AVALANCHE SIMULATIONS IN FORESTED TERRAIN: A FRAMEWORK TOWARDS A BAYESIAN PROBABILISTIC MODEL CALIBRATION

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ABSTRACT: Avalanche dynamics models are used for hazard zoning and engineering to predict runout distances and impact pressures of snow avalanche events. The effect of mountain forests as an effective biological protection measure against avalanches has rarely been addressed in this context. Avalanche runout distances of small to medium avalanches are strongly influenced by the structural conditions of forests in the avalanche path; however, this varying decelerating effect has not yet been implemented in avalanche models. Within the two-dimensional avalanche dynamics program RAMMS the standard Voellmy-Salm model can be applied to predict runout distances, flow velocities and impact pressures in complex three-dimensional terrain. Currently, the occurrence of forests is realized by increasing but constant friction parameters μ (dry-Coulomb type friction) and ξ (velocity squared friction) compared to open unforested terrain. Back-calculations of 41 well documented small avalanches which released in forests of the Swiss Alps emphasize the need for a further calibration dependent on differences in forest structure. Since the friction parameters are more conceptual than physical, they must be fitted by matching model results and recorded data which basically involves solving an inverse problem. A way of providing probabilistic statements about unobservable information is Bayesian inference. Therefore, we present a framework for a Bayesian probabilistic model calibration of the friction parameter ξ accounting for differences in forest structure in the avalanche path. Considering different forest characteristics within avalanche simulations will improve current applications for avalanche models, e.g. in mountain forest and natural hazard management.

1. INTRODUCTION

Avalanche dynamics models are widely used for hazard zoning and engineering to predict runout distances and impact pressures of snow avalanche events. The effect of mountain forests as an effective biological protection measure against avalanches has been rarely addressed in this context (Teich and Bebi, 2009); however, avalanche flow in forested terrain is strongly influenced by the condition and composition of vegetation in the avalanche path (e.g. Bartelt and Stöckli, 2001; Teich et al., accepted for publication). This effect has not yet been implemented in avalanche models (Anderson and McClung, 2012).

The Voellmy-Salm (VS) model (Salm, 1993) is the basis for hazard mapping in Switzerland. This numerical avalanche model requires two empirical friction coefficients to be defined by the avalanche expert; the total basal friction is split into a velocity independent dry-Coulomb type friction μ and a velocity dependent "viscous" or "turbulent" friction ξ. A sensitivity analysis on the influence of varying friction parameters for forests of a VS-based two-dimensional avalanche dynamics program has shown that slight alternations especially of the friction parameter ξ for forests could have a vital impact on risk calculations (Teich and Bebi, 2009). However, friction parameters for forested areas were only rarely verified with real avalanche events (e.g. Casteller et al., 2008; Takeuchi et al., 2011).

Since the friction parameters are more conceptual than physical, they cannot be measured for real avalanches and must be fitted by matching avalanche dynamics model results and recorded data which basically involves solving an inverse problem (Ancey et al., 2003). A way of

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providing probabilistic statements about unobservable information is Bayesian inference. Bayesian methods have already received attention in avalanche modeling (e.g. Straub and Grêt-Regamey, 2006; Gauer et al., 2009; Eckert et al., 2010); however, they have never been applied to calibrate the friction parameters of an avalanche dynamics model to improve avalanche simulations in forested terrain.

We applied the two-dimensional numerical avalanche dynamics program RAMMS (Christen et al., 2010) and back-calculated several avalanche events in forests. We compared the model output with observed runout distances to estimate the decelerating effects of different forest structures, and propose a Bayesian probabilistic framework to calibrate the friction parameter ξ for avalanche simulations in forested terrain based on the observations.

Implementing avalanche-forest interactions into numerical avalanche simulations will open new fields of application for avalanche models, e.g. for managing mountain forests and by better accounting for the protective effect of forests in natural hazard mapping.

2. AVALANCHE SIMULATIONS IN FORESTED TERRAIN

The two-dimensional avalanche dynamics program RAMMS (RApid Mass MovementS) is a practical tool to predict avalanche runout distances, flow velocities and impact pressures in complex three-dimensional terrain by solving a system of partial differential equations using first and second order finite volume techniques (Christen et al., 2010). The model allows to apply two different flow rheologies: (1) the standard Voellmy-Salm (VS) model (Salm, 1993), or (2) a random kinetic energy (RKE) model which additionally includes the random motion associated with the mass of flowing granules.

For our purpose, we applied the VS model which employs a 'Voellmy-fluid' flow law and splits the total basal friction into a velocity independent dry-Coulomb term (friction coefficient μ) and a velocity dependent "viscous" or "turbulent" friction (friction coefficient ξ) (Salm, 1993). Currently, the presence of forest in the avalanche path is realized by increasing but constant friction parameters, i.e. 0.02 is added to the μ-value and ξ is set to 400 m/s^2.

In order to evaluate the performance of RAMMS in forested terrain, we back-calculated 41 small avalanches which released in forests of the Swiss Alps with runout distances ranging between 50 and 700 m (for details see Teich et al., accepted for publication; Feistl et al., this proceedings; Teich et al., in prep.). We applied the friction parameters μ and ξ which were calculated automatically in RAMMS based on a digital elevation model (DEM) with a spatial resolution of 2 m and a shapefile characterizing forested areas. The avalanche simulations were accomplished assuming a 10 year return period, the stopping criteria of a 10% flow momentum threshold, a minimum flow height of 10 cm and a simulation time of 100 s. For the interpretation of the simulated avalanche runout distance, we used the maximum flow momentum as the product of flow height and velocity in m^2/s for avalanches with a release volume $V_R \geq 50$ m^3 or the maximum flow height for avalanches below this V_R threshold. The avalanche runout distance was measured along a representative flow line following the stream network identified by a GIS software.

Selected forest structural parameters (forest type and crown closure (see Table 1), vertical structure, stage of development), the type of snow (dry or wet snow avalanche), the mean slope angle over the whole avalanche area and the cross-slope curvature (flat or gully) were assigned to all 41 avalanches based on collected field data, orthophotographs and DEM analyses (for details see Teich et al., accepted for publication). Spearman's rank correlation coefficient (r_S) was then calculated and tested for significance ($p \leq 0.05$) to evaluate statistical dependencies between those variables and the modeled runout distances compared to the observed ones (Δ runout in %).

Table 1: Description of the forest parameters 'forest type' and 'crown closure' which were assigned to each observed forest avalanche.

Forest parameter	Categories and description
Forest type	(1) "Mixed forests" contain deciduous forest, mostly dominated by European beech (*Fagus silvatica* L.) (2) "Evergreen coniferous forests" dominated by Norway spruce (*Picea abies* (L.) H. Karst.) (3) "Deciduous coniferous forests" formed by European larch (*Larix decidua* Mill.) at the upper treeline
Crown closure	(1) Dense to loose (Crown coverage >70%) (2) Scattered (Crown coverage 40-70%) (3) Open (Crown coverage <40%)

The comparison of observed with simulated runout distances of our dataset reveals that runout distances of 28 avalanches were overestimated by the model (Fig. 1); for two avalanches by more than 400%. Calculations of Spearman's rank correlation coefficient have shown that the only variable which affects the difference between observed and simulated runout distances significantly was the mean slope angle (r_S=0.32; p=0.042) which supports our initial hypothesis that the varying effect of forests on avalanche runout is unsatisfactorily represented within RAMMS.

Even if the influence of different forest types was not statistically significant, we assume varying decelerating effects of the three forest types of our dataset since avalanche runout distances were highly overestimated by the avalanche model in mixed forests (median=137%; mean=166%) and evergreen coniferous forests (median=117%, mean=146%), but relatively well predicted in deciduous coniferous forests (median=100%, mean=120%). Based on cross-correlations between the forest parameters, we chose crown coverage as a second variable characterizing forest density for the characterization of differences in forest structure to be implemented in avalanche simulations. Regarding the practical application, both forest parameters (forest type and crown coverage) are easy to delineate from orthophotographs.

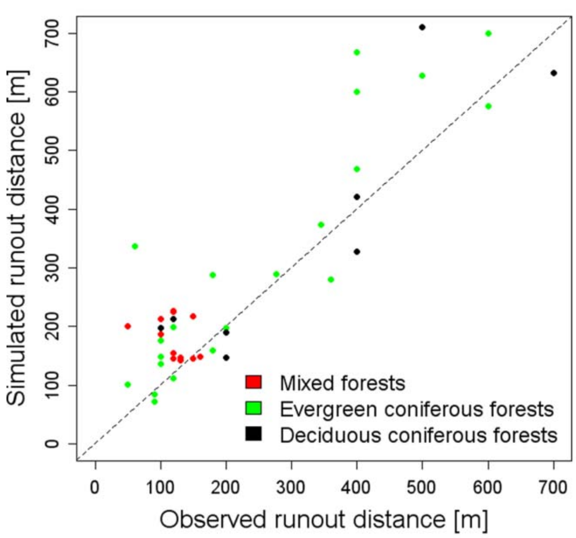

Figure 1: Observed vs. simulated runout distances of 41 small avalanches released in mixed (red), evergreen (green) or deciduous (black) coniferous forests.

3. BAYESIAN PROBABILISTIC MODEL CALIBRATION

In general, Bayes' theorem allows for updating a prior probabilistic model of unknown parameters Θ with the observed data q of the process under consideration. Bayes' theorem in its general form is given by:

$$p_{\Theta|q}(\theta) \propto L(\theta|q) p_{\Theta}(\theta) \quad (1)$$

The likelihood function $L(\theta|q)$ describes how likely the observed realizations of the random process q are, given a particular value of the variables θ. The posterior probability distribution $p_{\Theta|q}(\theta)$ represents the probabilistic solution to the inverse problem and is, thus, the joint probability function between the a-priori states of information associated to both the prior and the likelihood.

Here, ξ is the parameter modeled probabilistically while the second friction coefficient μ is considered deterministically, i.e. μ is part of a set of constants c which includes all inputs to the model that are considered as deterministic such as topography or the release height. Since different ξ-values are used in the avalanche model for the different topographical classifications and surfaces, we do not represent ξ by a single random variable. Instead, a parameter scenario represents the random variable Θ_ξ with realizations $\theta_{\xi 1}$, …, $\theta_{\xi 10}$ based on the original choice of the automatic assignment procedure of the avalanche model with varying ξ-values for forested areas (100-1000 m/s^2), assuming that one of these scenarios contains the "true" value for the respective forest conditions, yet it is unclear which.

Figure 2 shows the Bayesian network (BN) for the probabilistic calibration of the friction parameter ξ. BNs are directed acyclic graphs (DAGs) where each random variable in the model corresponds to a node and arrows between nodes show direct dependencies to structure the problem (see e.g. Jensen and Nielsen, 2007). Because the model is only a simplified representation of reality and some parameters which are considered as deterministic are actually uncertain, the error term ε is assumed to be additive in the runout distance. This random error term must be included since the avalanche model cannot exactly match the observed avalanches as some inaccuracies and errors are always present. Based on the defined forest conditions which affect modeled as well as observed runout distances, we end up with nine cases where the corresponding ξ-value needs to be updated for.

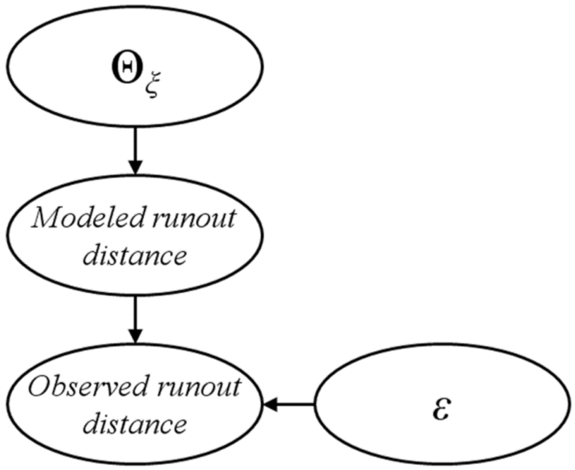

Figure 2: The a-priori Bayesian network for the probabilistic calibration of the friction parameter ξ of the avalanche dynamics program RAMMS.

As mentioned above, statistics used for the posterior formulation are calculated from the evidence available before the probabilistic solution to the inverse problem, i.e. observations and model predictions. For estimating the posterior for each forest condition included in Θ_ξ, it is required to integrate the posterior which can be solved numerically. This solution yields a full description of the uncertainty associated with Θ_ξ conditioned on the available data in contrast to deterministic optimization approaches where only one set of best estimates is retrieved. To solve the posterior integral, we will use WinBUGS (Lunn et al., 2000) which is a flexible software for Bayesian analysis using Marcov chain Monte Carlo (MCMC) methods. Resulting posterior distributions for Θ_ξ will allow estimating updated ξ-values to be applicable for simulations of small avalanches in forested terrain by accounting for differences in forest structure.

4. CONCLUSIONS AND OUTLOOK

The comparison between observed and simulated runout distances of 41 small avalanches applying currently used ξ-values for forests has shown that runout distances were relatively well predicted by RAMMS in deciduous coniferous forests, but highly overestimated in mixed forests and evergreen coniferous forests. Therefore, we assume that values for ξ<400 m/s^2 need to be assigned to areas covered with the two latter forest types.

The proposed Bayesian probabilistic framework is a promising approach for the calibration of RAMMS to better perform in forested terrain. In contrast to deterministic optimizations, this approach gives a full description of uncertainties associated with the updated ξ-values conditioned on the available observation data.

Simulations with alternating ξ-values for forested areas (100-1000 m/s^2) revealed also that runout distances of 19 avalanches were still overestimated by RAMMS when applying the smallest chosen ξ-value of 100 m/s^2. This indicates that calibrating only one friction parameter of the avalanche model might probably not lead to satisfying simulations in every case, and that other physical processes in avalanche dynamics modeling need to be taken into account when simulating small forest avalanches (Feistl et al., this proceedings).

Implementing avalanche-forest interactions into numerical avalanche simulations will improve current applications for avalanche models, e.g. for managing mountain forests and by better accounting for the protective effect of forests in natural hazard mapping. Especially when it comes to decisions about the size and extent of avalanche defense structures in potential starting zones in forested areas or directly above the treeline, forest and civil engineers could benefit from reliable avalanche simulations in forested terrain. Thus, there is an increasing need to consider different forest characteristics within avalanche simulations to be applicable for a practical natural hazard management.

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