TOPOGRAPHIC UNCERTAINTY IN AVALANCHE SIMULATIONS

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ABSTRACT: Snow avalanches can develop a massive destructive power in mountainous regions. An intensive effort has therefore led to the development of simulation tools to quantify their impact and to develop mitigation measures. What remains challenging are the various sources of uncertainties present in these highly idealized computational tools. Uncertainties in avalanche simulations can be divided into different types: Input uncertainty accounts for insufficient knowledge of the initial conditions, such as release volume and area. Model parameter uncertainty is associated with the calibration quality and often concerns friction coefficients. Structural uncertainty, e.g. topographic uncertainty, accounts for shortcomings of the terrain representation. In this contribution, we present first results of a newly started project that aims at systematically investigating uncertainties and predictive power of computer models for gravity-driven mass flows including avalanches. We first introduce our modular, non-intrusive Python based work flow PSI-slide (Predictive Simulation of slides). PSI-slide is a probabilistic engine that sets up Monte Carlo type simulations and is able to utilize existing solvers, such as RAMMS, r.avaflow and faSavageHutterFOAM in a non-intrusive way, while conducting statistical analysis on the simulation results. In this particular study, we utilize PSI-slide to develop a better understanding of the impact of filtering topographic high frequency features. We systematically compare simulation results for topography data of two quality levels and discuss its implications. We close with an outlook.

Keywords: avalanche simulation, uncertainty quantification, simulation data mining, topographic uncertainty.

1. INTRODUCTION

In recent decades, simulation-based hazard analysis for snow avalanches has become an integral component of mitigation studies to assess potential risks and to plan defense structures, see for instance Aydın et al. (2014) or Christen et al. (2012).

1.1. Dynamic avalanche models

In order to develop simulation-based hazard mitigation instruments the dynamic behavior of an avalanche, in particular its run-out distance as well as its potential impact pressure, has to be modeled. Relevant spatial scales are the height of the snow pack in release and deposition area (both orders of meters), and the length of the avalanche track (order of 10^3 meters). These scales justify a depth-averaged approach that results in shallow flow type models, see for instance Pudasaini and Hutter (2007) or Christen et al. (2010). The scaling arguments are also summarized in the recently published article Kowalski and Torrilhon (2018).

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1.2. Common simulation frameworks

Shallow flow type dynamic avalanche models could be solved with any software framework that supports the solution of advection dominated transport processes of hyperbolic type, e.g. the finite volume packages CLAWPACK and OpenFOAM. Simulation-based hazard mitigation, however, also requires a proper handling of digital terrain information as well as the integration of input information and simulation results into a geographic information system (GIS). For snow avalanches one of the most commonly used tools of the required quality is RAMMS, see Christen et al. (2010). Promising more recently developed, open source alternatives are the OpenFOAM module faSavageHutterFOAM, see Rauter and Tuković (2018) for snow avalanches, and r.avaflow, see Mergili et al. (2017), for general gravity driven mass flows. All three are considered in the probabilistic engine PSI-slide (section 3) developed by the authors of this paper.

1.3. Content of this paper

In section 2, we will briefly discuss relevant uncertainties when simulating snow avalanches. Next, we will describe the novel Python based meta simulation framework PSI-slide that is specifically developed for the purpose of studying the predictive power as well as the impact of uncertainties on the simulation of gravity-driven mass flows, see section

3. The focus of the particular study presented in this contribution lays on a preliminary topographic uncertainty assessment, while investigating the impact of filtering topographic high-frequency features. In section 4, we describe the numerical test case including deterministic simulation setup and quantities of interest to compare the various simulation runs. Results of our numerical experiment are discussed in 5 followed by an outlook in section 6.

2. The role of uncertainties

The aforementioned software platforms for dynamic avalanche simulations have been proven useful to assess the risks due to snow avalanche hazards in many studies. This success is partially due to many data being available for calibrating purposes. Yet the idealization of reality underlying these computer models is severe, and the uncertainties that arise from this are not well understood, or systematically quantified. For snow avalanches, one can pragmatically distinguish four major sources of uncertainties that impact on the predictive power of such simulation tools:

2.1. Input uncertainty

Input uncertainty accounts for our uncertain knowledge of the avalanche's initial conditions, such as release volume and release area. For the reanalysis of avalanche events input uncertainty can be minimized by means of high-quality observations after the event tool place. Input uncertainties will always remain a significant source of error, when wanting to forecast potential avalanches.

2.2. Model parameter uncertainty

Model parameter uncertainty is associated with our lack of knowledge on the most appropriate model parameters. For dynamic avalanche models, these are typically friction coefficients that have to be calibrated based on training data sets. Conclusive data yield a better calibration quality (smaller variance) than sparse data sets. Bayesian techniques allow to infer on the parameter's probability distribution that can subsequently be used for direct uncertainty quantification.

2.3. Topographic uncertainty

Topographic uncertainty accounts for shortcomings in the way the terrain is represented. Gravity-driven mass movements, including avalanches, are to leading order determined by the underlying topography. This implies the importance of taking these sources of uncertainties into account, yet it is seldom done so far. Especially the interplay between topography and model parameters is important, for instance when wanting to use friction parameters that have been calibrated based on a certain DEM data product for prognostic simulations based on a different DEM product.

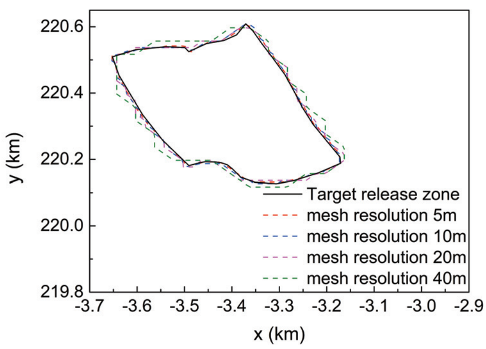


Figure 1: Translating the release zone polygon into the initial condition of a standard avalanche simulation tool (here RAMMS) heavily depends on the resolution of the chosen computational mesh. This makes it challenging to compare across simulation results achieved on computational grids of different resolution.

2.4. Numerical uncertainty

Numerical uncertainty accounts for discretization errors of the used numerical scheme. In principal it is well understood how the discretization error can be controlled due to many results in the discipline of numerical analysis. While the time integration of the physical model (that most of these works focus on) is therefore mostly uncritical, there are other sources of errors relevant to snow avalanches, which are often overlooked: One is for instance the projection of the release zone (often given as a polygon) on the computational grid, which heavily depends on mesh resolution and orientation, see figure 1. This not only complicates a convergence study of a realistic avalanches simulation, but also makes a grid modification challenging.

3. PYTHON FRAMEWORK PSI-SLIDE

The Python based probabilistic software framework PSI-slide (Predictive SImulation of SLIDEs) is developed for the purpose of systematically investigating the impact of the various sources of uncertainty on simulating gravity-driven mass movements. It is set up as a probabilistic engine that conducts Monte Carlo type simulations, while utilizing existing solvers, such as RAMMS, r.avaflow and faSavage-HutterFOAM in a non-intrusive way. This allows to switch between different computational models from within the same framework and make results comparable. It eventually enables us to conduct ensemble simulations across the various models. It is furthermore our goal to include an advanced simulation data mining module to conduct statistical analysis on the simulation results in order to detect trends and hidden patterns. First steps have been taken so far. PSI-slide's high-level structure is depicted in figure 2. It consists of four main parts:

3.1. *Uncertainty processor*

This module translates the assumed uncertainty into a set of deterministic problems by discretizing the random variable space (RVS) into representative point sets. As of now, we fully discretize the RVS prior to any process simulation (see module 3.3). In the future, we will consider stochastic processes, e.g. Markov chain Monte Carlo, that explore the RVS and seqentiylly sample posteriori distributions of interest.

3.2. *Initialization and input setup*

PSI-slide is set up to work with different state-of-the-art software platforms for dynamic avalanche simulations. These computational models differ in the way they initialize a simulation and the input files are set up. This module generates the initial input file sets to run the respective simulation based on representative point sets of the random variable space for a specific software. At present, it is set up for RAMMS as well as a self-implemented lumped mass point model that we use for reference purposes. We are in the process of including r.avaflow and SavageHutterFOAM into PSI-slide.

3.3. *Process simulation*

This module organizes the computational process simulations for the determined parameter configurations. Parallel distribution of the individual cases is applied to improve computational efficiency of the overall assessment.

3.4. *Postprocessing and simulation data mining*

Many simulation runs are necessary in order to systematically investigate the various sources of uncertainty and to conduct systematic sensitivity studies. This naturally results in a large number of output data. This module provides the capability to automatically extract quantities of interest from the output data (e.g. a polygon of the deposition area, or the apparent friction angle), and to apply data mining and statistical analysis on it to detect trends and hidden patterns.

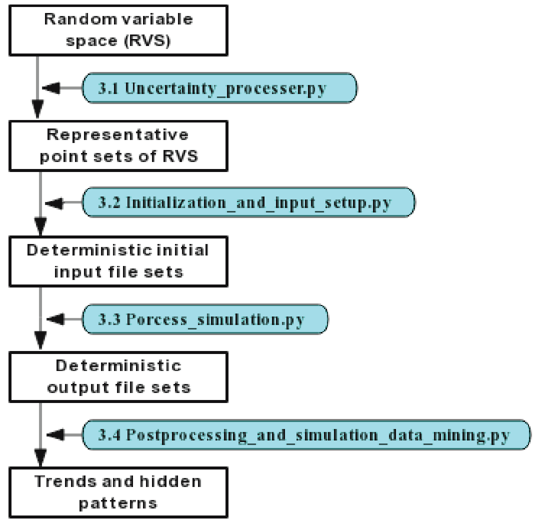


Figure 2: High-level structure of the Python based software framework PSI-slide.

4. NUMERICAL EXPERIMENT

In the following, we show results of a study that has been conducted with the PSI-slide software framework. It addresses the impact of filtering high frequency features from the underlying topography data and its interplay with other simulation properties, such as computational mesh resolution and friction parameters. As a simulation test case, we consider the Wolfsgruben avalanche that is also discussed in the recent publication Rauter et al. (2018).

4.1. *Topographic reference cases*

Topography data is typically available as DEM data products, which yield no further information about their inherent uncertainty. In order to assess topographic uncertainty systematically, it will therefore be necessary to quantify them directly from the remote sensing algorithms used to generate the respective DEM product. Until this is done rigorously, at least the role of potential topographic uncertainties can be assessed by using hypothesized proxies, see e.g. Stefanescu et al. (2012). In the presented study, we consider the quality level of the underlying topography data, in particular the role of high-frequency features. With respect to different DEM data products, a related study has also been conducted in Bühler et al. (2011). Our nominal topography reference is the Wolfsgruben DEM considered in Rauter et al. (2018), which has 10 m resolution. From this, we derive a second topographic reference by averaging the original elevation values on a 40 m x 40 m grid. This effectively dampens out high frequency information of the original DEM (10 m resolution) and can be regarded as a DEM of lower quality (or higher uncertainty). The novel

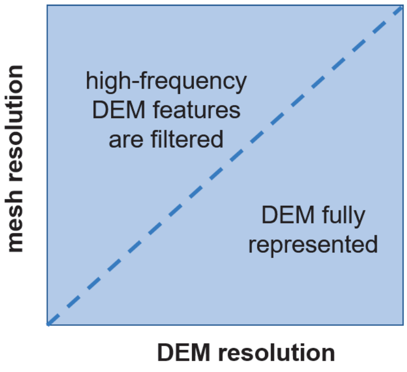


Figure 3: The resolution of the computational grid and the resolution of its underlying digital elevation model have to be carefully discriminated. If computational grid resolution is lower than the DEM resolution, high frequency components of the available topography information get filtered out.

aspect of our study is that we carefully distinguish between the DEM resolution that controls the error in representing the terrain data on the one side, and the computational mesh resolution that controls the numerical error on the other side, see also figure 3.

4.2. Simulation test case

The Wolfsgruben avalanche as presented in Rauter et al. (2018) is chosen as a test case. The event happened on 13 March 1988 and caused severe life and property loss. Data of the event is freely available. The digital elevation model and release zone data are taken from the aforementioned publication. The friction coefficients used in this study are based on the parameter range specified by Fischer et al. (2015). All simulations are conducted while utilizing PSI-slide for RAMMS and for both topography references as well as for various computational mesh resolutions. In the ongoing, we present results for a mesh of 5 m and for a mesh of 20 m resolution.

4.3. Post-processing of simulation results

The quantities of interest used in this study to compare the simulation results are twofold: First, we determine the polygon of deposited material. Second, and inspired by related work on landslides, we consider the apparent friction angle De Blasio (2011) as a scalar proxy to the run-out of avalanches. It is the angle between the line which connects the mass center of release zone and deposit zone and the horizontal plane. Note that for a straight avalanche track (quasi 1D situation) and in the absence of turbulent friction it corresponds to the dry Coulomb friction angle.

5. RESULTS AND DISCUSSION

In the following, we present a number of comparative studies conducted with the PSI-slide framework. In each of the studies, we consider both topography references as described in section 4.1 (DEM of 10 m resolution in black and DEM of 40 m resolution in red). Computational mesh resolution and friction coefficients are independently controlled.

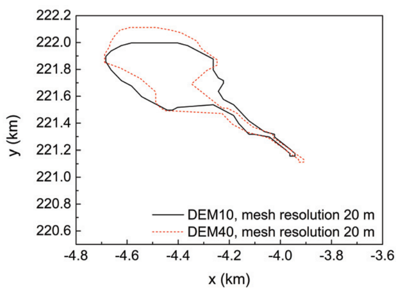
5.1. Deposition area

Figure 4b and 4a show the simulated deposition areas for a dry Coulomb friction value of μ=0.2 and a turbulent friction value of ξ=6000 m/s^2. A significant impact of the input DEM on the simulated deposition area can be observed (difference between black and red line in both plots). This qualitatively resembles findings that have previously also been reported in Bühler et al. (2011). Note, that the avalanche follows a completely different path shortly before deposition in 4b. In addition to previous findings, however, our results show that there is also a somewhat unexpected response in refining the resolution of the computational mesh. This behavior can be observed whenever complex topographies and release zone geometries are considered (in contrast to simple geometry benchmark cases). It represents the combined effect of a change in release zone geometry with mesh resolution, see figure 1, and the unintended filtering of high-frequency topographic features for large resolution computational meshes. Our results suggest that a sweep through different computational mesh resolutions should be used in simulation-based hazard assessment, and that a comparison across different computational models has to differentiate between DEM mesh resolution and the resolution of the computational grid.

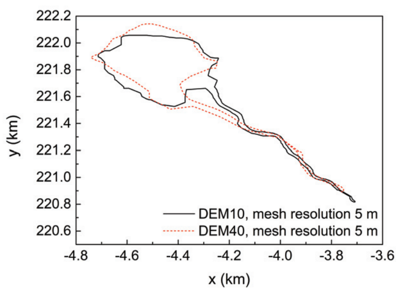
5.2. Apparent friction angle

Figure 4c shows the apparent friction angle as introduced in section 4.3 as a proxy for the mean travel distance of the avalanche. It is plotted with respect to different values of the Coulomb friction coefficient μ (x-axis) and the Chezy friction coefficient ξ (different columns). In this plot, we show results for a computational mesh of 5 m resolution. For a vanishing velocity dependent friction (rightmost column) the dependency between the apparent friction angle and Coulomb friction is almost linear, such as expected. For significant velocity dependent friction (leftmost column), the dependency is non-linear, likewise as expected. It is furthermore interesting to observe the difference between the apparent friction angle of DEM10 and DEM40 (vertical difference between red and black curve in each plot), which suggests that the avalanche's

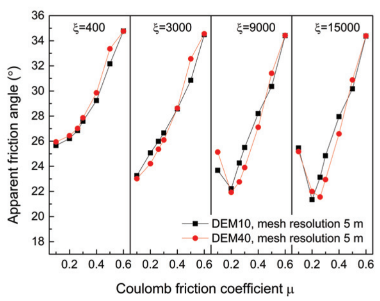
(a) Deposition area - mesh resolution 20 m



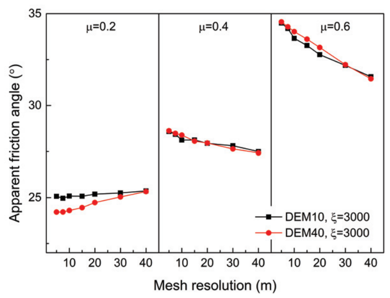
(b) Deposition area - mesh resolution 5 m



(c) Apparent friction angle vs. friction coefficients



(d) Apparent friction angle vs. mesh resolution and μ



(e) Apparent friciton angle vs. mesh resolution and ξ

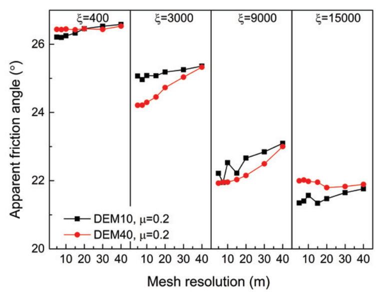


Figure 4: Simulation results of the Wolfsgruben avalanche for the original DEM (black: 10m resolution), and a synthesized (smoothed DEM (red: 40m resolution). Plot (a) and (b) show the impact on the deposition zone for two different values of the computational mesh resolution. Plot (c), (d), and (e) show combined sensitivity studies (friction coefficients versus computational grid resolution).

run-out length depends on the applied input DEM data. So, DEM uncertainty has an impact on the simulation result. Note that this dependency is not systematic with respect to the friction coefficients. While the apparent friction angle of the DEM10 case is lower for high Coulomb friction and turbulent friction, it is higher for moderate Coulomb and vanishing turbulent friction.

5.3. Grid mesh resolution

Figure 4d and figure 4e show the response of the apparent friction angle to a change in the computational mesh resolution and to a change of dry and turbulent friction coefficients μ and ξ. In each case, the apparent friction angle (hence the avalanches center of mass run-out length) changes with the computational mesh resolution, which again suggests to consider different mesh resolutions in a real case study. Furthermore, high-frequency topography components seems to be less important for events characterized by high dry friction values (difference between red and black curve in figure 4d). For a dry friction value of $\mu = 0.2$, a similar branching between DEM10 and DEM40 can be observed across a range of different turbulent friction values, see 4e. This suggests that the transfer of calibrated friction values to new avalanche tracks has to be done with care. In particular, matching the DEM resolution of the original calibration run is critical for the predictivity of the avalanche simulation.

6. CONCLUSION AND OUTLOOK

In this contribution, we describe our new meta software framework PSI-slide that aims at systematic studies of gravity-driven mass movements such as snow avalanches, with the goal of a rigorous uncertainty quantification and assessment of the model's predictive power. Our concrete study focuses on the impact of dampening out topographic high-frequency features and its interplay with mesh resolution and friction coefficients. It contributes to our understanding of the nature of topographic uncertainties in avalanche simulations. In particular, we find that

- topographic uncertainty has an impact on computational avalanche simulations and its effects need to be further explored
- their is an interplay between the resolution of the underlying DEM and the resolution of the computational mesh that needs to be disentangled in order to make avalanche simulations fully comparable across DEMs of different resolutions

- the avalanche run-out length (in our work coded as apparent friction angle) varies with both DEM resolution and computational mesh resolution.
- while the latter behavior has been known before, our study furthermore shows that the observed trends (how does the run-out length vary with the resolution) is affected by the frictional setting. This suggests to match both DEM and computational grid resolution, when using frictional parameters that had been calibrated on a different avalanche track.

These results increase our understanding of the impact of uncertainties on avalanche simulation studies. While further developing the PSI-slide framework, our long term goal is to utilize our findings in order to establish strategies that allow to assess the admissibility of transferring calibrated friction parameters to avalanches in other regions or of different sizes, while managing the arising inherent uncertainties and model errors.

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REFERENCES

Aydın, A., Bühler, Y., Christen, M., and Gürer, I. (2014). Avalanche situation in turkey and back calculation of selected events. *Natural Hazards and Earth System Sciences*, 14(5):1145–1154.

Bühler, Y., Christen, M., Kowalski, J., and Bartelt, P. (2011). Sensitivity of snow avalanche simulations to digital elevation model quality and resolution. *Annals of Glaciology*, 52(58):72–80.

Christen, M., Bühler, Y., Bartelt, P., Leine, R., Glover, J., Schweizer, A., Graf, C., McArdell, B. W., Gerber, W., Deubelbeiss, Y., et al. (2012). Integral hazard management using a unified software environment. In *12th Congress Interpraevent*, volume 2012, pages 77–86.

Christen, M., Kowalski, J., and Bartelt, P. (2010). RAMMS: Numerical simulation of dense snow avalanches in three-dimensional terrain. *Cold Reg. Sci. Technol.*, 63(1):1–14.

De Blasio, F. V. (2011). *Introduction to the physics of landslides: Lecture notes on the dynamics of mass wasting*. Springer Science & Business Media.

Fischer, J.-T., Kofler, A., Fellin, W., Granig, M., and Kleemayr, K. (2015). Multivariate parameter optimization for computational snow avalanche simulation. *Journal of Glaciology*, 61(229):875–888.

Kowalski, J. and Torrilhon, M. (2018). Moment methods and model cascades for shallow flow. *Communications of Computational Physics*, accepted for publication.

Mergili, M., Jan-Thomas, F., Krenn, J., and Pudasaini, S. P. (2017). r. avaflow v1, an advanced open-source computational framework for the propagation and interaction of two-phase mass flows. *Geoscientific Model Development*, 10(2):553.

Pudasaini, S. and Hutter, K. (2007). *Avalanche Dynamics - Dynamics of rapid flows of dense granular avalanches*. Springer-Verlag, Berlin-Heidelberg-New York.

Rauter, M., Kofler, A., Huber, A., and Fellin, W. (2018). fasavagehutterfoam 1.0: depth-integrated simulation of dense snow avalanches on natural terrain with openfoam. *Geoscientific Model Development*, 11(7):2923–2939.

Rauter, M. and Tuković, Ž. (2018). A finite area scheme for shallow granular flows on three-dimensional surfaces. *Computers & Fluids*, 166:184–199.

Stefanescu, E., Bursik, M., Cordoba, G., Dalbey, K., Jones, M., Patra, A., Pieri, D., Pitman, E., and Sheridan, M. (2012). Digital elevation model uncertainty and hazard analysis using a geophysical flow model. *Proc. R. Soc. A*, 468(2142):1543–1563.