WP04 IGT/IOG</td>
<td>Analysis of bDFA modelling effects</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2 and Figure 1 show the time plan and the structure of bDFA project. It can be seen that the second project year (report period) is focused on
- the acquisition of data
- finalization of the damage catalogue
- instrumentation and measurements at the Valle de la Sionne test site
- Computational bDFA simulations
- Evaluation of the expert interview

In chapter 2 (Progress of project) the achieved progress of each Workpackage is shown.

Due to the project budget cutback of about 30 % (from € 349.840,-- to 231.915,--), some changes in the project structure have been done. The respective details are presented in chapter 2.

Because of the financial cutback and the related difficulties for the project realization, the Office of the Vice Rector for Research of the University of Innsbruck supported the project by granting a doctoral Scholarship.
**Project extension**

An email request to Günther Köck was sent on 25\textsuperscript{th} October, 2017 concerning a self-financing project extension. The requested extension spans over four months from 31\textsuperscript{st} March, 2018 to the new project closure 31\textsuperscript{st} August, 2018. The reason for extension was a new technique for density measurements of powder snow avalanches developed within the project's scope. The extension was necessary in order to complete the analysis of these newly gained data, which would not have been possible within the original project duration. The National-Committee for Global Change approved the extension as reported in an email by Günther Köck on 12\textsuperscript{th} November, 2018.

During the calculation of impact pressures, there had been a slight shift from pure powder cloud simulations in OpenFOAM to mixed avalanches, since we wanted to have good input parameters for the conducted numerical wind channel tests. For this, the basis of a dense flow simulation in OpenFOAM had to be established. However, the coupling of dense flow with the powder cloud had to be postponed to a follow up project.

**1.3 Project meetings and Workshop participations**

Following bDFA project meetings were held within the first and second project years:

<table>
<thead>
<tr>
<th>Date</th>
<th>Venue</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>January 1, 2015</td>
<td>IOG</td>
<td>Cost plan adaption due to budget cutback</td>
</tr>
<tr>
<td>March 22, 2015</td>
<td>BFW</td>
<td>General discussion on the impact of powder snow avalanches on structures (buildings, …), the back-calculation of observed damages, set-up of the damage catalogue, Administrative issues, Discussion about an participation at Avalanche Dynamic Workshops (Chamonix, Innsbruck)</td>
</tr>
<tr>
<td>June 17, 2015</td>
<td>WLV</td>
<td>Preparation of the questionnaire</td>
</tr>
<tr>
<td>September 9, 2015</td>
<td>IOG</td>
<td>Finalization of the questionnaire</td>
</tr>
<tr>
<td>December 15, 2015</td>
<td>WLV</td>
<td>Agreement on the damage catalogue and the avalanches, which will be back-calculated, Discussion on the field experiments and the installation of sensors, Discussion on the participation at the ISSW 2016 workshop (USA), Presentation of the first opinion poll results</td>
</tr>
</tbody>
</table>
### Table 4: Second project year - bDFA meetings

<table>
<thead>
<tr>
<th>Date</th>
<th>Venue</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>June 28, 2016</td>
<td>BFW</td>
<td>- Radar suspension measurements</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Presentation of the master thesis of Max Mündler on Vulnerability functions</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- General discussion on the impact of powder snow avalanches on structures (buildings, …), simulation strategies</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Administrative issues</td>
</tr>
<tr>
<td>October 10, 2016</td>
<td>WLV</td>
<td>- Presentation of the questionnaire results and subsequent discussion</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Presentation of the work on CFD modelling</td>
</tr>
<tr>
<td>March, 21, 2017</td>
<td>WLV</td>
<td>- Presentation of the work on CFD modelling</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Density measurements in Val de la Sion</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Visit in Rigopiano</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Outline for RAMMS, SamosAT Calculations</td>
</tr>
</tbody>
</table>

### Table 5: Third project year - bDFA meetings

<table>
<thead>
<tr>
<th>Date</th>
<th>Venue</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>February, 28, 2018</td>
<td>IOG</td>
<td>- Recommendations on codes</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Simulation of the Swiss avalanches</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Planning of the project closure</td>
</tr>
<tr>
<td>Mai, 15, 2018</td>
<td>WLV</td>
<td>- Project closure</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Public presentation of project results (as a joint event with the 13th Avalanche Dynamics Workshop)</td>
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</tbody>
</table>

### Table 6: Workshop/conference participations

<table>
<thead>
<tr>
<th>Date</th>
<th>Workshop</th>
</tr>
</thead>
<tbody>
<tr>
<td>April 04-15, 2016</td>
<td>Numerical Modelling of Coupled Problems in Applied Physics with OpenFOAM, Zagreb, Croatia</td>
</tr>
<tr>
<td>April 21, 2016</td>
<td>European Geosciences Union (EGU) General Assembly 2016, Vienna, Austria</td>
</tr>
<tr>
<td>April 28-29, 2016</td>
<td>ICAS Nachwuchsforchertagung Phil.Alp, Luzern, Switzerland</td>
</tr>
<tr>
<td>June 02-04, 2016</td>
<td>18th Geo-DACH meeting, Reinischkogel, Austria</td>
</tr>
<tr>
<td>September 27, 2016</td>
<td>Symposium 20 years of avalanche research at Vallée de la Sionne, CH, 2016, Valais–Wallis, Sion, WSL Institute for Snow and Avalanche Research SLF “From avalanche experiments to Engineering Applications - An Austrian perspective”.</td>
</tr>
<tr>
<td>November 09, 2016</td>
<td>12th Avalanche Dynamics Workshop – Innsbruck, Austria</td>
</tr>
<tr>
<td>February 20-21, 2017</td>
<td>OpenFOAM Stammtisch United 2017, Kassel, Germany</td>
</tr>
</tbody>
</table>
2 Progress of project (reporting period)

2.1 Workpackage 1

WP01 aims at the development of a damage catalogue and a data base for the back-calculation of the according damages. The damage catalogue as well as the damage back-calculation will lead to the definition of AOI (areas of interest). Furthermore, in WP01 natural hazard engineers will be invited to take part workshops, their opinion will be analysed from qualitative interviews. The Milestones and the Deliverable of Workpackage 1 are summarized in Table 7.

<table>
<thead>
<tr>
<th>D/M</th>
<th>Description</th>
<th>Responsible</th>
<th>Due month</th>
</tr>
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<tbody>
<tr>
<td>M01-1</td>
<td>Damage catalogue and data base for bDFA damages</td>
<td>IGT</td>
<td>10</td>
</tr>
<tr>
<td>M01-2</td>
<td>Data base for bDFA damages</td>
<td>IGT</td>
<td>10</td>
</tr>
<tr>
<td>D01-1</td>
<td>Technical note to M01-1 and M01-2</td>
<td>IGT</td>
<td>12</td>
</tr>
</tbody>
</table>

Damage catalogue and back-calculations (D01-1)

Damage back-calculations of documented events have been completed in form of a master thesis (http://resolver.obvsg.at/urn:nbn:at-ubi:1-2698). The acquisition of additional data has been continued over the second project year. Additional records of avalanche damages, such as damaged avalanche galleries, could be gathered in cooperation with the Felbertauernstraße AG. Also, the recent avalanche disaster in Farindola, Italy has been investigated in cooperation with the local authorities. This allowed us to gather first-hand information.
Acquisition of bDFA data and damage categorization

With package M01-1 we aimed to find categories of frequently observed damages, which are representative for a certain pressure level. The wide variation of such catalogues has been investigated and reviewed in terms of changed construction standards and new calculation methods like numerical simulations.

With package M01-2 we aimed to create a data base for documented catastrophic avalanche events, including indications for the occurred pressure on buildings. We summarized and reviewed documentations and calculations of avalanche pressures based on destroyed buildings. Existing back-calculations have been repeated according to updated construction standards (European standards) and with new methods like finite element simulations (see Figure 3). Moreover, we aimed to describe the uncertainty of such back-calculations by incorporating unknown boundary conditions and varying limit states.

The full data base and recalculation have been published by Schroll (2015), a summary of scientific outcomes (i.e. technical note) has been published by Schroll et al. (2017).
Figure 3: The left figure shows a Finite Element simulation of a masonry wall with horizontal pressure as caused by snow avalanches. The red zones indicate material failure (plastic strain). The right figure shows cracks in a damaged wall of the Stettiner hut after an avalanche event (Foto: M. Platzer, 2014).

Expert interview
From the survey, carried out in the first project year and presented in the first interim report, a discrepancy could be identified. Model input parameters are considered having high uncertainties and a fairly strong influence on the model result. But still the results are considered to be reliable. This finding highlights the importance of the simulation process and the way how the expert employs simulations. The credibility of the simulations is the result of a simulation study, where different assumptions are tested and model results are compared with supplemental data. Another aspect is concerned with the occurrence of damages of buildings. Here, it seems that the prevention of damages is more associated with zoning limits rather than with pressure values produced by an avalanche model. Further major results of the expert survey have been summarized and published (Schmidtner et al. 2017a,b,c,d) and presented at the 13th avalanche-Workshop, Innsbruck, Austria. The findings of the interview gave reason to the conception of a consecutive interview. For that purpose a contribution at the International Snow Science Workshop (ISSW) 2018 was submitted and has been accepted. The second interview aims at the investigation of different hazard assessment approaches and how their interaction looks like.
2.2 Workpackage 2

The aims of WP02 are to analyse existing measurement data and to install specific pressure sensor arrays in two full-scale test sites (Valle de la Sionne, Switzerland; Bschlabs, Austria). In particular, bDFA specific quantities of the measurements will be extracted to gain an extended knowledge of the behaviour of bDFA. The pressure sensor arrays will be part of long-term avalanche monitoring strategies in Austria and Switzerland.

Table 1: Milestones and Deliverables of Workpackage 2

<table>
<thead>
<tr>
<th>D/M</th>
<th>Description</th>
<th>Responsible</th>
<th>Due month</th>
</tr>
</thead>
<tbody>
<tr>
<td>M02-1</td>
<td>Installation of pressure sensors Valle de la Sionne</td>
<td>SLF</td>
<td>12</td>
</tr>
<tr>
<td>D02-1</td>
<td>Technical note on flow variable – pressure relation</td>
<td>SLF</td>
<td>30</td>
</tr>
</tbody>
</table>

Due to new developments, the project team has in cooperation with the stakeholders from the Austrian Avalanche and Torrent control decided to put the instrumentation foci on the Valle de la Sionne test site in Switzerland. Hence, test site Bschlabs, Austria, will not be utilized for further investigations within the bDFA project. The above mentioned new development concerns primarily the radar system that has been developed at the Ruhr-University Bochum. In cooperation with the Ruhr-University Bochum (RUB) a novel radar system has been developed and evaluated (Baer et al. 2016). The radar has been developed with the aim to measure the snow concentration and density in powder snow clouds. Results of a first test in March 2016 look promising. The measurement system has been enhanced at RUB within the last year and two devices have been deployed at the Vallée de la Sionne test site (see Figure 4). First results under realistic conditions have been gathered during a measurement campaign on March 08, 2017. Two artificially released avalanches have been recorded, the data will be analysed within the next year. The density plays an important role in numerical bDFA models. These measurements are therefore imperative for many of the following working packages.
Flow variable pressure-relation (D02-1)

The flow variable – pressure relation turned out to be of major interest in this project. This relation represents the missing link between current bDFA models and impact pressures and therefore bDFA damages.

To establish such a link, we perform three-dimensional Eulerian multiphase fluid dynamic simulations with OpenFOAM. A big portion of the last project period has been invested into model development and evaluation considering snow avalanches in OpenFOAM. This model
has been applied to the simulation of the flow – structure interaction. This gives us detailed insights into the dynamic behaviour of snow-particle loaded flows around obstacles, such as illustrated in Figure 5 and Figure 6. Details are worked out in WP 4.

Figure 5: 3D Eulerian multiphase model of a powder snow avalanche hitting an obstacle (bottom left). The flow is colored according to the snow concentration of the mixture, the surface is colored according to pressure.

Figure 6: Detailed view of the pressure field around the obstacle. At the front a high-pressure zone is developed, at top, sides and back, low-pressure zones, i.e. wake is formed. This result will be used in the development of recommendations for engineering codes.
2.3 Workpackage 3

In WP03 selected avalanches (outcome of WP01) were back-calculated with two numerical snow avalanche models (RAMMS, Switzerland; SamosAT, Austria). The reference quantities for each avalanche are either the back-calculated pressures of affected buildings or the run-out zone of the avalanche itself. One central aim of WP03 is the test of both numerical snow avalanche simulation models based on the findings of WP01 and the outcomes of WP02. Finally, this allows to address the question whether operational bDFA models are capable of capturing observed bDFA quantities.

Moreover, we have been working towards a unified numerical framework for snow avalanches based on the open source toolkit OpenFOAM. Two mechanical frameworks for snow avalanche simulations are now available in OpenFOAM: (1) Depth-integrated shallow flow models as known from SamosAT and RAMMS and (2) the three-dimensional Eulerian multiphase model as used in WP02. Both flow models have been evaluated during the last project period: The shallow flow model has been applied to dense flow avalanches (see Figure 7, WP02).

The long-term goal is the possibility to evaluate bDFA models (e.g. the SamosAT and RAMMS models) within a unified framework. The mentioned frameworks are available as open source and we hope that our development will be continued.

Table 2: Milestones and Deliverables of Workpackage 3

<table>
<thead>
<tr>
<th>D/M</th>
<th>Description</th>
<th>Responsible</th>
<th>Due month</th>
</tr>
</thead>
<tbody>
<tr>
<td>M03-1</td>
<td>Simulation results of back-calculations RAMMS</td>
<td>SLF</td>
<td>24</td>
</tr>
<tr>
<td>M03-2</td>
<td>Simulation results of back-calculations SamosAT</td>
<td>BFW</td>
<td>24</td>
</tr>
<tr>
<td><strong>D03-1</strong></td>
<td><strong>Technical note on M03-1 and M03-2</strong></td>
<td>BFW</td>
<td>30</td>
</tr>
</tbody>
</table>

Figure 7: Simulation of the Ryggfonn avalanche with a shallow flow model in OpenFOAM. The color marks the depth-averaged velocity.
Back-calculations of selected avalanche events (D03-1)

Based on the available data (WP01), 9 avalanches were chosen for the back-calculations:

- Valle de la Sionne
- Alaqua
- San Gian/St. Moritz
- Hubelwang/Zermatt
- Wolfsgrubenlawine
- Moosbachlawine
- Fleisgergraben
- Wasserleiterlawine
- Hochlaufenlawine.

All Avalanches have been calculated using RAMMS by the SLF. During the reporting period a new version of the SamosAT avalanche model has been accomplished. The new version included the introduction of a “smoothed particle hydrodynamics” (SPH) approach to describe the particle movement in the avalanche core. The most benefit with this approach is the removal of numerical irregularities that could be observed with the older version. Another invention was the implementation of a powder-particle collision model. The collision of the particles in the powder cloud has been neglected so far. Another aspect of the revised SamosAT version concerns the entrainment. In the previous version a snow cover depth of 0.3 m for a designated area was assumed to take account for entrainment effects. In the new version the explicit consideration was disposed. The entrainment is now treated implicitly. Moreover, the standard procedure to retrieve the release heights has been revised. Due to the updates, an updates parameter set is being calibrated by the WLV. A preliminary set is already accomplished but still under revision. Special attention was paid at the particle-collision coefficient and the particle diameter. Here, efforts were focused to reproduce a more realistic lateral spreading of the powder cloud, which has been underestimated in the older version. Figure 8 gives an illustrative example of the Fleisskargraben. It shows the standard simulation of the old version and two simulations with the new version with different particle-diameters. It can be seen, the observed lateral spreading of the avalanche in the runout zone is reproduced more accurately.

The back-calculation of observed avalanches is a good opportunity to elaborate model differences. Therefore simulations with RAMMS and SamosAT have been performed by focussing on the Swiss avalanches. Here, elaboration of model differences regarding the reproduction of observed psa behaviours was of special interest. An example of such model comparison is depicted in Figure 9. One of the key differences stems from the approach how the respective simulation tools treat the coupling of the powder cloud to the dense flowing core. In RAMMS, the cloud movement is strongly coupled to the core, whereas in SamosAT the powder cloud is able to move more independently.

The results of that comparison has been submitted and accepted at the ISSW 2018. Further, the formulation of a more detailed article that will be submitted to an international journal (e.g. Cold Regions Science and Technology) is planned. All the work on the simulations with RAMMS and SamosAT have been conducted with the support of the SLF and the WLV.
Figure 8: Simulations of the Fleisskargraben avalanche using SamosAT. (a) standard simulation with the old SamosAT-version. (b) Simulation with the new SamosAT-version with altered particle-diameter (0.001m), SPH-model and altered particle-collision-coefficient ($10^{-6}$) (c) Simulation with the new SamosAT-version with altered particle-diameter (0.0008m), SPH-model and altered particle-collision-coefficient ($10^{-6}$)

Figure 9: Simulations of the All’Acqua avalanche. On the left hand side are the RAMMS simulations (a: peak velocity, c: peak pressure). On the right hand side are the SamosAT simulations (b:peak velocity, d: peak pressure)
2.4 Workpackage 4

WP04 aims at the investigation of the socio-economic impacts of bDFA and their back-calculations, which will be done in WP03. It is planned to develop general recommendations for the further improvement of the numerical models or if necessary new developments of model or model components. Furthermore, it is intended to make contributions to ONR (Austrian Standards) which deal with the design in snow avalanche prone areas.

Table 3: Milestones and Deliverables of Workpackage 4

<table>
<thead>
<tr>
<th>D/M</th>
<th>Description</th>
<th>Responsible</th>
<th>Due month</th>
</tr>
</thead>
<tbody>
<tr>
<td>M04-1</td>
<td>Vulnerability functions and socio-economic analysis</td>
<td>IOG</td>
<td>34</td>
</tr>
<tr>
<td><strong>D04-1</strong></td>
<td>Report on M04-1</td>
<td>IOG</td>
<td>34</td>
</tr>
<tr>
<td><strong>D04-3</strong></td>
<td>Report on recommendations for further developments of numerical snow avalanche simulation models</td>
<td>BFW</td>
<td>34</td>
</tr>
<tr>
<td><strong>D04-4</strong></td>
<td>Report on effects of bDFA modelling on engineering design / codes and recommendations</td>
<td>IGT</td>
<td>34</td>
</tr>
<tr>
<td><strong>D05-5</strong></td>
<td>Final report to be sent to the funding organisation ŬAW</td>
<td>IOG</td>
<td>36</td>
</tr>
</tbody>
</table>

Furthermore, in WP04 the derivation of vulnerability functions relating powder snow avalanches intensities to building damages is scheduled. Such vulnerability functions serve as an instrument for socio-economic considerations related to powder snow avalanches.

The flow models developed in WP02 have been used to investigate the interaction of powder snow avalanches with buildings. Preliminary results, e.g., pressure estimates have been obtained with a simplified model. To improve results, we migrated all applications to the high-performance cluster LEO3e (900 Haswell cores, 3.7 TB RAM), where we are currently running simulations with improved flow models and finer resolution. The final goal of these numerical investigations is the development of recommendations for engineering codecs considering bDFA effects.

Furthermore, the already finished work of WP01 will directly contribute to deliverable D04-4.

Vulnerability functions and socio-economic analysis (D04-1)

Vulnerability functions relate avalanche intensities to the degree of loss (a value between 0:no loss and 1:total loss). Such functions are a valuable tool for planning issues and to estimates socio-economic effects related to avalanche events.

With his master’s thesis Mündler (2017) accomplished an approach to derive a comprehensive vulnerability function that describes the adverse effects of powder snow avalanches especially for massive constructed building types.

This was achieved by integrating as many events as possible, where sufficient documentation material is available. For the investigation the following avalanche events were analysed:

- Marchkarlawine 2009, Bucheben, Rauris
- Bruckwieslawine 2009, Mittersill
- Fleisskarlawine 2005, Nikolai im Söltal
- Wolfsgrubenlawine 1988, St. Anton am Arlberg
- Wasserleiterlawine 1999, Galtür
- Innere-Riefenbachlawine 1999, Valzur

From these events a total of 76 damaged buildings were taken into consideration. The derivation of the vulnerability functions followed an approach adopted after Papathoma-Köhle et al. (2012) and illustrated in Figure 10. The vulnerability function is derived empirically by reconstructing avalanche intensities and relating them to observed building damages, which are ultimately expressed in monetary terms. The principle variables for that function are the avalanche’s intensity and the degree of loss.

**Estimation of the degree of loss**

The estimation of the degree of loss is divided in several steps. First, the observed damages are classified in damage classes, where the destruction is expressed as percentage (0: no damage of the building, 100: total destruction of the building).

In parallel, the building value was calculated based on an approach by Keiler et al. (2006) that considers different types of usage for each story of the building and assigns a value to them. The building value is then calculated by summing up all story values. For the reason of comparability all building values were aligned based on the building-cost index for the year 2016.

After the allocation to a damage class, the damage is quantified as a monetary value. The damages were calculated by using standardized values for engineers. Here, for different building parts and material types prices are given that can be adapted to the given damages yielding the amount of loss for the respective damage. Thus, the degree of loss is calculated by dividing the amount of loss by the building value.

Indeed, this could only be realized for fairly light damages. Very severe damages up to the total destruction it is not possible to puzzle out all the necessary details when large enough parts of the building are fragmented. In this case the percentage of the assigned damage class divided by 100 serves as the degree of loss.

**Estimation of the avalanche intensity**

The avalanche intensity can be derived either by estimating the avalanche pressure based on a structural analysis of the observed damages or by using avalanche simulation tools that yield pressure values of the avalanche flow. For the investigated events the work of Kobald (2015) gives a comprehensive overview of the estimated pressure values. These values are partly based on structural analysis or by avalanche simulations with SamosAT (provided by the WLV).
Derivation of the Vulnerability curve

In the literature several distribution functions are proposed to relate the intensity to the degree of loss. Figure 11 shows the result for different tested functions. The Frechet distribution reached slightly highest score with $R^2 = 0.648$, hence was chosen as the final vulnerability function (Figure 12), which reads:

$$y = e^{-x^{1.978}}$$
The presented Vulnerability is only valid for massive constructed buildings. Light weighted and mixed types of constructions were analysed as well, sample size of these building types were too small to derive representative results. The presented function can serve as a beneficial instrument for planning issues such as cost-benefit analysis. However, uncertainties remain. One ongoing issue is the accurate estimation of avalanche intensities that caused a specific damage. In terms of vulnerability assessments they can be derived by either back calculations from the observed damages or by the simulation of the avalanche. Both approaches bare uncertainties affecting the informative value of the vulnerability function. A Further challenge is the quantification of the degree of damage, which is accomplished by assigning the observed damages to damage classes leading to respective wide value ranges of the degree of loss. The estimation of a building’s value is another challenge, since accurate information is often inaccessible and hence, only rough approximations can be made. To address these challenges is object to further investigations.

Details about the work presented here can be found by Mündler (2017). A publication of the key findings of that work is currently under progress and planned for the near future.

**Effects of bDFA modelling on engineering design / codes and recommendations (D04-4)**

Working packages M01-1 and M01-2 revealed open questions, which are of great importance for the dimensioning of buildings. Impacts of dilute snow clouds on obstacles and the corresponding pressures are not described in sufficient detail by current engineering codes. A large unknown, with regard to the design of buildings, is the interaction between avalanche and obstacle, also known as flow variable – pressure relation. There is a gap between the simulation of avalanche flow variables, such as height, density or velocity and the calculation of loads, which are required for further calculations, which we aimed to close.
We investigated the flow variable – pressure relation, in order to give reliable pressure estimations when flow variables are known. Respective physical experiments would be expensive and difficult to carry out. Therefore, we chose to carry out numerical experiments using multiphase fluid dynamics simulations. However, physical experiments to validate respective numerical models are highly recommended and should be carried out in the future.

We used the open source software package OpenFOAM. The application of open source allowed a cost-effective application and modification of the source code when needed.

Respective simulations have been carried out on the High-Performance-Cluster LEO3e at the University of Innsbruck.

OpenFOAM implements a Finite Volume Method to numerically solve various physical models which can be chosen and modified by the user. Various models for the simulation of air-particles-mixtures are available in OpenFOAM and can be used to simulate the dilute powder cloud regime.

Figure 13: Sketch of the simulation setup as applied with OpenFOAM. The avalanche enters the left side with a predefined height and concentration profile and hits the obstacle in the middle of the simulation domain. Pressures on the surface of the obstacle can be.

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Figure 14. Evaluation of surface pressure with respect to flow variables, e.g. the avalanche height is shown in Figure 15. The flow variable – pressure relation is expressed in terms of the shape factor $c_{pe}$, defined as the relation between stagnation pressure and actual pressure on the surface.

Our simulations indicate that current recommendations underestimate the impact pressure at the front and overestimate suction at the roof. This tendency increases with decreasing avalanche height. This can be explained with the concentration of mass and momentum in lower areas of the flow and thus a higher redirection angle as visible in Figure 14. For very low avalanches, the shape factor is estimated as approximately $c_{pe} = 2$, which corresponds to theoretical maximum, following a simple redirection model (Rauter and Fellin, 2017a,b,c). Moreover, we observed high pressure concentrations at the front, which would lead to shape factors of up to $c_{pe} = 5$ for small areas.

Respective methods and outcomes have been presented and discussed at various conferences and meetings (Rauter, 2016a, 2017b; Rauter and Fellin, 2017a,b). Main findings have been summarized into a recommendation for further development of engineering codes.
(Rauter and Fellin, 2017c). Further, we recommend to supplement numerical experiments with physical ones to validate model assumptions, mathematical models and numerical methods. Moreover, we would like to point out, that more detailed bDFA simulations, incorporating all stages, from release to runout, are required to provide accurate boundary conditions for the simulation of flow-structure-interaction. Accurate shape factors can not compensate for uncertainty in density and velocity and the respective vertical distributions. This highlights the importance of package D04-3 for package D04-4. We expect that impact pressure simulations can be substantially improved with better bDFA simulation.

Figure 14: Numerical simulation of powder snow impact pressures with OpenFOAM. Three simulations are shown: low powder snow avalanche (top), tall powder snow avalanche (middle) and the reference simulation with pure air (bottom). The left side shows the flow behaviour, highlighted by streamlines and the content of ice particles in the air. The right side shows the impact surface pressure on the obstacle.
Recommendations for further developments of numerical snow avalanche simulation models (D04-3)

**Coupled dense flow - powder cloud simulations with open-source software (OpenFOAM)**

Working packages M01-1 and M01-2, as well as the conducted impact pressure simulations (D04-04), revealed the lack of knowledge in terms of density and velocity profiles of bDFA. Density and velocity profiles are important boundary conditions to determine appropriate loads on obstacles. We found, that there is a gap between depth-integrated snow avalanche simulations, describing the dynamic evolution from release area to runout, and three-dimensional two-phase models, as used for the calculation of impact pressures.

For this reason, we aimed to implement depth-integrated flow models into OpenFOAM, the software which has also been used for the three-dimensional simulations (see D04-4). The idea was to couple depth-integrated dense flow models with three-dimensional bDFA models, within a flexible open-source application (similar to SamosAT; Sampl and Zwinger, 2004). This would allow us to simulate snow avalanches, from release to runout, respective regime changes and the interaction with obstacles with a single application.

For this reason we developed a new depth-integrated flow model, which fits into the numerical framework as implemented in OpenFOAM. Beside the Finite Volume Method, OpenFOAM provides the so-called Finite Area Method, which allows a simple application of depth-integrated flow models to complex terrain. The respective model has been published by Rauter and Tukovic (2018) and has been presented at various conferences and meetings (Rauter, 2016b; Rauter, 2017a; Rauter and Köhler, 2017).

We provide our model and the respective numerical implementation as open source and it has been accepted into the main development branch of OpenFOAM (see OpenCFD, 2017). This

![Figure 15: Evaluation of OpenFOAM impact simulations. The left line shows powder cloud simulation with varying avalanche heights (left is lower). The two additional datapoints show the reference simulation with pure air and the recommendation according to European engineering code EC 1991-1-4. Blue lines show impact pressure at the front, red lines suction on the roof.](image)
makes the model available to a large community, free of charge and without any substantial barriers. In fact, the standard distribution of OpenFOAM will contain our solver, meaning that simulation of avalanches will be possible with every standard installation of OpenFOAM.

The Finite Area Method is able to solve depth-integrated flow models on the surface mesh of a Finite Volume Mesh, as shown in Figure 6. This enables coupling of depth-integrated flow models (see Figure 16, cf. Rauter et al. (2018) with three-dimensional powder cloud models (see Figure 17). The coupling of the novel dense flow model with powder cloud models (as implemented in OpenFOAM) was intended but could not be finished within the project period due to limited time and resources. However, all important components for a new mixed snow avalanche model are now available as open source.

Towards a description of regime transitions: Applications of extended kinetic theory
Regime transitions play a major role for bDFA. Their mathematically consistent description is still a serious challenge and highly debated in the avalanche community (see, e.g., Bartelt et al., 2016; Issler et al. 2017). However, it is a common view, that an appropriate description of regime transitions is imperative to predict the frictional behaviour of dense flow avalanche and thus the respective runout. Moreover, the coupling of dense flow and powder cloud regimes will require an appropriate model, which should include the regime transition from dense to dilute flows and vice versa.

For these reasons, we evaluated a series of new developments of the kinetic theory community, known as extended kinetic theory. Extended kinetic theory provides a micromechanical model for granular flows at slow and high deformation rates. This model is valid in multiple regimes and thus contains a description of regime transitions. The model of Vescovi et al. (2013) has been evaluated with regards to snow avalanches by Rauter et al. (2016a,b,c). A simplified derivation of the respective model has been used to describe the
frictional behaviour of dense snow avalanches. Results have been compared to the traditional Voellmy (1955) friction model and improvements with regards to multiple observations have been archived.

Figure 17: The Finite Volume Method allows to numerically solve three-dimensional two-phase powder snow avalanche models within a volumetric mesh. The boundary of the volumetric mesh can be used by the Finite Area Method to solve depth-integrated dense flow models. Both methods are developed to allow simple coupling between dense flow and powder cloud.
3 Summary

Table 4 summarizes the achieved progress of each Milestone and Deliverable.

Table 4: Adapted plan for Milestones and Deliverables of bDFA Workpackages and achieved progress

<table>
<thead>
<tr>
<th>D/M</th>
<th>Description</th>
<th>Responsible</th>
<th>Due month</th>
<th>Progress (March 31st, 2017)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M01-1</td>
<td>Damage catalogue and data base for bDFA damages</td>
<td>IGT</td>
<td>10</td>
<td>100 %</td>
</tr>
<tr>
<td>M01-2</td>
<td>Data base for bDFA damages</td>
<td>IGT</td>
<td>10</td>
<td>100 %</td>
</tr>
<tr>
<td><strong>D01-1</strong></td>
<td><em>Technical note to M01-1 and M01-2</em></td>
<td>IGT</td>
<td>12</td>
<td>100 %</td>
</tr>
<tr>
<td>M02-1</td>
<td>Installation of pressure sensors Valle de la Sionne</td>
<td>SLF</td>
<td>12</td>
<td>100 %</td>
</tr>
<tr>
<td><strong>D02-1</strong></td>
<td><em>Technical note on flow variable – pressure relation</em></td>
<td>SLF</td>
<td>30</td>
<td>100 %</td>
</tr>
<tr>
<td>M03-1</td>
<td>Simulation results of back-calculations SLF</td>
<td>SLF</td>
<td>24</td>
<td>100 %</td>
</tr>
<tr>
<td>M03-2</td>
<td>Simulation results of back-calculations SamosAT</td>
<td>BFW</td>
<td>24</td>
<td>100 %</td>
</tr>
<tr>
<td><strong>D03-1</strong></td>
<td><em>Technical note on M03-1 and M03-2</em></td>
<td>BFW</td>
<td>30</td>
<td>100 %</td>
</tr>
<tr>
<td>M04-1</td>
<td>Vulnerability functions and socio-economic analysis</td>
<td>IOG</td>
<td>34</td>
<td>100 %</td>
</tr>
<tr>
<td><strong>D04-1</strong></td>
<td><em>Report on M04-1</em></td>
<td>IOG</td>
<td>34</td>
<td>100 %</td>
</tr>
<tr>
<td><strong>D04-3</strong></td>
<td><em>Report on recommendations for further developments of numerical snow avalanche simulation models</em></td>
<td>BFW</td>
<td>34</td>
<td>100 %</td>
</tr>
<tr>
<td><strong>D04-4</strong></td>
<td><em>Report on effects of bDFA modelling on engineering design / codes and recommendations</em></td>
<td>IGT</td>
<td>34</td>
<td>100 %</td>
</tr>
<tr>
<td><strong>D05-5</strong></td>
<td><em>Final report to be sent to the funding organisation ÖAW</em></td>
<td>IOG</td>
<td>36</td>
<td>100 %</td>
</tr>
</tbody>
</table>
WP01:
A damage catalogue has been completed. The damage catalogue comprises back-calculations of documented events, gathered records of damaged avalanche galleries in cooperation with the Felberntauernstraße AG and first-hand investigations of the avalanche disaster in Farindola, Italy. Results are published in Schroll (2015) and Schroll et al. (2017).

An expert questionnaire has been conducted within the first project year to evaluate strengths and weaknesses of existing avalanche simulation tools and how they are employed in practice. For the survey 51 participants could be won to contribute to the survey, forming a representative collective for the German-speaking Alpine region. The survey revealed interesting insights in how practitioners deal with model uncertainties and how national safety regulations influence their decision in a hazard assessment. Results are published in Schmidtner et al. (2017a,b,c,d). Based on the Insights of the interview a secondary interview is scheduled to be conducted during the ISSW 2018 upcoming October in Innsbruck.

WP02:
In cooperation with the Ruhr-University Bochum (RUB) a novel radar system has been developed and evaluated (Baer et al. 2016). The radar has been developed with the aim to measure the snow concentration and density in powder snow clouds and two devices have been deployed at the Vallée de la Sionne test site. Two artificially released avalanches have been recorded.

The flow variable – pressure relation turned out to be of major interest in this project. This relation represents the missing link between current bDFA models and impact pressures and therefore bDFA damages. To establish such a link, we performed three-dimensional Eulerian multiphase fluid dynamic simulations with OpenFOAM applied to the simulation of the flow – structure interaction.

WP03:
Two mechanical frameworks for snow avalanche simulations are now available in OpenFAOM: (1) Depth-integrated shallow flow models as known from SamosAT and RAMMS and (2) the three-dimensional Eulerian multiphase model. The three-dimensional Eulerian multiphase model has been applied to estimate impact pressures. Both frameworks are available as open source and provide the opportunity to evaluate bDFA models in a unified framework. The achievements of that work has been published e.g. by Rauter and Tuković (2016) and Rauter et al. (2018).

Furthermore, back-calculations of ten avalanches from Austria and Switzerland have been conducted using RAMMS::Extended and SamosAT. Within in the project period SamosAT has been enhanced by a Smoothed Particle Hydrodynamic (SPH) model and a particle collision model. That had to be considered in a revised back-calculation of the test avalanches which contributed to the development to a new standard parameter set for operational usage.

A comparison of the SamosAT and RAMMS::Extended model based on selected Swiss avalanches was initiated, whose results will be presented at the ISSW 2018.
WP04:
Investigations of socio-economic impacts of bDFA have been completed in WP04. Therefore a Vulnerability function has been derived that relates the degree of loss of typical Alpine buildings to the intensity of powder snow avalanches. With the function the loss in monetary terms due to an avalanche event can be estimated, which is a valuable source of information for planning issues and decision makers.
Moreover, contributions to ONR (Austrian Standards) have been achieved. It turned out that current engineering codes do not describe sufficiently the impact of dilute snow clouds on obstacles. Here, a large unknown is the flow variable pressure relation, i.e. the interaction between avalanche and obstacle. To investigate the missing link numerical experiments have been carried out using multiphase fluid dynamics simulations implemented in OpenFOAM. Our simulations indicate that current recommendations underestimate the impact pressure at the front and overestimate suction at the roof. This tendency increases with decreasing avalanche height. Main findings have been summarized into a recommendation for further development of engineering codes (Rauter and Fellin, 2017c). Regarding the future model development, we recommend to supplement numerical experiments with physical ones to provide to validate model assumptions, mathematical models and numerical methods.
Further efforts have been made to investigate model regime transitions (from dense to deliute) by evaluating new developments known as the extended kinetic theory for frictional considerations of the avalanche flow. The new approach has been compared to traditional approaches and has been published by Rauter et al. (2016).
All simulation tools developed in the OpenFOAM platform are on an open source basis, and hence freely available for everyone to use.
4 Outlook

Validation and further development of flow variable – pressure relations
Numerical simulations of powder cloud impacts revealed some interesting phenomena, which have far-reaching consequences for practice and engineering codes. Simulation results indicate that current recommendations underestimate impact forces at some parts of the building. It is imperative to address these issues in future developments. Simulations have only been conducted for simple geometries and they should be extended to complex geometries to identify further phenomena. Furthermore, we recommend to carry out such simulations for individual cases with the actual geometry as well as the expected densities and velocities. Finally - and maybe most important - numerical simulations should be validated with physical experiments before a practical application.

Development of coupled mixed avalanche models with open-source software (OpenFOAM)
Detailed velocity and density profiles are required for the reliable estimation of impact loads. Future bDFA models should be developed with this requirement in mind. OpenFOAM has proven to be an effective tool for the simulation of dense snow avalanches and powder snow avalanches. However, respective models have been applied independently from each other. It was intended to couple both models to create a mixed bDFA model. This has not been accomplished within the project duration to limited time and resources, and should be conducted in a follow up project.

Extended kinetic theory in bDFA models
Extended kinetic theory and similar models will play a major role in further developments of bDFA models. The implementation of respective models into numerical avalanche tools should be further improved. Extended kinetic theory may be able to consistently describe compressibility, flow regime transitions and similar phenomena on a solid basis.

Expert Interview
Within the bDFA project the user point of view for model applications was investigated. It could be found that this is an important aspect when it comes to sanctioning model results and when applying them for hazard assessment purposes. The insights gained from the first interview could serve as a precious base for a second interview to shed light to the user-simulation interaction in the context of avalanche hazard assessment.
5 Publications related to project

Presentations


Journal Articles


Conference Proceedings


Master's Thesis


Further Contributions


6 References


