ON THE POTENTIAL OF PARTICLE TRACKING IN SNOW AVALANCHES

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ABSTRACT: Knowledge of particle motion in snow avalanches is crucial to understand the driving pro-cesses, determining transport phenomena or to quantify the avalanche's destructiveness and mobility. To investigate the dynamics of avalanches on a particle level we concentrate on the combination of two ap-proaches: measurement data of a newly developed inflow sensor system, the so called AvaNodes, and simulation results of the thickness integrated computational module com1DFA, recently introduced within the open avalanche framework AvaFrame. The AvaNodes travel with the avalanche flow as synthetic particles. Equipped with a global navigation satellite system (GNSS), it is possible to record particle trajectories with cor-responding velocities. Com1DFA is based on a numerical particle grid method, which due to its open-source structure allows for the direct implementation of numerical particle tracking functionalities. The combination of these two fundamentally different methods directly implies the question of comparability between simulations and measurements. We approach this by comparing the measurement and simulation data on a particle level and introduce a common reference system, an avalanche thalweg following coordinate system. The coordi-nate transformation and resulting, natural avalanche path perspective allows to investigate and compare the spatio-temporal evolution of velocities and to define travel lengths or travel angles in a standardized manner. Furthermore, this analysis allows us to distinguish distinct avalanche flow phases and their features on a particle level. With this work we highlight the potential and current limitations when comparing synthetic particle sensor systems to numerical simulation particles with an example of an observed avalanche event at the Nordkette test site, providing a first insight of how the presented methods can be used in terms of optimization and evaluation of simulation tools on a particle level. The analysis of the AvaNode sensor data points towards future potential in investigating the influence of snow and particle properties, such as size, shape, or density, on the avalanche flow.

Keywords: Avalanche Dynamics, Avalanche Simulation, Sensor Nodes, Particle Tracking, AvaFrame com1DFA, Thalweg-Time, Thalweg-Altitude.

1. INTRODUCTION

Knowledge of particle motion in snow avalanches is crucial to understand the driving processes, determining transport phenomena or to quantify the avalanche's destructiveness and mobility.

The two major approaches to investigate avalanche dynamics are either computational or experimental ones. Existing tools for simulating snow avalanches cover a wide range of numerical implementations and vary from proprietary, operational (e.g. Christen et al., 2010; Sampl and Zwinger, 2004; Zugliani and Rosatti, 2021; Li et al., 2021) to open source, mostly scientific software (e.g. Hergarten and Robl, 2015; Mergili et al., 2017; Rauter et al., 2018; Oesterle et al., 2022). An experimental measurement technique that has previously been applied in snow chute experiments (Vilajosana et al., 2011) and recently gained attention in full scale rockfall applications (Caviezel et al., 2021; Noël et al., 2022) are in flow sensors, which travel with the flow and record corresponding motion data. In this study, to investigate the dynamics of avalanches on a particle level we concentrate on the combination of two approaches: measurement data of a newly developed inflow sensor system, the so called AvaNodes (Winkler et al., 2018; Neurauter et al., 2022; Neuhauser et al., 2022) and simulation results of the thickness integrated computational module com1DFA, recently introduced within the open avalanche framework AvaFrame (Tonnel et al., 2023; Oesterle et al., 2022).

In this work, we want to study in how far data from measurement particles (AvaNode sensors) is comparable to the data from numerical simulation

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Figure 1: Measurement methods (AvaNodes): Sensor in the field set-up and the outline of an avalanche experiment (light pink) with the estimated trajectory of the particle and the deposition point, as well as the AvaNodes in the avalanche deposit.

particles. There is a fundamental difference between the two, the simulation particles represent numerical columns with thickness integrated properties that travel in two dimensional space along the predefined digital elevation model, while the measurement particles are synthetic particles that should imitate snow granules in the avalanche, potentially moving relative to the given mountain surface in three dimensional space. To tackle this question we implement particle tracking functionalities in the thickness integrated gravitational mass flow simulation module com1DFA and introduce transformations into an avalanche thalweg following coordinate system. The velocity evolution in time and space is then analyzed to identify if the behaviour of the measurement particles is reproduced by the simulation particles. Additional tools, namely the thalweg-altitude and thalweg-time analysis allow to further relate the particle motion with the whole avalanche flow.

The experimental and computational framework is briefly described in Sections 2 and 3. Section 4 introduces the test site and avalanche data while Section 5 describes the crucial steps of transforming and projecting between simulation and measurement and thalweg following reference systems. Sections 6 and 7 include results, discussion and conclusion of the particle tracking and presented methods.

2. MEASUREMENT: AVANODES

The AvaNodes travel with the avalanche flow as synthetic particles. As these are equipped with motion tracking sensors, it is possible to reconstruct particle trajectories with corresponding orientations, as well as translational and angular velocities, and to identify different flow phases (Winkler et al., 2018; Neurauter et al., 2022; Neuhauser et al., 2022). Figure 1 shows a typical avalanche experiment using the sensor systems. The AvaNodes, 3D-printed cube like sensor housings with a side length of 16 cm and a varying density between $415\,\mathrm{kg\,m^{-3}}$ and $688\,\mathrm{kg\,m^{-3}}$, are equipped with widely used hardware such as a global navigation satellite system (GNSS) and an inertial measurement unit (IMU). This study focuses on the position and velocity data obtained from the GNSS sensors of the AvaNodes. For temporal synchronization we determine the onset of motion utilizing the IMU data. This leads to the fact, that the presented data sets of filtered GNSS velocities stop abruptly when the IMU indicates the end of motion (Neuhauser et al., 2023).

3. SIMULATION: AVAFRAME com1DFA

Simulation tools are important to investigate and predict mobility and the destructive potential of gravitational mass flows (e.g. snow avalanches). AvaFrame - the open avalanche framework - offers well established computational modelling approaches, tools for data handling and analysis as well as ready-to-use modules for evaluation and testing. AvaFrame's computational module com1DFA (version 1.3; Tonnel et al. (2023); Oesterle et al. (2022)) is based on a thickness-integrated flow model, solved by a numerical particle grid method. Due to its open-source structure, direct implementation of numerical particle tracking functionalities is straightforward.. In the left panel of Figure. 2, the simulated particle velocity 20 seconds after the snow mass is released is shown with superimposed AvaNode measurement particles. In the right panel, a map view of the outline of the simulated peak flow velocity field is shown including the given release area scenario and superimposed GNSS AvaNode trajectories. For this study, particle tracking functionalities have been added to com1DFA, allowing to track the numerical particles within a predefined radius of a given coordinate point.

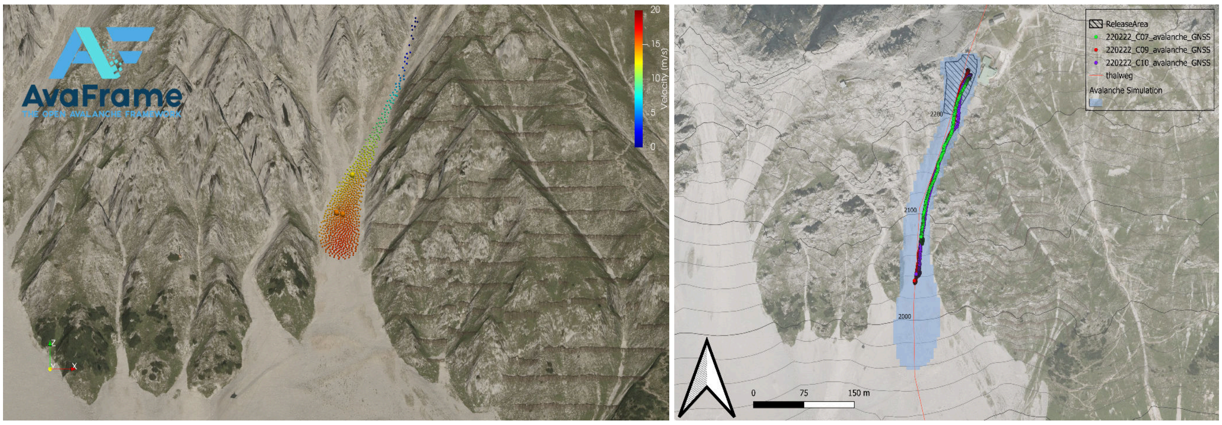

Figure 2: Simulation methods (AvaFrame com1DFA): (left) Simulation result 20 seconds after release highlighting the numerical particle velocities with the superimposed AvaNode measurement particles and (right) an orthophoto of the test area with an underlying simulation result in light blue, measured AvaNode GNSS trajectories in green, red and violet. The manually defined avalanche thalweg is shown in yellow and the release area as dashed region.

4. NORDKETTE TEST SITE: AVALANCHE EVENT AND SIMULATION SCENARIO

The avalanche test site (Figures 1 and 2) is located at the *Nordkette* ski resort, which is situated above Innsbruck, Austria. The site is easily accessible and equipped with different remote avalanche control systems. Avalanche control work on the main avalanche path Seilbahnrinne (47°18’44”N, 11°22’60”E, 2269 m a.s.l.) is carried out throughout the winter season and allows to incorporate the AvaNode experiments, placing the sensor systems in the release area. The confined release area, located the zone of origin with a S to SW aspect, has an average slope angle of 46°. Along the transit zone, the thalweg slope angle decreases towards 30 °. In the potential deposition zone an artificial avalanche dam is situated at 1,800 m a.s.l., resulting in an approximate altitude difference of max. 450 m. Mostly avalanches reach medium to large size, according to the European Avalanche Warning Service (EAWS) classification.

4.1. Measurement: Avalanche Event

Avalanche 220222 was released on 22.02.2022 within a storm cycle ($\approx$ 40 cm of new snow at $\approx$ 1900 m a.s.l.) with ambient temperatures of -5 °C and poor visibility. Three AvaNodes (nr. C07, nr. C09 & nr. C10) travelled with the avalanche (nr. C07 being a high density Node). Due to the poor visibility conditions, information on the dense flow deposition outline is not available, which may considerably deviate (Faug et al., 2018) from the dilute parts of the avalanche, that reached the catching dam at 1,800 m a.s.l.

4.2. Simulation: Avalanche Scenario

To perform the simulations we define a scenario utilizing a digital elevation model with a spatial resolution of 5 meters (data available at `www.data.gv.at`). The delineation of the release area is performed according to the experimental observations and a corresponding terrain analysis (Maggioni and Gruber, 2003). Release thickness estimates ($\approx$ 0.7 m) are based on the near by weather station and local storm board observations with adaptations to altitude and assumed wind drift leading to a release volume of $\approx$ 1900 m^3. The default configuration of com1DFA is designed for very to extremely large avalanches with a respective friction relation and corresponding friction coefficients. In order to account for the (medium-large) size of the studied avalanche event, an adapted Voellmy friction relation with minimum shear stress has been applied and the respective friction parameters have been optimized by minimizing the difference of the temporal velocity evolution, considering mean avalanche simulation velocities and the average velocity of the three measurement particles (coulomb friction coefficient $\mu = 0.6$, turbulent friction coefficient $\xi = 4000\,\mathrm{m/s^2}$, and minimum shear stress $\tau_0 = 70$Pa, Dick, 2023)[1]. Regarding the numerical parameters, several modifications of the latest development state of com1DFA have been used (Tonnel et al., 2023), i.e. regarding the numerical treatment of the friction force, an adaptive time stepping and how the particles are intialized.

5. REFERENCE AND COORDINATE SYSTEMS

When comparing measurement and simulation particles, first a common reference system has to be

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[1] `docs.avaframe.org/`

type	particle #	colour	δv [m/s]	v_{max} [m/s]	Δt [s]	S_{xy}^{start} [m]	S_{xy}^{stop} [m]	ΔS_{xy} [m]	ΔZ [m]	α [°]
measurement	C07	green	-	13.6	34.5	183	425	242	174	35.7
simulation	15	blue	1.7	14.3	36.6	174	428	254	195	37.5
measurement	C09	red	-	16.3	36.8	174	477	303	228	36.9
simulation	0	blue	1.2	15.7	39.3	183	493	310	230	36.6
measurement	C10	violet	-	17.1	36.9	178	466	288	210	36.1
simulation	2	blue	1.6	15.5	38.1	178	477	299	222	36.5
simulation	avalanche	light blue	-	17.6	41.0	145	601	455	326	35.7

Table 1: Summary of the particle properties for each measurement and corresponding best fit simulation counterpart. Listed are the values for root-mean-square-deviation of the temporal velocity evolution δv, the maximum velocity v_{max}, the duration of movement Δt, starting, stopping position $S_{xy}^{start}, S_{xy}^{stop}$ and travel lengths ΔS_{xy} along the thalweg, altitude difference ΔZ and resulting travel angle α. Avalanche refers to the respective minimum or maximum over all simulation particles. A consistent colouring for each AvaNode is used for all visualizations in the following figures and given in the table row *colour*.

defined. AvaNode sensors provide positions in WGS 84 (EPSG:4326) while simulations are handled in MGI / Austria GK West (EPSG:31254), which is then used as a common reference system to compare measurement and simulation particles. Once in the same projection, particle positions and velocity evolution over time can be compared. However, in order to derive standardized scalar measures such as e.g. runout lengths or travel angles, that are not determined for each particle trajectory individually, a common reference system is required. To do so, we introduce the avalanche dependent thalweg system, providing a unified coordinate system for experimental and computational data. This further allows us to compare starting and stopping positions with respect to the entire avalanche flow. In this study, the thalweg, which follows the main flow direction of the avalanche is defined manually, but it is also possible to identify the thalweg automatically, following the center of mass, momentum or kinetic energy of a specific simulation run. The tools to perform this coordinate transformation and related analysis are based on Fischer (2013) and implemented in the ana3AIMEC and ana5Utils analysis modules within AvaFrame. It is important to note that in addition to the coordinate transformation into the thalweg dependent system most analysis tools require a projection from two dimensional data, distributed in the terrain, to one dimensional data along the avalanche thalweg. Utilizing the thalweg specific analysis tools allows to further evaluate, interpret and compare the particle results: Travel lengths, altitude differences and resulting travel angles are directly obtained from the thalweg-altitude analysis and the relative position within the avalanche flow is evaluated using the thalweg-time analysis.

6. PARTICLE TRACKING - MEASUREMENT AND SIMULATION

The evaluation of the simulation results and comparison to the measured AvaNode trajectories and corresponding velocities is twofold: In a first step (Figure 3) we track a limited number of simulation particles within the spatial vicinity (i.e. 5 m radius of the initial sensor location, which corresponds to the GNSS position accuracy) of the measurement particles. From these tracked particles we use the temporal velocity evolution along the specific particle trajectories to identify the best fit particles and evaluate their correspondence to the measurements. In a second step (Figure 4) we analyse the simulation and measurement results in the thalweg coordinate system, utilizing the additional thalweg analysis tools, to investigate the particle behaviour in relation to the entire avalanche flow.

6.1. Velocity evolution in time and space

Figure 3 shows the simulation results of all simulation particles (light blue), highlighting the tracked particles (dark blue) and the measurement data of the AvaNodes (colored) in three different ways:

- map view and spatial outline of the avalanche simulation based on peak flow velocities, highlighting the tracked and measured particle trajectories,
- temporal evolution of particle velocities,
- spatial evolution of particle velocities along the avalanche thalweg.

The map view and spatial outline of the simulation results allows to qualitatively cross check the trajectories of measured and tracked particles, particularly with respect to all simulation particles. Effectively 19 simulation particles are tracked within a 5 m radius of the center of the AvaNode release locations. One can observe that measured and tracked particle trajectories qualitatively match quite well - showing flow trajectories towards the orographic left side of the manually defined avalanche thalweg and stopping positions at the opening of the main chute. Both, the temporal and spatial velocity

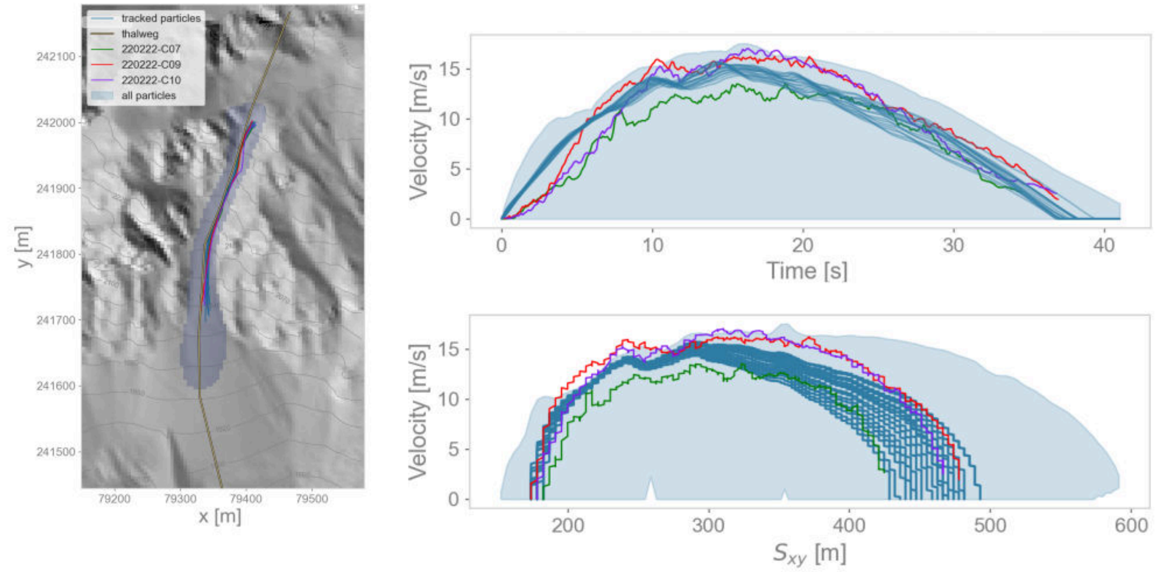

Figure 3: Map view and spatial outline of the avalanche simulation based on peak flow velocities, highlighting the tracked and measured particle trajectories (left). Temporal evolution of particle velocities (right, top), as well as spatial evolution of particle velocities along the avalanche thalweg (right, bottom).

evolution indicate three different phases: (I) rapid initial acceleration, (II) a steady state flow with the highest velocities (up to 17 ms^{-1}), and (III) a longer deceleration phase until the particles stop. Comparing the temporal and spatial velocity evolution it appears that the measurement particles have a slightly delayed acceleration phase in the temporal evolution. Because of the initially lower velocities the measurement particles have smaller travel lengths at the beginning of the flow. For this reason the spatial velocity evolution along the thalweg appears to have a better agreement than the temporal one in the initial acceleration phase. To further investigate the simulation results we identify the best fit between tracked- and measurement particles by determining the root mean square deviation of the temporal velocity evolution (δv), which shows good agreement between measurement and simulation (1-2 m/s). Resulting travel times (Δt) are also in good agreement. Table 1 summarizes the corresponding simulation and measurement values. By transforming the measured and simulated velocities into the thalweg coordinate system, it is possible to evaluate their starting and stopping positions ($S_{xy}^{start}, S_{xy}^{stop}$), as well as total travel lengths (ΔS_{xy}) along the manually defined thalweg. The obtained travel length differences are on the order of 10-25 m ($\Delta S_{xy}^{measurement} = 242, 303, 287$ m vs $\Delta S_{xy}^{simulation} = 265, 310, 299$ m). Again it is important to note that the travel lengths are not measured along the individual particle trajectories but in the common thalweg coordinate system, which follows the main flow direction of the avalanche. Taking a closer look at the starting (S_{xy}^{start} between 174-183 m for simulation and measurement) and stopping (S_{xy}^{stop} between 425-477 m for the measurements and 428-477 m for the simulations) we observe a significant spreading of the avalanche body in both, measurements and simulations. Comparing the maximum velocities (v_{max}) we observe that the corresponding values are in a similar range (1-2 m/s). Interestingly the measurement results show a larger spread in maximum velocities than their simulated, tracked counterparts.

6.2. Thalweg analysis tools

In Figure 4, in addition to the map view of the simulated peak flow velocities, the thalweg-altitude (right, top) and thalweg-time analysis with superimposed measurement particles (right, bottom) are shown, which allow to investigate the particle behavior with respect to the total avalanche.

The thalweg altitude analysis is particularly useful to investigate the avalanche and particle travel lengths, corresponding altitude differences and the resulting travel angle differences ($\alpha^{measurement} = 35.7, 36.9, 36.1°$ and $\alpha^{simulation} = 37.6, 36.6, 37.0°$), which are in the range of $1-2°$. Additionally, it is possible to relate terrain features to the different flow phases. For example, in case of the Nordkette test site the total extent and slope angle differences are rather small, leading to rather similar travel angles, which in turn may also contribute to the large spread from starting to stopping positions of the tracked particles. Logically, the extent of the whole avalanche exceeds any travel length of the tracked simulation particles. The differences to the avalanche's maximum velocity, runout lengths or resulting runout angle are related to the fact that the

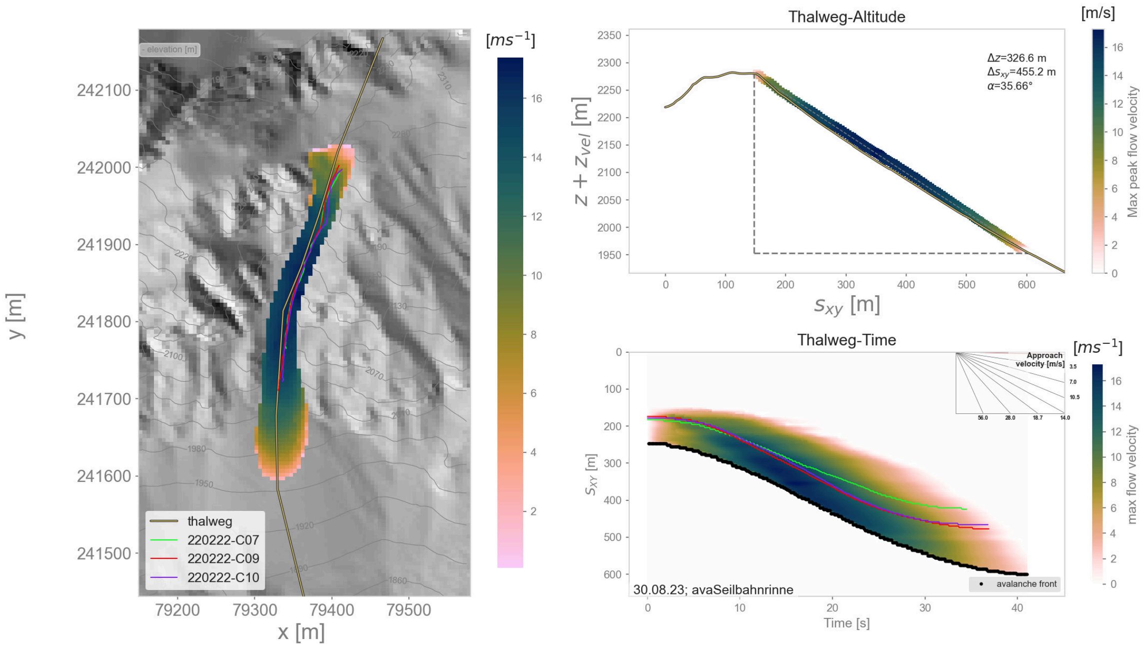

Figure 4: Map view of the total simulation outline with superimposed peak velocities (left). Thalweg-Altitude with the velocity altitude $Z_{vel} = \sqrt{v^2/(2\,g)}$ (right-top) and Thalweg-Time (right-bottom) with measured AvaNode data and particle tracking for specific numerical particles.

tracked particles only cover a certain part of the avalanche extent. However, considering all simulation particles we observe that the mixing of numerical particles, and in particular overtaking or resorting cannot be observed. This observation appears obvious considering the thickness integrated approach in the underlying flow model, and is also supported when evaluating the starting and stopping positions and the related spreading of the simulation particles along the thalweg (starting positions within a 10 m range, while the stopping positions are distributed along ≈50 m, compare Figure 3 and Table 1). The thalweg-time analysis (Figure 4) directly relates the temporal and spatial flow velocity evolution along the thalweg (Figure 3). The measured and tracked simulation particles travel rather towards the tail of the avalanche. Maximum velocities are reached in the middle of avalanche duration and thalweg close to the avalanche front. Generally, avalanche front and particle motion show a similar behaviour, with a maximum velocity of 17,6 m/s at the peak of the steady state flow phase. The two low density AvaNodes (C09 and C10) show a very similar acceleration and deceleration behavior, similarly to the avalanche front, while the denser one (C07) reaches lower velocities as well as travel lengths and is consequently deposited closer to the avalanche tail.

7. CONCLUSIONS AND OUTLOOK

This research paper introduced an approach for particle tracking in the thickness integrated gravitational mass flow simulation module com1DFA of AvaFrame. We compare the spatio-temporal evolution of simulated particle velocities to the measurement data of the AvaNode sensors. One crucial step for this comparison appeared to be the coordinate transformation into an avalanche thalweg dependent system. This transformation allows to introduce suitable evaluation tools, such as the thalweg-altitude or thalweg-time analysis.
The presented methods enable the identification of best fit particles between simulation and measurement, with predefined model parameters. The evaluation shows surprisingly low differences in the evaluated properties, such as associated velocities on the order of 1-2 m/s, travel length between 10 m to 25 m and travel angle differences within the range of $1-2°$. This study utilizes an avalanche simulation, where friction coefficients have been optimized by minimizing the deviation of the temporal evolution of mean simulated and measured particle velocities. The comparison and evaluation shows a surprisingly good match on a particle level for different result parameters. In a next step, other parameters, such as the total avalanche runout or measured radar velocities (Gauer et al., 2007; Fischer et al., 2014; Köhler et al., 2018) should be taken into account in the optimization and evaluation pro-

cess. Additionally, one has to bear in mind the fundamental differences between simulations and measurements. As the simulations are performed using a thickness-integrated model, numerical particles represent 2D columns traveling in two dimensional space along the predefined digital elevation model, which e.g. inhibits overtaking in the vertical dimension. Hence, in the thalweg-time analysis (Figure 4) no overtaking or resorting effects are observed in the simulation data. In contrast, the low density AvaNodes (C09 and C10) overtake the high density one (C07), switching the order of starting and stopping position along the thalweg (Table 1. Other expected challenges on the measurement side arise considering reproducibility of the environmental avalanche conditions, varying particle properties (e.g. differences between high density or low density AvaNodes) or potential systematic errors in the measurement techniques itself. Open modeling questions of this study relate to the general choice of a two dimensional thickness integrated approach, the employed friction relation, corresponding parameter optimizations, as well as the investigation of associated uncertainties (Fischer et al., 2015, 2020). A future step would therefore be to extend and apply the presented methods using models that resolve the full three dimensional velocity field (Li et al., 2021), employ different rheologies (Jop et al., 2006) or explicitly take potential segregation and separation processes into account (Gray and Ancey, 2015; Pudasaini and Fischer, 2020) .

This study presented a research application, employing an open source simulation tool for gravitational mass flows that aims to be used for operational hazard mapping. We highlight the potential and current limitations when comparing synthetic particle sensor systems to numerical simulation particles. The presented methods furthermore build the foundation for an in depth flow model parameter optimization which is out of the scope of this study. The analysis of the AvaNode data points towards future potential in investigating the influence of snow and particle properties, such as size, shape, or density, on the avalanche flow. In addition to revealing distinct avalanche flow phases and their features (e.g. velocities and travel lengths) on a particle level, the presented methods pave the way for future simulation applications, towards predicting flow intensities (e.g. burial or impact) along flow trajectories, that may serve useful for optimal search design or terrain classification with respect to the potential destructiveness.

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REFERENCES

Caviezel, A., Ringenbach, A., Demmel, S. E., Dinneen, C. E., Krebs, N., Bühler, Y., Christen, M., Meyrat, G., Stoffel, A., Hafner, E., et al.: The relevance of rock shape over mass—implications for rockfall hazard assessments, Nature communications, 12, 1–9, 2021.

Christen, M., Kowalski, J., and Bartelt, P.: RAMMS: Numerical simulation of dense snow avalanches in three-dimensional terrain, Cold Regions Science and Technology, 63, 1–14, 2010.

Dick, O.: How can snow particle tracking in field experiments help to improve the friction law used in avalanche flow simulations?, Master's thesis, KTH Royal Institute of Technology, 2023.

Faug, T., Turnbull, B., and Gauer, P.: Looking beyond the powder/dense flow avalanche dichotomy, Journal of Geophysical Research: Earth Surface, 2018.

Fischer, J.-T.: A novel approach to evaluate and compare computational snow avalanche simulation, Natural Hazards and Earth System Science, 13, 1655–1667, doi:10.5194/nhess-13-1655-2013, 2013.

Fischer, J.-T., Fromm, R., Gauer, P., and Sovilla, B.: Evaluation of probabilistic snow avalanche simulation ensembles with Doppler radar observations, Cold Regions Science and Technology, 97, 151–158, doi:10.1016/j.coldregions.2013.09.011, 2014.

Fischer, J.-T., Kofler, A., Fellin, W., Granig, M., and Kleemayr, K.: Multivariate parameter optimization for computational snow avalanche simulation, Journal of Glaciology, 61, 875–888, doi:10.3189/2015JoG14J168, 2015.

Fischer, J.-T., Kofler, A., Huber, A., Fellin, W., Mergili, M., and Oberguggenberger, M.: Bayesian Inference in Snow Avalanche Simulation with r. avaflow, Geosciences, 10, 191, doi:10.3390/geosciences10050191, 2020.

Gauer, P., Kern, M., Kristensen, K., Lied, K., Rammer, L., and Schreiber, H.: On pulsed Doppler radar measurements of avalanches and their implication to avalanche dynamics, Cold Regions Science and Technology, 50, 55–71, doi:10.1016/j.coldregions.2007.03.009, 2007.

Gray, J. and Ancey, C.: Particle-size and-density segregation in granular free-surface flows, Journal of Fluid Mechanics, 779, 622–668, 2015.

Hergarten, S. and Robl, J.: Modelling rapid mass movements using the shallow water equations in Cartesian coordinates, Natural Hazards and Earth System Science, 15, 671–685, doi:10.5194/nhess-15-671-2015, URL `http://www.nat-hazards-earth-syst-sci.net/15/671/2015/`, 2015.

Jop, P., Forterre, Y., and Pouliquen, O.: A constitutive law for dense granular flows, Nature, 441, 727–730, 2006.

Köhler, A., McElwaine, J., and Sovilla, B.: GEODAR data and the flow regimes of snow avalanches., Journal of geophysical research: earth surface., 123, 1272–1294, 2018.

Li, X., Sovilla, B., Jiang, C., and Gaume, J.: Three-dimensional and real-scale modeling of flow regimes in dense snow avalanches, Landslides, 18, 3393–3406, 2021.

Maggioni, M. and Gruber, U.: The influence of topographic parameters on avalanche release dimension and frequency, Cold Regions Science and Technology, 37, 407–419, doi:10.1016/S0165-232X(03)00080-6, 2003.

Mergili, M., Fischer, J.-T., Krenn, J., and Pudasaini, S. P.: r. avaflow v1, an advanced open-source computational framework for the propagation and interaction of two-phase mass flows, Geoscientific Model Development, 10, 553–569, doi:10.5194/gmd-10-553-2017, 2017.

Neuhauser, M., Neurauter, R., Tuermer, S., Gerstmayr, J., Dressler, F., Adams, M., Köhler, A., and Fischer, J.-T.: Investigating the potential of GNSS-modules for inflow avalanche measurements, in: EGU General Assembly, EGU2022-6416, doi:10.5194/egusphere-egu22-6416, 2022.

Neuhauser, M., Neurauter, R., Adams, M., Köhler, A., Winkler, R., Dressler, F., Fellin, W., Gerstmayr, J., and Fischer, J.-T.: Multisensor investigation of particle movement in snow avalanches, in: IUGG General Assembly, p. IUGG23–3488, Berlin, Germany, 2023.

Neurauter, R., Neuhauser, M., Blobel, J., Winkler, R., Dressler, F., Fischer, J.-T., and Gerstmayr, J.: An in-flow sensor system for data acquisition in snow avalanches, in: EGU General Assembly, EGU2022-11328, doi:10.5194/egusphere-egu22-11328, 2022.

Noël, F., Jaboyedoff, M., Caviezel, A., Hibert, C., Bourrier, F., and Malet, J.-P.: Rockfall trajectory reconstruction: a flexible method utilizing video footage and high-resolution terrain models, Earth Surface Dynamics, 10, 1141–1164, doi:10.5194/esurf-10-1141-2022, URL `https://esurf.copernicus.org/articles/10/1141/2022/`, 2022.

Oesterle, F., Wirbel, A., Tonnel, M., and Fischer, J.-T.: avaframe/AvaFrame: latest Version, https://doi.org/10.5281/zenodo.4721446, doi:10.5281/zenodo.4721446, URL `https://doi.org/10.5281/zenodo.4721446`, 2022.

Pudasaini, S. P. and Fischer, J.-T.: A mechanical model for phase separation in debris flow, International Journal of Multiphase Flow, 129, 103 292, doi:10.1016/j.ijmultiphaseflow.2020.103292, 2020.

Rauter, M., Kofler, A., Huber, A., and Fellin, W.: faSavageHutterFOAM 1.0: depth-integrated simulation of dense snow avalanches on natural terrain with OpenFOAM, Geoscientific Model Development, 11, 2923–2939, doi:10.5194/gmd-11-2923-2018, URL `https://www.geosci-model-dev.net/11/2923/2018/`, 2018.

Sampl, P. and Zwinger, T.: Avalanche simulation with SAMOS, Annals of Glaciology, 38, 393–398, 2004.

Tonnel, M., Wirbel, A., Oesterle, F., and Fischer, J.-T.: Avaframe com1DFA (version 1.3): a thickness integrated computational avalanche module – Theory, numerics and testing, EGUsphere, 2023, 1–37, doi:10.5194/egusphere-2022-1291, URL `https://egusphere.copernicus.org/preprints/egusphere-2022-1291/`, 2023.

Vilajosana, I., Llosa, J., Schaefer, M., Surinach, E., and Vilajosana, X.: Wireless sensors as a tool to explore avalanche internal dynamics: Experiments at the Weissflühjoch Snow Chute, Cold Regions Science and Technology, 65, 242–250, 2011.

Winkler, R., Fischer, J.-T., Hergel, P., Neuhauser, M., Sovilla, B., and Steinkogler, W.: Challenges and limitations of in situ particle tracking in avalanches, in: International Snow Science Workshop (ISSW 2018), Innsbruck, Austria, 2018.

Zugliani, D. and Rosatti, G.: TRENT2D: An accurate numerical approach to the simulation of two-dimensional dense snow avalanches in global coordinate systems, Cold Regions Science and Technology, 190, 103 343, doi:10.1016/j.coldregions.2021.103343, URL `https://www.sciencedirect.com/science/article/pii/S0165232X21001245`, 2021.