

EVALUATION OF PROTECTION MEASURES AGAINST AVALANCHES IN FORESTED TERRAIN

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ABSTRACT: Small to medium sized avalanches release in forest gaps and open forest above roads and infrastructure in the Prealps regularly each winter. Avalanche bombing, silvicultural management and technical prevention measures such as glide snow tripods, snow fences and galleries can prevent road closure during the winter season. Besides historical data and expert knowledge, avalanche dynamics models are recently increasingly employed as additional danger assessment tool. Modelling small to medium sized avalanches in forested terrain requires high resolution digital terrain models and detailed process understanding concerning forest-avalanche interaction. Removal of snow by trees, energy loss through tree breakage and higher surface friction are the main processes that lead to earlier avalanche stopping. In this study we performed avalanche dynamics simulations for four well documented case study areas in the Bavarian Alps where forest influences avalanche runout distance. Wet and dry snow avalanche regimes were assumed for the south, west and north facing slopes, respectively. We found differing effect of forests on velocity and lateral spread of these avalanches depending on the flow regime, the forest stand characteristics and the underlying terrain features. Whereas technical avalanche defense structures to hinder snow gliding and support tree re-growth are the most promising courses of action in three cases, a dam to protect the road is the most effective measure for the fourth slope. These case studies demonstrate how avalanche dynamics models can support local authorities in facilitating the planning of optimal avalanche prevention measures.

KEYWORDS: avalanche, forest, public safety, modelling.

1. INTRODUCTION

Roads and infrastructure in mountainous regions are endangered by small to medium sized avalanches each winter. Avalanche commissions and local authorities have to guarantee public safety by establishing well adapted avalanche defense strategies. Permanent technical structures, protection forest management, avalanche bombing and road closure are the most common safety measures in Bavaria. Economical and ecological constraints, however, influence the decision making process. The optimal measure depends on the risk for injuries or fatalities, terrain features, avalanche characteristics and forest extent and composition.

A comprehensive evaluation strategy to identify the optimal defense measure includes field studies, analysis of historic events and avalanche dynamics simulations. Avalanche dynamics models provide valuable information on the spatial extent and runout distance of avalanches for different hazard scenarios. At present the focus of such model calculations is on

extreme events where small scale topography, forest-avalanche interaction and snow-cover properties are secondary (Völlmy, 1955; Salm, 1993). Including vegetation effects in avalanche dynamics models can improve simulation results and thereby the evaluation of optimal avalanche defense measures, especially in complex, forested terrain. A careful testing on well documented example cases is however essential to reduce uncertainties and establish the model's application range.

Recently we have seen an increased demand for forecasts concerning the runout of small to medium sized avalanches in Bavaria. The application of advanced avalanche dynamics models to predict the runout of frequent events remains an on-going research theme. Recent models couple high resolution terrain models with more physics-based approaches (Bartelt et al., 2011; Buser and Bartelt, 2009, 2015). These approaches are able to model both dry and wet avalanche flow regimes (Vera Valero et al., 2015; Bartelt et al., 2015) that include forest-avalanche interaction (Feistl et al., 2014; Teich et al., 2012). The models must include entrainment to simulate avalanche growth, and important aspect of small avalanches (Dreier et al., 2014). First studies have demonstrated the

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application of such approaches in pre-defined areas, for example the dangerous avalanche slopes threatening mining operations in Chile (Vera Valero et al., 2015). A prerequisite for application is both an avalanche cadastre, as well as a network of automatic weather stations (Wever et al., 2016). Most applications have purposely avoided vegetated regions, concentrating instead on high-altitude applications. How to model frequent avalanches in forested terrain requires further experience and testing, above all to provide road and forest management with engineering and silvicultural advice for different hazard scenarios and forest disturbances. This is the purpose of our study.

We back-calculated avalanches on four specific frequent avalanche slopes in the Bavarian Pre-Alps. These avalanches endanger roads which are highly frequented and public interest increases to keep them permanently open. Safety can generally be assured by a dense protection forest if growth conditions are supportive. However, the protection forest on these slopes is under pressure through extensive damage by game animals, uprooting by dense snow glide movements, storm breakage, forest fires and droughts. In our model calculations we take such differences and evolution in the forest cover and their effects on avalanche dynamics into account. Additionally snow wetness and therefore flow regimes vary depending on exposition, altitude level and weather conditions and are considered by applying different temperature scenarios.

Optimizing avalanche protection measures is of great public interest. Local authorities, avalanche commissions and even ecosystems, especially in highly sensitive alpine regions profit from sustainable avalanche defense concepts. This study reveals that the integration of snow-cover properties and forest-avalanche interaction into avalanche dynamics models provides valuable information on erosion and deposition processes and finally shows how avalanche protection measures can be optimized.

2. Avalanche model equations

To model avalanche flow we numerically solve a system of differential equations that is conveniently written as a single vector equation:

$$\frac{\partial \mathbf{U}_\Phi}{\partial t} + \frac{\partial \Phi_x}{\partial x} + \frac{\partial \Phi_y}{\partial y} = \mathbf{G}_\Phi. \quad (1)$$

Flow of the avalanche core Φ is described by nine state variables \mathbf{U}_Φ :

$$\mathbf{U}_\Phi = (M_\Phi, M_\Phi u_\Phi, M_\Phi v_\Phi, R_\Phi h_\Phi, E_\Phi h_\Phi, h_\Phi, M_\Phi w_\Phi, N_K, M_w)^T. \quad (2)$$

The vector equation Eq. 1 is defined in a horizontal X - Y coordinate system. The elevation of the mountain profile $Z(X, Y)$ is specified for each (X, Y) coordinate pair. This information is used to define the local surface (x, y, z) coordinate system with the directions x and y parallel to the geographic coordinates X and Y . The slope-parallel avalanche velocities are $\mathbf{u}_\Phi = (u_\Phi, v_\Phi)$. The avalanche mass M_Φ and flow height h_Φ (volume) are tracked over time t .

The model equations include an explicit calculation of the dispersive pressure N_K which is induced by mechanical energy fluxes associated with the hard basal boundary and random particle movements. The mechanical energy of the random movements is denoted R_Φ . The dispersive pressure induces slope-perpendicular z -velocities w_Φ causing an expansion of the avalanche core. The density of the avalanche core is therefore not constant, but changes according to the basal boundary conditions. This modelling approach allows us to simulate both "Fluidized" dry avalanches and dense, wet snow avalanches.

The model tracks the total amount of meltwater M_w entrained by the core ($\dot{M}_{\Sigma \rightarrow w}$), or produced by dissipative heating ($\dot{M}_{\Phi \rightarrow w}$). Tracking phase changes facilitates the modelling of wet avalanche flows which are governed by lubricated sliding surfaces (Vera Valero et al., 2015).

The components (Φ_x, Φ_y) are:

$$\Phi_x = \begin{pmatrix} M_\Phi u_\Phi \\ M_\Phi u_\Phi^2 + \frac{1}{2} M_\Phi g' h_\Phi \\ M_\Phi u_\Phi v_\Phi \\ R_\Phi h_\Phi u_\Phi \\ E_\Phi h_\Phi u_\Phi \\ h_\Phi u_\Phi \\ M_\Phi w_\Phi u_\Phi \\ N_K u_\Phi \\ M_w u_\Phi \end{pmatrix}, \quad \Phi_y = \begin{pmatrix} M_\Phi v_\Phi \\ M_\Phi u_\Phi v_\Phi \\ M_\Phi v_\Phi^2 + \frac{1}{2} M_\Phi g' h_\Phi \\ R_\Phi h_\Phi v_\Phi \\ E_\Phi h_\Phi v_\Phi \\ h_\Phi v_\Phi \\ M_\Phi w_\Phi v_\Phi \\ N_K v_\Phi \\ M_w v_\Phi \end{pmatrix}. \quad (3)$$

The flowing avalanche is driven by the gravitational acceleration in the tangential directions $\mathbf{G} = (G_x, G_y) = (M_\Phi g_x, M_\Phi g_y)$ where g_x and g_y are the slope-parallel gravitational accelerations in the x and y directions, respectively. The frictional resistance $\mathbf{S}_\Phi = (S_{\Phi x}, S_{\Phi y})$

consists of both a Coulomb friction S_μ (coefficient μ) and a velocity dependent stress S_ξ (coefficient ξ),

$$\mathbf{S}_\Phi = \frac{\mathbf{u}_\Phi}{\|\mathbf{u}_\Phi\|} [S_\mu + S_\xi]. \quad (4)$$

These acceleration and friction terms are the principle components of the right-hand side vector \mathbf{G}_Φ

$$\mathbf{G}_\Phi = \begin{pmatrix} \dot{M}_{\Sigma \rightarrow \Phi} - \dot{M}_{\Sigma \rightarrow \Gamma} - \dot{M}_{\Phi \rightarrow \Psi} \\ G_x - S_{\Phi x} \\ G_y - S_{\Phi y} \\ \dot{P}_\Phi + \dot{P}_{\Sigma \rightarrow \Phi} \\ \dot{Q}_\Phi + \dot{Q}_{\Sigma \rightarrow \Phi} + \dot{Q}_w \\ w_\Phi \\ N_K \\ 2\gamma \dot{P}_\Phi - 2Nw_\Phi/h_\Phi \\ \dot{M}_{\Sigma \rightarrow w} + \dot{M}_{\Phi \rightarrow w} \end{pmatrix}. \quad (5)$$

The snow entrainment rate is specified by $\dot{M}_{\Sigma \rightarrow \Phi}$. Splashing mass at the front of the avalanche by $\dot{M}_{\Sigma \rightarrow \Gamma}$. Mass detrained by forest interaction by

$$\dot{M}_{\Phi \rightarrow \Psi} = K / \|\mathbf{u}_\Phi\|, \quad (6)$$

where K depends on the tree species, stand density and surface roughness (Feistl et al., 2014).

In this avalanche model the friction S_Φ is made a function of the energy R_Φ (degree of fluidization) and water content (lubrication). The Coulomb friction term decreases to zero $S_\mu \rightarrow 0$ for two extreme avalanche flow regimes: dry fluidized avalanches and dense wet snow avalanches.

The model accounts for fluidization by calculating the free mechanical free energy of the avalanche R_Φ , which is divided into the random *kinetic* energy R_Φ^K and the *configurational* energies R_Φ^V ,

$$R_\Phi = R_\Phi^K + R_\Phi^V. \quad (7)$$

The configurational energy is the potential energy resulting from a volume increase of the core; that is, the expansion of the core and therefore the degree of fluidization.

To model the decrease in friction from fluidization we make the Coulomb stress dependant on the configurational energy R_Φ^V ,

$$S_\mu = \mu(R_\Phi^V, M_w)N \quad (8)$$

where N is the total normal force consisting of the avalanche weight, dispersive pressure and centripetal forces. Higher configurational energies indicate lower flow densities and therefore lower Coulomb friction values.

Note that S_μ is also a function of the meltwater content M_w . High meltwater contents facilitate lubricated sliding surfaces and therefore lower S_μ values.

The velocity dependent stress S_ξ is also a function of the configurational energy

$$S_\xi = \rho_\Phi g \frac{\|\mathbf{u}_\Phi\|^2}{\xi(R_\Phi^V)}. \quad (9)$$

The production of free mechanical energy \dot{P}_Φ , is given by an equation containing two model parameters: the production parameter α and the decay parameter β , see Buser and Bartelt (2009).

$$\dot{P}_\Phi = \alpha [\mathbf{S}_\Phi \cdot \mathbf{u}_\Phi] - \beta R_\Phi^K h_\Phi. \quad (10)$$

The production parameter α defines the generation of the total free mechanical energy from the shear work rate $[\mathbf{S}_\Phi \cdot \mathbf{u}_\Phi]$; the parameter β defines the decrease of the kinetic part R_Φ^K by inelastic particle interactions. The energy flux associated with the configurational changes is denoted \dot{P}_Φ^V and given by

$$\dot{P}_\Phi^V = \zeta \dot{P}_\Phi. \quad (11)$$

The parameter ζ therefore determines the magnitude of the dilatation of the flow volume under a shearing action. When $\zeta = 0$ there is no volume expansion (no fluidization) by shearing. The free mechanical energy produced during entrainment is denoted $\dot{P}_{\Sigma \rightarrow \Phi}$.

Temperature dependent effects are introduced by tracking the depth-averaged avalanche temperature T_Φ within the flow (Vera Valero et al., 2015). The temperature T_Φ is related to the internal heat energy E_Φ by the specific heat capacity of snow c_Φ

$$E_\Phi = \rho_\Phi c_\Phi T_\Phi. \quad (12)$$

The avalanche temperature is governed by (1) the initial temperature of the snow T_0 , (2) dissipation of kinetic energy by shearing \dot{Q}_Φ , as well as (3) thermal energy input from entrained snow $\dot{Q}_{\Sigma \rightarrow \Phi}$ and (4) latent heat effects from phase changes \dot{Q}_w (meltwater production), see Vera Valero et al. (2015).

Dissipation is the part of the shear work not being converted into free mechanical energy in addition to the inelastic interactions between particles that is the decay of random kinetic energy, R_Φ^K

$$\dot{Q}_\Phi = (1 - \alpha) [\mathbf{S}_\Phi \cdot \mathbf{u}_\Phi] + \beta R_\Phi^K h_\Phi. \quad (13)$$

The model equations are solved using the same numerical schemes outlined in Christen et al. (2010). The model stopping criteria used sets that the simulation

Tbl. 1: Model parameter values for the four example cases. The spatial resolution for all avalanches was 2 m. We consider curvature effects and assume a flow density of $\rho = 450 \text{ kg/m}^3$. The density of the released and entrained snow was also assumed to be constant $\rho = 200 \text{ kg/m}^3$. The initial Coulomb friction value $\mu = 0.55$ and cohesion $c = 100 \text{ Pa}$ are similar for all avalanches (Bartelt et al., 2015). Entrainment specifications are: one meter of snow-cover on 1500 m.a.s.l. decreasing 10 cm per 100 m; we assume velocity driven entrainment.

Name	$\xi_0 \text{ [m/s}^2\text{]}$	μ	erodability	ϵ	α	β	R_0
Fahrenberg	1800	0.55	0.3	0.1	0.07	0.8	2.0
Hagenberg	1800	0.55	0.3/0.4	0.1/0.3	0.07	0.8	2.0
Weißwand	1800	0.55	0.3	0.1	0.07	0.8	2.0
Antoniberg	1000	0.55	0.4	0	0.05	1.0	2.0

stops when the moving mass is only 5% of the maximum moving mass (Christen et al., 2010). The derivation of the thermal energy and vertical motion equations are presented at Vera Valero et al. (2015); Buser and Bartelt (2015). The chosen model parameter values for the avalanche simulations on each of the four example slopes are denoted in Table 1.

3. EXAMPLES

3.1 Overview

We investigated four specific example cases where avalanches endanger roads in Bavaria. In several situations road closures were necessary, cutting off alpine communities from surrounding regions. Public authorities need to assure access of public services such as fire department, police and health care. The pressure to keep access roads open increases with the time of closure. In the following sections we present the specific characteristics of each avalanche track, providing safety strategies that take forest management, bombing, technical avalanche prevention measures and road closure into account (Table 2).

3.2 Fahrenberg

The Fahrenbergs' steep ($35^\circ - 45^\circ$) southerly slopes rise above the northern shore of lake Walchensee and avalanches endanger the national highway between the community of Kochel and the village of Walchensee. This road is highly frequented by tourists in winter and the local economy strongly depends on its opening. The Herzogstand cable car provides access to the summit thereby crossing the avalanche track which is investigated in this study. Damage caused by game animals, forest fire and drought stress lead to a considerable decay of the protection forest. New potential avalanche release areas subsequently developed in the last century. Steep rocky gravel impedes tree growth and areas with long compacted

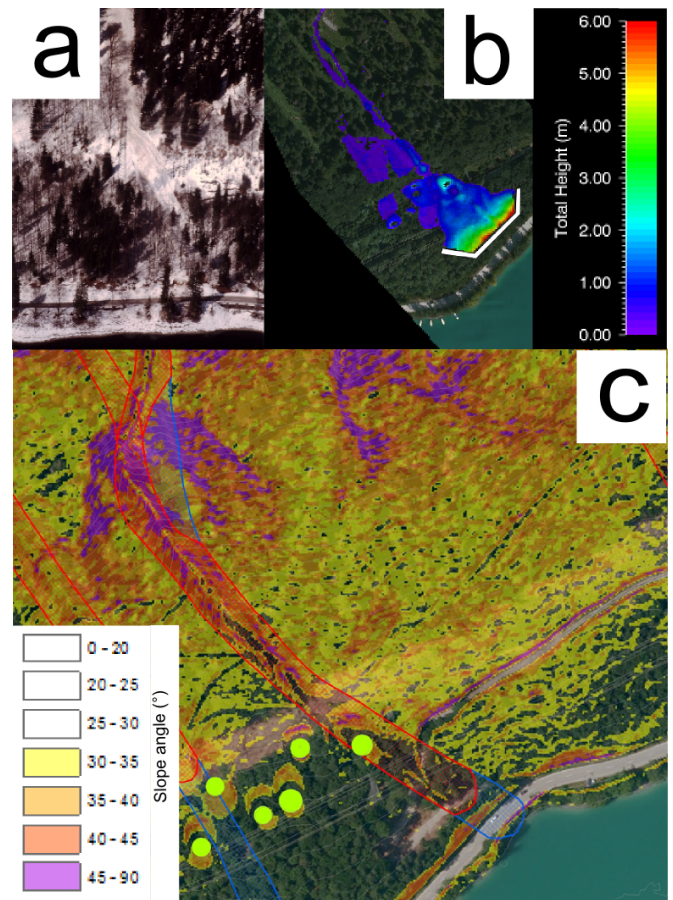


Fig. 1: The Fahrenberg: The aerial photograph shows an avalanche event on the 17th of March 2000 (a). The avalanche ran through a narrow gully and hit the road on several meters length before it ended in lake Walchensee. The red polygon in the excerpt of the Bavarian cadastral avalanche register highlights the lower avalanche path (b). Green dots denote velocity reduction bumps that were built some 50 years ago. A possible protection dam (white polygon) and the accumulated snow from all possible avalanche release areas is shown in picture (c). Following our simulations we expect deposition heights up to 6 m.

Tbl. 2: Characteristics of four slopes that are regularly hit by avalanches which originate from several potential release areas. For each slope we present the range of potential release (M_0), entrainment ($M_{\Sigma \rightarrow \Phi}$) and detrainment ($M_{\Phi \rightarrow \Psi}$) volumes. Note that the release volume M_0 is usually smaller than the entrained volume $M_{\Sigma \rightarrow \Phi}$ as the tracks are narrow and long. Snow build-up behind trees $M_{\Phi \rightarrow \Psi}$ varies according to the length the avalanche runs through forested terrain and the avalanche velocity. In the wet snow case on Antoniberg, where flow velocities are small, the detrained volume is larger than the entrained volume $M_{\Phi \rightarrow \Psi} > M_{\Sigma \rightarrow \Phi}$. For Weißwand we compared simulations with and without forest cover. The altitude level is specified from release to runoff.

<i>Name</i>	M_0 [m^3]	$M_{\Sigma \rightarrow \Phi}$ [m^3]	$M_{\Phi \rightarrow \Psi}$ [m^3]	<i>altitude</i> [<i>m.a.s.l</i>]	T_0 [$^\circ$]	<i>exposition</i>
Fahrenberg	1057 - 2968	1507 - 10542	571 - 3222	1600 - 800	- 5	SSE
Hagenberg	1752 - 2332	2299 - 4251	917 - 1742	1550 - 1000	- 10	NW
Weißwand	2256	1758 - 5286	0 - 958	1400 - 770	- 5	W
Antoniberg	307 - 1433	122 - 355	143 - 512	800 - 630	0	SSW

grass support snow gliding, thereby hindering forest regeneration. Several release areas on Fahrenberg were secured with technical protection measures; snow sheds protect the road. Additionally tree re-growth is supported by wooden tripods and fences to stop snow gliding. Two avalanche events reached the highway in the western part of Fahrenberg in the last decades, increasing the pressure for further protection measures (Fig. 1b). The avalanche in the year 2000 was well documented and followed a period of intense snowfall (Fig. 1a). We suppose a fairly dry snowpack in the upper part of the slope heating up along the track down to 800 m.a.s.l. Potential release areas were defined by analyzing photo and video material from helicopter flights. The maximum three day snow accumulation sum for this region was extrapolated from data measured at a meteorological station close by and used for our model calculations.

3.3 *Hagenberg*

Avalanches that release on the northwesterly slopes of Hagenberg endanger the only access road to the village of Spitzingsee, in winter a highly frequented ski sports center. The pressure on keeping the road open is especially high as fire department, hospital and rescue service are situated in the nearby community of Schliersee. Several avalanche paths further down along the road are secured with technical defense measures and frequent bombing. Avalanche bombing is highly controversial here as important protection forest might be destroyed. In the upper, not protected part of the slope several avalanches released, ran through a dense forest and reached the road in the last decades (Feistl et al., 2014).

The documented events that reached the road all released with dry cold snow conditions. Release areas in the lower part of the avalanche track were defined according to aerial photographs and expert knowledge.

Further release of avalanches in the uppermost part of the slope cannot be ruled out. We therefore calculated two possible scenarios: 1. One avalanche with two release areas in the lower part of the slope which were defined by an analysis of the aerial photographs. In this case we assumed release with a time shift of 10 seconds, such that the first avalanche triggers the second release area. Temperatures were particularly low for this region and we therefore suppose high entrainment rates (erodability: 0.4; epsilon: 0.3, see Table 1). 2. One avalanche that releases above the documented case on a slope where isolated trees grow. Avalanche formation in this area cannot be eliminated.

3.4 *Weißwand*

The westerly slope of Weißwand rises above the national highway between Schneizreuth and Bad Reichenhall. Protection forest management including shooting of game animals, glide-snow protection measures and avalanche fences support the re-growth of forest on a large part of this slope. Damage by game animals made these silvicultural measures necessary. One avalanche event that reached the road is documented in the unsecured westerly part. The question arose if the danger for further events increased after a devastating storm broke a large part of the trees in the upper part of the slope.

We assumed various potential avalanche release areas on the steep upper part of the Weißwand. Forest re-growth and terrain undulations reduce the size of these areas and separate them. In all cases forest effects are important in stopping these avalanches. Model calculations with and without forest were performed to characterize the situation before and after the storm.

A dense young forest developed in the wind sheltered

gully, that was previously an avalanche release area (Fig. 2). Around the gully forest can until now not fully prevent avalanche formation but storm loss starts to be compensated by young trees. Rigorous reduction of the game animal population shows its positive effect here.

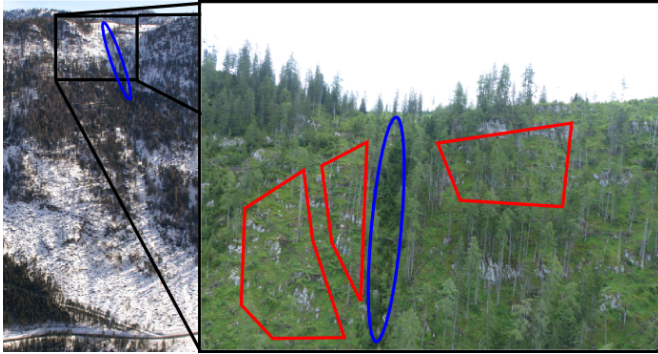


Fig. 2: The left hand side shows the Weißwand slope after it was hit by a destructive storm. The protection forest was destroyed in large parts of the slope. Following this event potential release areas developed (red frame on the right hand side). The gully which is now covered with dense young forest is highlighted with a blue ellipse.

3.5 Antoniberg

The southwesterly steep slopes above the highly frequented national highway between Inzell and Schneizlreuth are called “Antoniberg”. Due to the low altitude and mostly southern exposition wet snow events are to be expected regularly on this slope. The long compacted grass underneath reduces surface friction and is supportive for glide-snow avalanche formation (Feistl et al., 2014). Additionally rain on snow events are typical. New release areas were defined in forest gaps that developed recently due to damage by game animals and droughts. We assume the avalanches to release independently as the release areas are separated through terrain undulations and forest cover. The snow runs down through a shallow gully until it hits the road.

4. RESULTS AND DISCUSSION

4.1 Fahrenberg

Model calculations revealed that a burial of the road from avalanches originating from release areas in the western part of the Fahrenberg is possible, especially with a cold and deep snow-cover. The forest in the lower part of the track has an immense influence on the runout distance of these avalanches and reduces the potential endangered section of the highway to a few

meters. Subsequent to field assessments, simulations and consultations of the local avalanche commission and the cable car management two possible courses of action are discussed by the Bavarian avalanche service to ascertain safety:

1. A collection dam right above the road could catch the expected avalanche snow (Fig. 1b). It would be easy accessible and enough space for deposited snow must be guaranteed. We calculated a maximum deposited snow volume of 32,000 m³ consisting of 17,000 m³ release volume plus 21,000 m³ eroded snow minus 6,000 m³ snow which is detained by forest. The collection dam would at least need to be six meters of height.
2. Alternatively all areas where avalanches can release and reach the road need to be secured with technical defense measures. A potential release area of 20,000 m² was identified where technical defense measures need to be installed. Silvicultural management in the upper part of the slope could decrease the number and area of these release zones and reduce the number of critical events. Regularly avalanche bombing from the cable car in the uppermost section of the slope to secure a ski path decreases potential avalanche release volumes. Forest fire, storm breakage, damage by game animals and bark beetle outbreaks endanger the recovery of the forest, therefore careful management is essential. This set of protection measures would relieve the local avalanche commission and would assure safety for the public, keeping nature and landscape protection in mind.

4.2 Hagenberg

Our simulations show the potential of avalanches to reach the road. Especially cold powder avalanches that release in the upper part of the slope are not stopped by the dense forest along the track. Forest destruction depends on flow height, velocity, snow density, tree diameter and tree species (calculated with equ. 16 in Feistl et al. (2015)) and is denoted in Fig. 3a. The turbulent friction is subsequently increased and the Coulomb friction decreased dependent on the K value if tree breakage is assumed. Additionally the detrainment parameter K was decreased to 20% of its original value as build-up of snow behind trees is minimized. The maximum erosion height was defined according to the altitude level and the forest cover. We assume less erodable snow in forested terrain where interception hinders snowpack accumulation. Forested areas are therefore blueish in comparison to non-forested areas

(yellow/green in Fig. 3c). The amount of snow that is detained by trees is relatively small due to the high velocity of the cold snow and the reduced detrainment rates after forest destruction (Fig. 3b).

Protection measures need to consider the important role of the forest. Light fences that allow forest re-growth are the best option in the uppermost part of this slope.

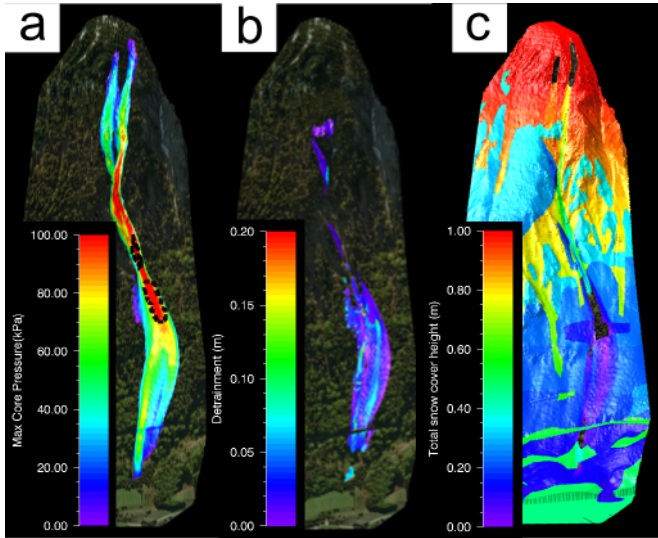


Fig. 3: Simulation results for the upper release area on Hagenberg. The maximum core pressure is shown in (a). Calculated tree destruction is highlighted with black dashes. The detained snow which is removed by trees is shown in the second picture (b). The maximum erodable snow-cover on the Hagenberg slope is highlighted in (c). It depends on the altitude (1m on 1500 m.a.s.l decreasing by 10 cm per 100 m) and on the forest cover (Maximum erosion height is a function of the forest parameter K.).

4.3 *Weißwand*

Our model calculations underline the protective effect of the forest. Forest destruction by the storm was compensated with high roughness of the dead wood and stumps which were kept in the release zone. Recently re-growth of young trees partly fulfill the protective function in these areas, especially in the distinctive gully. Rapid re-growth of the young forest in the lower part of the slope is expected to ensure safety for the road in the future. Temporal technical defense measures, however, need to be taken into account.

4.4 *Antoniberg*

Two possible events where the road gets hit by a wet snow avalanche were revealed by the model calculations (Fig. 4). These are the avalanches

with the largest release volumes. We are convinced that a healthy protection forest would hinder avalanche formation, reduce release area size and therefore prevent avalanches to reach the road. Conditions for forest regeneration are generally good; however, game animals and gliding snow suppress young tree growth and undermine forest management interventions. We suggest therefore a considerable reduction of the game animal population and fences to protect the young plantations. Glide-snow is an issue and should be reduced for example with wooden tripods. Temporal technical defense measures need to be considered if road opening needs to be assured.

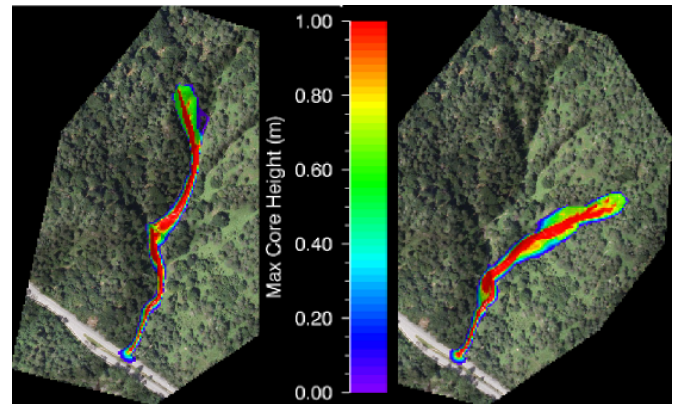


Fig. 4: We present the simulations of two avalanches that release on Antoniberg and reach the road. We always assume wet snow conditions to take exposition and altitude level of this slope into account. Several other potential release areas are too small to reach the highway.

5. CONCLUSIONS

To evaluate avalanche protection measures against small to medium sized avalanches that run through forested terrain, avalanche flow dynamics, forest composition and small-scale terrain features must be taken into account. Avalanche dynamics simulations are a helpful tool to evaluate different hazard scenarios and quantify the effectiveness of different mitigation methods. Model applications highlight the need to simulate:

- snow interception by trees which lowers entrainable snow heights in forest terrain,
- the amount of snow that is stopped by trees. This strongly depends on forest stand characteristics, surface friction and avalanche flow regime.
- the change in avalanche behaviour when trees are broken and entrained in the flow

- the avalanche flow regime which changes from dry to wet snow, from fast (fluidized) to slow (but lubricated). Thus, avalanche phase transitions have an influence on forest detrainment rates and tree breakage.

These processes have been parameterized and included in our model calculations. Clearly, model applications require the specification of a new set of snow-cover boundary conditions, including snow-cover heights and temperature distribution in forested (low-elevation) terrain. Our case studies show that engineers need to evaluate various scenarios and only knowledge on individual processes can guarantee an optimal avalanche defense strategy for a specific slope. Comparison of model calculations to documented events, both dry and wet, therefore remains a priority in avalanche practice. Each comparison would help identify how our understanding of avalanche flow in forests can be improved in order to evaluate mitigation methods and the role of ecological and manmade disturbances in forest-avalanche practice.

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