Towards a probabilistic avalanche simulation strategy for hazard mapping

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ABSTRACT: Computer simulations are a common tool for assessing the potential hazard associated with the rapid movement of snow avalanches. Their application is straightforward and setups for valuable simulation results are quite easy to determine. Setup guidelines exist for hazard mapping and engineering issues, making them transparent and easy to replicate. But often these are estimates, and due to model assumptions and further simplifications in the mathematical description of physical process (i.e. moving snow), uncertainties in the simulations arise. Being aware of these uncertainties, as well as those for input data, we investigated the main sources for the simulation tool SamosAT. Prioritizing in regard to practical application leads to a base set of parameter variations to include in a first prototype for probabilistic avalanche simulations. The assessment builds on the requirement of practical applicability for operational use at the Austrian Service for Torrent and Avalanche Control. These include constraints on computational time and power, as well as prior knowledge of parameter ranges. Presenting benefits and issues that arose during our testing period, we highlight the necessity to accept inherent uncertainties of input data and simulation tools. Handling these is necessary for future advancement of avalanche simulations in engineering applications and our presented strategy is a first step towards this goal.

Keywords: avalanche dynamics, hazard mapping, uncertainties

1. INTRODUCTION

Assessing potential hazard areas originating from snow avalanches is an important task of the Austrian's Torrent and Avalanche Control (WLV). Along historic events and experts knowledge, numerical simulations of avalanche dynamics play a pivotal role in developing natural hazard maps. Current standard procedure at the WLV for model simulations utilizes a "poor man's ensemble' by employing different models/methods (SamosAT Sampl (2007), RAMMS Christen et al. (2010), Alpha-Beta Wagner et al. (2016)) and comparing results. Additionally, within each model different scenarios according to model capabilities are investigated. This ranges from dense flow avalanches (DFA) to powder snow avalanches (PSA), including variations for release areas, entrainment- and resistance areas. This allows the end user to get a range of potential runout scenarios.

Previous studies calibrated process model parameter to observations, trying to find 'best' optimal parameter sets (Oberndorfer and Granig, 2007; Gruber and Bartelt, 2007). Recent developments introduced multivariate parameter optimization approaches to extend investigated parameter ranges and result variables (Fischer et al., 2015). The aim of the current work is to document the major sources of uncertainties and investigate their relative importance. Instead of optimizing single parameter values or distributions to observed events, we quantify the result variation, originating from operational scenarios and map these to simulation input ranges. Due to the scope of the project, we concentrate on SamosAT DFA avalanches. As a further constraint we mainly want to concentrate on parameters that are relevant and understood by the end users. We are aware of and documented a lot more (model-) intrinsic sources of uncertainties, but these need to be addressed in further studies. Our work results in a first automatic prototype for testing and future development of presenting dynamic avalanche model results with uncertainties/probabilities attached.

2. Model uncertainties

The methods uses SamosAT - DFA, version v2017_07_05 (Parameter Standard Std:03_2017). SamosAT solves DFA dynamics via shallow water equations and uses the SamosAT friction law (see Oberndorfer and Granig (2007)).

Relevant uncertainties arise from these main areas:

- the process model itself: model assumptions, simplifications and process model parameters (e.g. flow density ρ, bottom friction angle μ),

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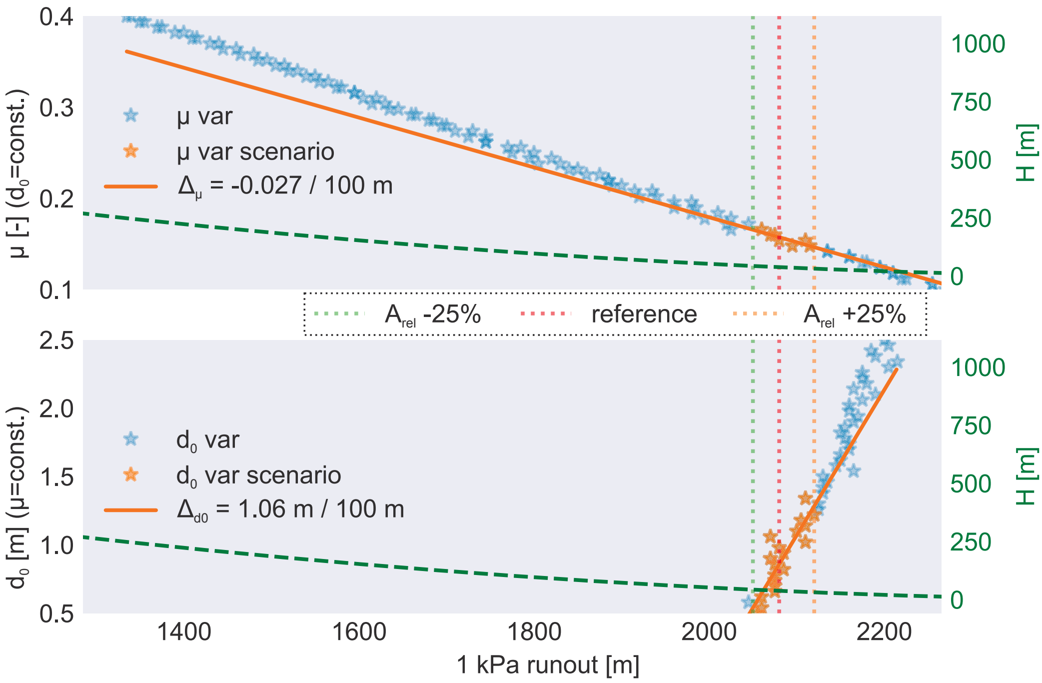

Figure 1: Scenario release area ($\pm 25\%$: dotted green and orange vertical line; reference: dotted red vertical line) for generic topography. Dashed green: topography profile. Each blue star denotes one simulation which varies μ (upper panel) and d_0 (lower panel) (left y-axis). Orange solid line shows the gradient fitted to the variations within the boundaries of the scenario (orange stars).

- initial and boundary conditions (e.g. DEM (resolution), release depth d_0),
- numerical implementation and numerical parameters (e.g. simulation end time t_{end}, calculation time step Δt),
- extraction and presentation of (derived) results. I.E the transfer of process model results to simulation results (e.g. flow variables depth $\bar{h}$ and velocity u to impact pressure p).

3. Method

3.1. Comparison

Due to the scope of the pilot project we concentrate on a selection of the simulation input, mainly an initial condition (release depth d_0) and a main process model parameter (frictional parameter μ). Investigation of the numerical implementation and the influence of the results extraction is outside the scope of this effort, but will be addressed in future projects.

As one of the most relevant results, the projected 1 kPa-runout is targeted. In here the 1 kPa-runout refers to the furthest 1 kPa reach of the dynamic peak pressure in a path relative coordinate system (AIMEC Fischer, 2013).

To enable a direct comparison between the scenarios and test cases, we introduce the runout gradient Δ. It is a measure which quantifies the associated simulation input change for a prescribed runout difference of 100 m.

3.2. Test cases

To assess the relevant result variation in the operational scenarios and to determine the corresponding parameter ranges four different test cases are used. For each of them, a reference run is performed, starting from the current standard procedure used at the WLV. Using statistical extreme value analysis (Hoelzl et al., 2017) a 3-day new snow sum (3DNSS) is determined. Release area size and possible entrainment and resistance areas are determined on site by expert analysis. The reference run uses the 3DNSS, a 5m digital elevation model and the main release areas.

The test cases are the following, with further details in table 1:

- generic topography flat,
- generic topography channeled,
- Gidis-avalanche,
- Arzleralm-avalanche.

Starting from the reference run, the following scenarios are investigated:

- variation of release area ($\approx \pm 25$ %),

test case	V_{rel}	fall height	1 kPa-runout
generic topography flat	67000 m^3	1020 m	2080 m
generic topography channeled	67000 m^3	1050 m	2185 m
Gidis-avalanche	25000 m^3	900 m	1605 m
Arzleralm-avalanche	83200 m^3	1250 m	2430 m

Table 1: Selected properties release volume V_{rel}, fall height and 1 kPa-runout for the reference setup.

- entrainment of 30 cm,
- change in DEM properties (e.g. resolution, smoothing).

For each scenario, the runout change ϵ_r, the runout gradient Δ and the respective parameter ranges are determined (see table 2). The differences in the 1 kPa-runout are all of the same magnitude, ranging from -30 m to +95 m. Generic topographies show higher sensitivity to the scenarios, leading to larger runout differences and smaller gradients. This can be attributed to the generally higher roughness of natural terrain. The influence of natural terrain is also seen in threshold effects across flat planes or dams (e.g. overtopping of dam at the Arzleralm-avalanche). The small gradients for μ highlight its relative importance compared to d_0 for the operational investigation of runout length. The small impact of d_0 is in contrast to user perception, which often see d_0 as one of the main parameters (see Schmidtner et al. (2018)).

4. Operational prototype

Based on the investigation in section 3.2, we design a prototype for application to hazard mapping. To keep the method easily applicable and fast, a predetermined limit of maximum 50 DFA-runs was set. This means a runtime for the DFA part of the analysis of about 20 minutes (on a multicore processor). The range of the input parameters are extracted from table 2 (e.g. intersection of scenarios for μ), but kept within limits set by WLV-experts based on experience and practical relevance (e.g. release depth d_0).

4.1. Algorithm

Starting from the reference run (current WLV standard procedure), the following variations are applied:

- release depth d_0 by $\pm$ 20 %,
- entrainment and resistance on/off,
- bed friction angle μ from 0.142 to 0.160,
- different combinations of release areas as set by the end user.

4.2. Visualization

Figure 2 shows an example result as presented to selected expert end users. To keep the method as transparent as possible all 1 kPa and 10 kPa - lines (ie. yellow and red hazard zones in Austria) of all simulations are shown as well as the highlighted reference run. Once the method is refined and stable, we plan on producing probability maps, i.e. as heatmaps or similar.

4.3. Considerations for operational application

As shown in the previous sections, the main concerns for operational use are the efficient computation and the transparency of the method. This has mainly to do with user acceptance of a new product and consistency with past and current methods used to determine hazard maps.

We are aware that a mathematical/statistical verification of our results is neither done, nor might it be possible in future. Too little verification data for the chosen return level is the main problem. However our analysis allows the end user to get an idea about model uncertainties within the scope of the hazard map procedure.

5. Conclusions

In taking a first step towards a probabilistic interpretation of dynamic avalanche model results, we investigate and rank sources of uncertainties for runout results. Using the metric Δ, describing the change of simulation input per 100 m runout change, the independent impact of input parameters are compared to each other, making this ranking of uncertainty sources possible. These include scenarios such as variation of release area, entrainment and DEM. Other sources were investigated as well, but dismissed for our prototype, needing more thorough work.

Following practical constrains, we concentrate on uncertainties easily understood by the end users, mainly simulation input variations. Our prototype method starts from the current WLV standard method, then adds variations in release depth (therefore release volume), release area, entrainment/resistance areas (where applicable) and μ. Results are presented to selected end users in a

scenario	range			Δ	
	ϵ_r	μ	d_0	Δ_μ	Δ_{d_0}
release	-30 m bis $+70$ m	0.142 - 0.166	0.70 m - 1.58 m	-0.077 / +100 m	+2.01 m / +100 m
entrainment	$+20$ m bis $+95$ m	0.130 - 0.160	0.81 m - 2.05 m	-0.097 / +100 m	+2.84 m / +100 m
DEM	$+21$ m	0.100 - 0.172	0.82 m - 1.78 m	-0.612 / +100 m	6.62 m / +100 m

Table 2: Evaluation of scenario variation, with runout change $epsilon_r$, runout gradients Δ and parameter ranges.

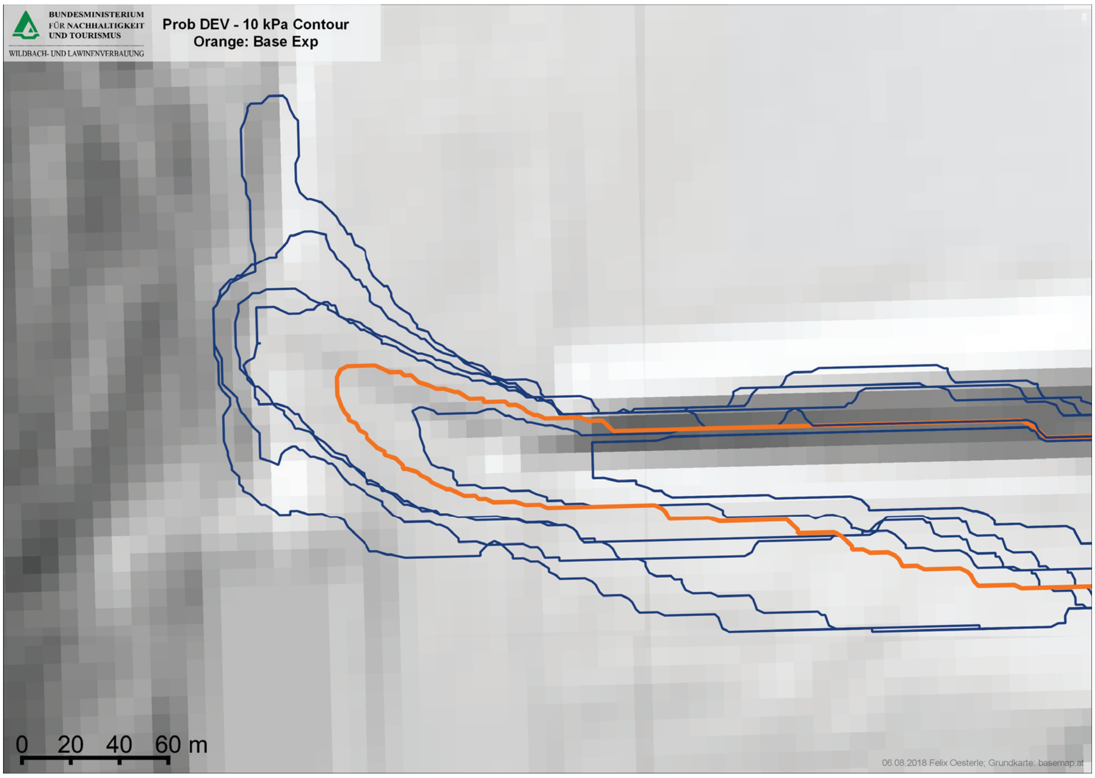

Figure 2: Simple visualization of the 10kPa peak pressure contour of multiple simulation results. Blue: scenarios/variations. Orange: reference run (standard procedure). Background: hillshading of DEM.

simple and transparent way in order to get feedback on the applicability of the prototype.

We expressly do not want to change the way hazard maps are presented, but we want to raise awareness of model uncertainties and how the hazard zones were determined. We suggest moving away from pure deterministic thinking and accepting that a certain remaining risk is unavoidable. Therefore tools that allow assessment of these uncertainties and risks are needed. This is already being done, e.g. for rock fall simulations, for complex process chains (impact indicator scores, see Mergili et al. (2018)) or other avalanche simulation tools (probability maps with r.avaflow, see Kofler et al. (2018)). Moving discussions for operational applications away from difficult to understand and reproduce model parameter tuning to a focus on uncertain input parameters as e.g. d_0. Also our research does not mean research in deterministic dynamic models should is unnecessary. The exact opposite is true: at the base of our method are deterministic models, therefore the better our base, the better the results.

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