FOREST DAMAGE BY WET AND POWDER SNOW AVALANCHES

Thomas Feistl[1,2,*], Peter Bebi[1], Stefan Margreth[1] and Perry Bartelt[1]
[1] WSL Institute for Snow and Avalanche Research SLF, Davos Dorf, Switzerland
[2] Technical University Munich (TUM), Munich, Germany

ABSTRACT: Wet and powder snow avalanches can break, uproot and overturn trees, causing widespread damage to forests. Mapping the extent of forest damage is a useful method to estimate and delineate the avalanche pressure field and therefore a valuable tool in mitigation studies. The impact forces of avalanches on trees, however, depend strongly on the avalanche flow regime. In this paper, we analyzed the flow dynamics of two characteristic avalanche types with the goal of relating avalanche flow regime to forest damage. Powder avalanches are characterized by a high velocity but low density suspension cloud. Evergreen trees oppose a large area to the powder blast and are prone to overturning. The destructive force of powder clouds is governed primarily by their expansion velocity, height and density. In comparison, wet snow avalanches have lower velocity and higher density. Plug-like wet snow avalanches exert large quasi-static forces at lower stem heights. Using an avalanche dynamics model that simulates both powder and wet snow avalanches, we studied two well-documented case studies. A critical impact force could be found for specific tree types independent of the avalanche flow regime. We also found that the forces exerted by wet snow avalanches cannot be calculated with velocity dependent drag laws. We propose a method to determine wet snow avalanche pressures on trees by calculating the quasi-static forces which depend on the avalanche volume and terrain features. Our work contributes to the general understanding of tree-avalanche interaction and enables the prediction of forest damage in avalanche modeling.

KEYWORDS: avalanche dynamics, forest damage, modeling.

1. INTRODUCTION

Forest damage caused by avalanches reveals the complex and highly variable nature of avalanche flow. Avalanches cut through forests leaving paths of broken and fractured tree stems, overturned root plates and torn branches (de Quervain, 1979; Bartelt and Stöckli, 2001) (Fig. 1). The ground is covered with woody debris interlaced with dirty avalanche snow. Powder clouds often displace further than the avalanche core, causing massive blow-downs, leaving the tree stems pointing in the direction of the cloud velocity. The reach of the powder clouds is visible by studying which trees still have snow held in their branches. This destruction (and non-destruction) provides important information concerning the spatial distribution of the impact pressures exerted by both the avalanche core and powder cloud.

In recent years the problem of avalanche-forest interaction has received renewed interest. This is due to the ability of forests to hinder and stop small and frequent avalanches (Feistl et al., 2014; Teich et al., 2012). These studies have concentrated on the stopping effect of

Fig. 1: Woody debris after avalanche cut through forest.

forests without damage. However, damaged protection forests increase the risk for subsequent avalanches and other natural hazards such as rockfalls and debris flows. Natural disturbances such as bark beetle outbreaks, forest fire or windthrow can alter forest structure and therefore the protective capacity. Economic loss for forest owners and negative ecologic implications are

* *Corresponding author address:* Thomas Feistl,
WSL Institute for Snow and Avalanche Research SLF,
Davos, Switzerland;
email: thomas.feistl@slf.ch

additional consequences of avalanche-forest interaction (Bebi et al., 2009; Weir, 2002). Our primary interest, however, is to exploit recent advances in modeling avalanche flow regimes (Bartelt et al., 2011; Buser and Bartelt, 2009; Vera et al., 2014) to predict forest damage and therefore improve the inclusion of forests in avalanche dynamics calculations. The protective capacity of forests depends strongly on the ability to survive avalanche loading, which depends on the avalanche flow regime and impact intensities.

The degree of destruction depends on both the avalanche loading and tree strength. Trees break if (1) the bending stress exerted by the moving snow exceeds the bending strength of the tree stem (Johnson, 1987; Peltola and Kellomäki, 1993; Peltola et al., 1999; Mattheck and Breloer, 1994) or (2) if the applied torque overcomes the strength of the root-soil plate, leading to uprooting and overturning (Coutts, 1983; Peltola and Kellomäki, 1993). Avalanche loading is more difficult to define. It depends primarily on the avalanche flow regime and the forest structure, which is not regular. To define the avalanche loading, flow variables such as avalanche density, velocity and height must be known. These vary not only along the track but also in the flow width and with flow height. The best example is the structure of dry, mixed avalanche containing both a flowing core and powder cloud. The core also varies in the streamwise flow direction between the avalanche head and tail.

Pressures from fast moving avalanches ($Fr > 1$) appear to be well modeled by the equation

$$p = c_d \rho \frac{u^2}{2}. \tag{1}$$

This formula cannot be applied to predict quasi-static wet snow avalanche pressures (Thibert et al., 2008; Sovilla et al., 2010). Eq. 1 accounts for the local momentum exchange between the avalanche and the obstacle. It does not account for pressures arising from the transfer of static pressures to the obstacle. This is a mechanically indeterminate problem involving the interplay between the gliding surface (controlling the force transfer to the ground) and other terrain features in the immediate vicinity of the obstacle. Wet snow avalanche pressure resembles the static snow pressure exerted on obstacles by snow gliding. Snow forces by creep and glide have been studied by In der Gand and Zupančič (1966); Margreth (2007b) and formulas have been invented quantifying the mechanisms of gliding.

In this paper, we define four loading cases to represent four different avalanche flow regimes. These are *powder*, *dry*, *intermittent* and *wet*. The wet flow regime requires an equation to describe the indeterminate, quasi-static loading. We compare the loadings to tree strength to find the critical flow properties (density, velocity, height) for a particular flow regime to break trees. We assume breaking is always in bending.

2. AVALANCHE LOADING

2.1 Moment and Stress

In the following we use the double prime superscript to denote a pressure p''; that is a loading per square meter. A single prime p' denotes a force per unit height of the trees and a value without superscript denotes the total force p acting on the tree. Because trees grow vertical to the slope and the avalanche applies a pressure in the slope parallel direction, the loading p is related to the avalanche impact pressure p'' by

$$p = p'' A \cos \alpha \tag{2}$$

where A is the loading area of the tree, which depends on the affected height and width of the tree. The angle α defines the slope inclination (see Fig. 2).

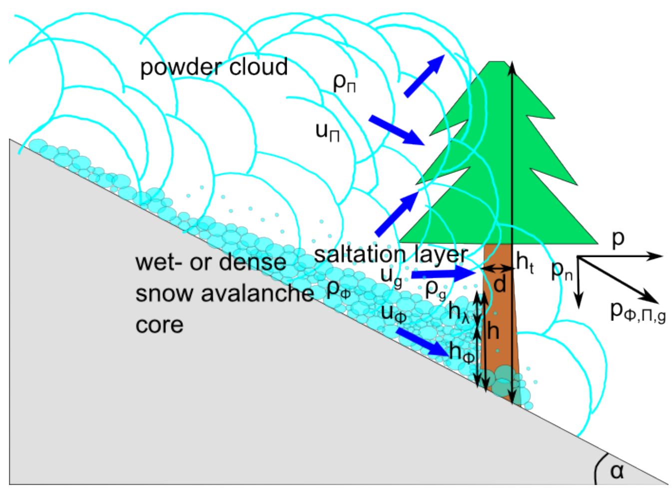

Fig. 2: Schematic illustration of an avalanche with velocity u on a slope with angle α hitting a tree. The avalanche has three parts: 1. the powder cloud (Π), 2. the saltation layer (g) and 3. the wet- or dense flow avalanche core (Φ). The density depends on the flow regime and is denoted ρ_Π for powder clouds, ρ_g for the saltation layer, $\rho_{d\Phi}$ for dry snow avalanche cores and $\rho_{w\Phi}$ for wet snow avalanches. Flow height is denoted h_Φ, stagnation depth h_λ, the total flow height affecting the tree h and the height of the tree h_t. The diameter of the stem is assumed to be constant $d(z) = d$. The pressure force of the avalanche $p_{\Pi,\Phi,g}$ is acting parallel to the slope and can be split in a vertical part due to gravitation p_n and a force acting perpendicular to the tree p.

The total force p with the moment arm defines the torque M and therefore determines the bending stress σ within the tree. The bending stress is related to the applied moment by the relation:

$$\sigma = \frac{Md}{2I} \tag{3}$$

where d is the diameter of the tree and I is the cross-sectional moment of inertia. As we assume round tree trunks, $I = \frac{\pi d^4}{64}$ and therefore

$$\sigma = 32\frac{M}{\pi d^3}. \tag{4}$$

The bending stress is calculated from the maximum torque, which is located at the stem base. In the analysis we make use of Mattheck's observation that the tree grows in relation to the applied forces from the natural environment, for example wind (Mattheck and Breloer, 1994). This implies that the tree strength σ_t in relation to the applied moment is constant and must only be determined at one point. We choose this point to be the tree stem base. It also implies that the moments to break the tree in bending and to overturn the tree are similar (Bartelt and Stöckli, 2001). Trees do not always break at the stem base, especially if loaded by wind or powder clouds, but we assume the bending stress to be independent of the breaking height. The initial snow height before the avalanche is another factor which we disregard in this article. We assume the avalanche to flow close to the slope surface. An avalanche flowing on a deep snow cover hits the tree higher up on the stem and will exert a larger moment. Snow on branches increases the self-weight of trees and can in addition to bending increase the loading. The bending stresses we calculate here are therefore minimum values, that can be higher for deep snow covers and snow loading on branches.

We define four avalanche impact pressures (p''_Π, p''_g, $p''_{d\Phi}$, $p''_{w\Phi}$) depending on two avalanche type regimes, dry and wet respectively, see Tbl. 1.

2.2 Dry, Mixed Avalanche Loading p''_Π, p''_g, $p''_{d\Phi}$

A dry mixed flowing avalanche exerts three different loadings, p'' on a tree. These arise from the powder cloud p''_Π, the flowing core $p''_{d\Phi}$ and the intermittent loading from granules contained in saltation like layers p''_g. The powder cloud has density ρ_Π, height h_Π and velocity u_Π whereas the flowing core has density $\rho_{d\Phi}$, height h_Φ and velocity $u_{d\Phi}$.

Powder Cloud Loading p''_Π

According to the Swiss guidelines on avalanche dynamics (Salm et al., 1990) and the report from the European commission on the design of avalanche protection dams (Johannesson et al., 2009) the pressure exerted on a narrow obstacle is calculated according to

$$p''_\Pi = c_t \rho_\Pi \frac{u_\Pi^2}{2}, \tag{5}$$

where c_t is the drag factor depending on the tree species and wind speed (Mayhead, 1973). Mayhead (1973) derived an average value of c_t = 0.4 for different tree species in Great Britain in wind tunnel experiments for wind speeds of u = 25 m/s . We adopt this value for the powder cloud loading. The total force is

$$p = p''_\Pi w_t h_t \cos\alpha. \tag{6}$$

The total force p depends on the powder cloud height h_Π and on the tree height h_t. We assume the powder cloud to be larger than the tree height $h_\Pi > h_t$. The quantity w_t is the loading width of the tree. In this first analysis we assume the width to be constant over height $w_t(z)$ = w_t as indicated in Fig. 3. The loading width depends on the location of the tree in the forest (Indermühle, 1978). Single trees in the avalanche path have a larger loading width than trees in dense forest stands. Leafless trees have smaller loading widths than evergreen trees (Fig. 3). Larch and birch trees for example have smaller loading widths than spruce or pine trees.

The total momentum that is applied on the tree by the powder cloud is therefore

$$M_\Pi = c_t \rho_\Pi \frac{u_\Pi^2}{4} w_t h_t^2 \cos\alpha. \tag{7}$$

The bending stress of a powder cloud flowing over a tree is

$$\sigma_\Pi = 8 c_t \rho_\Pi \frac{u_\Pi^2}{\pi d^3} w_t h_t^2 \cos\alpha. \tag{8}$$

Intermittent Loading p''_g

According to Bozhinskiy and Losev (1998) is the pressure exerted by a snow clod of the suspension layer defined as

$$p''_c = \rho_c \frac{4u_g^2}{3}. \tag{9}$$

The impact pressure exerted by the saltation layer p''_g is the sum of the point loads exerted by the clods $\sum p''_c$ on the tree. The clod densities can be large ($\rho_c > 300$ kg/m^3). The number of clods that hit the tree per unit time depends on the speed of the avalanche and the height and density of the intermittent layer. Assuming an intermittent layer density of ρ_g = 30 kg/m^3 only a few clods will hit the stem at the same time. In this short paper we will not consider the intermittent loading for the bending stress analysis, although we recognize that the forces from individual particles can be large.

Tbl. 1: Denotation for the different flow regimes: ρ for density, h for the flow height, u for the velocity and p'' for the impact pressure per m^2. The load is distributed linearly along the tree besides the intermittent loading by the saltation layer which exerts the loading pointwise.

Flow regime		*Density*	*Flow height*	*Velocity*	*Impact pressure*	*Loading*
dry, mixed	powder	ρ_Π	h_Π	u_Π	dynamic, p''_Π	linear distributed
	intermittent	ρ_g	granule diameter	$u_{d\Phi}$	granular impact, p''_g	point
	dense	$\rho_{d\Phi}$	h_Φ	$u_{d\Phi}$	dynamic, $p''_{d\Phi}$	linear distributed
wet	creep and glide	$\rho_{w\Phi}$	h_Φ	$u_{w\Phi}$	quasi-static, $p''_{w\Phi}$	linear distributed
	gliding block	$\rho_{w\Phi}$	h_Φ	$u_{w\Phi}$	quasi-static, $p''_{w\Phi}$	linear distributed

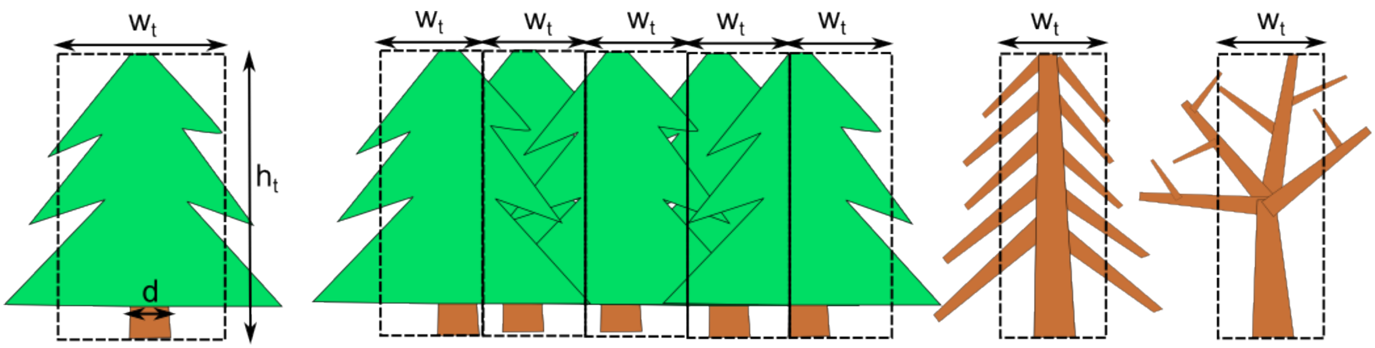

Figure 3: The loading width of the tree depends on the location in the forest. In dense forest stands tree crowns tend to be narrower than if they stand alone. Additionally the loading width w_t depends on the foliation of different tree species.

Dry Flowing Core Loading $p''_{d\Phi}$

The pressure per unit area that a dense flowing avalanche exerts on a tree is calculated similarly to the powder cloud loading except that now we consider the avalanche core Φ:

$$p''_{d\Phi} = c_t \rho_{d\Phi} \frac{u^2_{d\Phi}}{2}. \tag{10}$$

Fluidization leads to bulk avalanche flow densities ρ_Φ that vary in the streamwise flow direction. Values for c_t for cylindrical obstacles (trees) are in range between $1 < c_t < 2$ depending on the literature (McClung and Schaerer, 1985; Norem, 1991). For our analysis we chose c_t = 1.5 according to Johannesson et al. (2009) for trees in dry flowing avalanches. We assume the fluidized height h_Φ of the avalanche to be located beneath the tree crown and therefore the loading width is equal to the stem diameter $w_t = d$, therefore

$$\sigma_{d\Phi} = c_t \rho_{d\Phi} \frac{8u^2_{d\Phi}}{\pi d^2} \left(h_\Phi + \frac{u^2_{d\Phi}}{2g\lambda} f(d/h_\Phi) \right)^2 \cos\alpha. \tag{11}$$

The loading is adjusted to account for the stagnation height h_λ

$$h = h_\Phi + h_\lambda. \tag{12}$$

The stagnation height is calculated according to the Swiss guideline formula

$$h_\lambda = \frac{u^2_\Phi}{2g\lambda} f(d/h_\Phi), \tag{13}$$

where $f(d/h_\Phi)$ = 0.1 Salm et al. (1990) for a flow height $h_\Phi >> d$. Furthermore, λ = 1.5 for fluidized flows.

2.3 *Wet Avalanche Loading* $p''_{w\Phi}$

The pressure formula Eq. 1 has been applied to back-calculate measurements of pressure exerted by wet snow avalanches on obstacles (Sovilla et al., 2010). Application of this formula to the wet snow avalanche problem assumes that the pressures arise from a slow drag flow regime. However, to model the measured pressures with the observed avalanche velocities requires using unrealistic and non-physical drag coefficients, $c_t > 2$. This fact suggests that the nature of the wet snow avalanche pressure is not dynamic, but similar to quasi-static glide pressures exerted on pylons and defense structures. In the following we will assume that dynamic pressures are small in comparison to the static pressure arising from the weight of the snow that loads the tree. Our assumption is based on observations of wet snow avalanche deposits and levees formation (Bartelt et al., 2012; Feistl et al., 2014). Often wedges of snow pile up behind an obstacle. The avalanche flows around these stationary pile-ups; shear planes develop. Any dynamic force must be transferred by frictional mechanisms across the shear planes separating the stationary and moving snow. We assume these dynamic forces to be small and that the total force acting on the obstacle depends on the distribution of static forces behind the obstacle. This is an indeterminate problem because it depends on the terrain and roughness in the vicinity of the obstacles. Therefore, we assume that the applied pressure cannot be represented by Eq. 1 which describes only the local transfer of momentum and not the static weight of the avalanche pushing on the obstacle.

We present the application of two possible alternative calculation methods. The first is based on the Swiss guidelines on avalanche protection measures (Margreth, 2007a) and the report of the European commission (Johannesson et al., 2009). The second method was used to investigate the formation of glide snow avalanches, based on the failure of the stauchwall (Bartelt et al., 2012; Feistl et al., 2014). In this model the stauchwall is replaced by the tree. The model is similar to the approach developed by In der Gand and Zupančič (1966) to find glide-snow pressure acting on obstacles.

Glide Snow Pressure

We apply the snow pressure model developed by Salm (1978) and Häfeli (1967), which is applied in the Swiss Guidelines on avalanche prevention (Margreth, 2007a) to calculate the snow pressure of snow gliding:

$$p''_{w\Phi} = \rho_{w\Phi} g K N \eta \frac{h_\Phi}{2\cos\alpha} \quad (14)$$

where

$$K = \left(2.5\left(\frac{\rho_{w\Phi}}{1000}\right)^3 - 1.86\left(\frac{\rho_{w\Phi}}{1000}\right)^2 + 1.06\left(\frac{\rho_{w\Phi}}{1000}\right) + 0.54\right)\sin(2\alpha) \quad (15)$$

is the creep factor, N the gliding factor and

$$\eta = 1 + c\frac{h_\Phi \cos\alpha}{d} \quad (16)$$

the efficiency factor.

According to Eq. 4 the bending stress is calculated by

$$\sigma_{w\Phi} = 8\rho_{w\Phi} g K N \eta \frac{h_\Phi}{\pi d^2}\left(h_\Phi + \frac{u_{w\Phi}^2}{2g\lambda} f(d/h_\Phi)\right)^2, \quad (17)$$

Gliding Block Model

A second method was also developed to calculate glide snow pressure by In der Gand and Zupančič (1966). In this method the snow exerts a static pressure on the tree (Fig. 4). The magnitude of the static pressure depends on the volume of snow captured. The pressure will be highest before a wedge with shear planes develops behind the tree. The angle γ and the length l are used to define the volume, see Fig. 4. The volume length γ depends on the location of the tree in the forest and the forest structure, because pressure can be distributed to other tree groups in the forest. The volume length l depends on the terrain and the avalanche length. It increases for open slopes and long avalanches and decreases for rough, twisted avalanche tracks where surface elements and channel sides take up the avalanche pressure. Surface roughness is parameterized with the Coulomb friction coefficient μ.

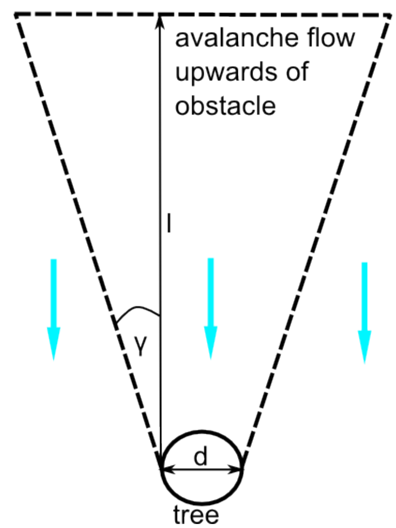

Fig. 4: Schematic illustration of a wet snow accumulation behind a tree. The volume of the snow depends on the volume angle γ, the volume length l and the width of the tree d.

The quasi-static pressure of the avalanche in this case is therefore

$$p''_{w\Phi} = \rho_{w\Phi} g h_\Phi l (l\tan\gamma + d)\cos\alpha(\sin\alpha - \mu\cos\alpha). \quad (18)$$

The bending stress of the avalanche on the tree is then

$$\sigma_{w\Phi} = \frac{16}{\pi d^2}\rho_{w\Phi} g h_\Phi l (d + l\tan\gamma)(\sin\alpha - \mu\cos\alpha) \left(h_\Phi + \frac{u_{w\Phi}^2}{2g\lambda} f(d/h_\Phi)\right)^2 \cos\alpha^2. \quad (19)$$

Tbl. 2: Bending strength of different tree species according to Grosser and Teetz (1985). Note that these values are average values and vary depending on the healthiness, the location in the forest and other stand characteristics.

	Spruce	*Larch*	*Scots Pine*	*Maple*	*Beech*	*Birch*
Bending strength σ_t [MN/m^2]	66 - 78	93 - 99	80 - 100	95 - 112	105 - 123	120 - 147

2.4 Tree Breaking

Trees break if the bending stress exceeds the bending strength of the tree $\sigma > \sigma_t$. The stability of a tree depends on its position in the forest, on its healthiness and on its species. Grosser and Teetz (1985) listed the bending strengths σ_t of various tree species of the European Alps (Tbl. 2). According to Tbl. 2 the bending stress of avalanches to destroy mature trees must exceed a minimum value of $\sigma >$ 66 MN/m^2. Spruce is the species with lowest strength whereas birch is the strongest species growing in alpine terrain in Europe.

3. EXAMPLES AND DISCUSSION

3.1 Wet snow avalanche Monbiel, 2008

A large wet snow avalanche released in winter 2008 near Monbiel, Switzerland and destroyed a small spruce forest before it stopped in the river bed of the Landquart. An approximation of the flow velocity and flow height was possible by analyzing a movie documentation (Sovilla et al., 2012). The deposition height was measured using laser scan. Subsequently this avalanche was simulated by Vera et al. (2014) with the avalanche modeling software RAMMS, applying a new model extension that accounts for random kinetic energy fluxes and snow temperature. They compared the model results with the data and Vera et al. (2014) found the calculated velocities, flow heights and deposition heights to resemble the real avalanche. These calculations allowed us to determine the parameters necessary to calculate the impact pressure, flow height h_Φ = 3 m and velocity $u_{w\Phi}$ = 5 m/s. The slope angle at the location of the spruce forest was α = 10°. We assume the density of the snow $\rho_{w\Phi}$ = 450 kg/m^3 as the avalanche was wet. The stem diameter was approximately d = 0.5 m.

3.2 Powder Snow Avalanche Täsch, 2014

A dry snow, powder avalanche released on March 4, 2014 in Täsch in Wallis, Switzerland. The road and the rail tracks to Zermatt were buried in deep snow. Pictures from a helicopter and our visit to the site the next day allowed us to reconstruct the avalanche volume, deposition patterns and forest damage along the track. We used a DGPS device to measure the deposition heights along the track. Velocities, flow height and the powder cloud diffusion were modeled with the extended RAMMS version. The simulations enabled us to calculate bending stresses of the dry flowing avalanche core $\sigma_{d\Phi}$ and the powder part σ_Π. The avalanche core was flowing with an approximate speed, $u_{d\Phi}$ = 25 m/s, flow height h_Φ = 3 m and a density of $\rho_{d\Phi}$ = 300 kg/m^3. The powder cloud had a density ρ_Π = 5 kg/m^3, velocity u_Π = 30 m/s and a flow height h_Π higher than the trees it passed and destroyed. One larch that broke had an approximate stem diameter d = 0.5 m and its height was h_t = 30 m.

3.3 Bending Stresses

We calculated the bending stresses exerted on the destroyed trees for these two avalanches: σ_Π, σ_g, $\sigma_{d\Phi}$ and $\sigma_{w\Phi}$. The constants N, c, c_t, $f(h_\Phi/d)$, λ were chosen according to the Swiss guidelines (Margreth, 2007a) (Tbl. 3).

The avalanche in Monbiel consisted of wet snow and therefore we tested the three applicable approaches to calculate the impact pressure on the trees. 1. The dynamic approach resulted in $\sigma_{d\Phi}$ = 5 MN/m^2, assuming c_t = 5; 2. $\sigma_{w\Phi}$ = 15 MN/m^2 for the creep and glide approach assuming extreme gliding (N = 3, c = 2) and $\sigma_{w\Phi}$ = 81 MN/m^2 with the gliding block model, for a volume length l = 30 m which is reasonable for the slope above the first trees and γ = 25°.

Bending stresses exerted on the larch tree in the avalanche track in Täsch were calculated for the powder cloud σ_Π and the dense flowing part $\sigma_{d\Phi}$. The powder cloud was higher than the tree top and the width of the tree was assumed to be small as the larch was leafless, therefore w_t = 3 m. We calculated bending stresses σ_Π = 93 MN/m^2 exerted from the powder cloud and $\sigma_{d\Phi}$ = 71 MN/m^2 for the dense flowing core.

3.4 Static Pressure vs. Dynamic Pressure

The dynamic pressure approach (Eq. 10) does not predict avalanche pressures for wet snow avalanches which are high enough to break trees (Tbl. 3). Even for c_t = 5, is $\sigma_{w\Phi} <$ 10 MN/m^2 for velocities below 10 m/s. Wet snow avalanches hardly exceed velocities of $u_{w\Phi}$ = 10 m/s. Our calculations correspond to pressure measurements captured in the Vallee de la Sionne test

Tbl. 3: σ for constant slope angle α = 20° for the avalanche in Täsch and α = 10° for the avalanche in Monbiel, g = 9.81 m/s^2, c_t = 1.5 for the avalanche core (Φ) and c_t = 0.4 for the powder snow avalanche (Π). For the snow pressure model we assume c = 2, N = 3.0. To calculate the stagnation height h_λ we chose λ = 1.5 and $f(h_\Phi/d)$ = 0.1 according to the Swiss guidelines (Margreth, 2007a). To calculate the pressure with the snow block model we assume a volume length l = 30 m, γ = 25° and the friction on the ground or on the gliding surface μ = 0.1. For powder snow avalanches we assume a tree of height h_t = 30 m and w_t = 2 m for the larch in Täsch (Indermühle, 1978).

Avalanche type	ρ *[kg/m^3]*	$h_{\Phi,\Pi}$ *[m]*	u *[m/s]*	d *[m]*	σ *[MN/m^2]*	p'' *[kN/m^2]*
powder (dynamic)	5	30	$>$ 30	0.5	93	1
dry (dynamic)	300	3	25	0.5	71	140
wet (dynamic)	450	3	5	0.5	5	28
wet (creep and glide, snow pressure model)	450	3	5	0.5	15	77
wet (glide, snow block model)	450	3	5	0.5	81	426

site (Sovilla et al., 2010), that could not been explained with dynamic drag terms. The creep and glide model (Salm, 1978) provides values $\sigma_{w\Phi}$ = 15 MN/m^2. Bending stresses above the bending strength of spruces are calculated with the gliding block model $\sigma_{w\Phi}$ = 81 MN/m^2. Impact pressures of the powder cloud are high enough to break the larch in Täsch σ_Π = 93 MN/m^2. The dense core pressures are slightly below the bending strength of larch $\sigma_{d\Phi}$ = 71 MN/m^2.

4. CONCLUSIONS

To investigate how snow avalanches destroy forests, we developed three flow regime dependent impact formulas. These are *powder*, *dry dense* and *wet dense*. The impact formulas were tested on two case studies Monbiel and Täsch, involving a wet snow avalanche and a dry mixed flowing avalanche with powder part.

Dry and powder snow avalanches exert dynamic pressures on the tree stem and the crown. The destructive potential of powder clouds depends on the crown area that is affected by the snow blast and the velocity of the avalanche. The crown area varies with tree position in the forest and on the foliation. Single, evergreen trees are exposed to the full avalanche blast and bending stresses are higher than for leafless trees sheltered in clustered forest stands. Destructive pressures can easily be reached even if the density of the snow-air mixture is low. For evergreen trees such as spruce we calculated a powder cloud speed $u_\Pi > 20$ m/s to be sufficient to break them whereas the leafless larch requires $u_\Pi > 30$ m/s to be damaged. The impact pressure from the fluidized core of a dry snow avalanche can reach destructive values if the velocity is high enough ($u_{d\Phi} > 20$ m/s). Trees can break even if the force is only applied on the stem.

Destructive pressures by wet snow avalanches were back-calculated using two quasi-static modeling approaches and the dynamic approach. The gliding block model provided the highest bending stresses and the most realistic results. The glide snow pressure model underestimated the applied loading. Dynamic models could not reproduce the bending stresses required for tree breakage. The unknowns of the block model are the volume length l and the volume angle λ, which depend on the location of the tree in the forest, terrain and avalanche dimensions.

ACKNOWLEDGEMENTS

This work was funded by the Bavarian Environment Agency.

REFERENCES

Bartelt, P., T. Feistl, Y. Bühler, and O. Buser, 2012: Overcoming the stauchwall: Viscoelastic stress redistribution and the start of full-depth gliding snow avalanches. *Geophysical Research Letters*, **39**, 16.

Bartelt, P., J. Glover, T. Feistl, Y. Bühler, and O. Buser, 2012: Formation of levees and en-echelon shear planes during snow avalanche run-out. *Journal of Glaciology*, **58**, 980–992.

Bartelt, P., L. Meier, and O. Buser, 2011: Snow avalanche flow-regime transitions induced by mass and random kinetic energy fluxes. *Annals of Glaciology*, **52**, 159–164.

Bartelt, P., and V. Stöckli, 2001: The influence of tree and branch fracture, overturning and debris on snow avalanche flow. *Annals of Glaciology*, **32**, 209–216.

Bebi, P., D. Kulakowski, and C. Rixen, 2009: Snow avalanche disturbances in forest ecosystems–State of research and implications for management. *Forest Ecology and Management*, **257**, 1883–1892.

Bozhinskiy, A., and K. Losev, 1998: *The fundamentals of avalanche science*. Mitteilungen Eidgenössisches Institut für Schnee- und Lawinenforschung, Davos, 280 pp.

Buser, O., and P. Bartelt, 2009: Production and decay of random kinetic energy in granular snow avalanches. *Journal of Glaciology*, **55**, 3–12.

Coutts, M., 1983: Root architecture and tree stability. *Plant and soil*, **71**, 171–188.

de Quervain, M., 1979: Wald und Lawinen. In: *Mountain Forests and Avalanches*, pp. 219–239.

Feistl, T., P. Bebi, L. Dreier, M. Hanewinkel, and P. Bartelt, 2014: Quantification of basal friction for glide-snow avalanche mitigation measures in forested and non-forested terrain. *Natural Hazards and Earth System Sciences Discussions*, **2**, 2947–2980.

Feistl, T., P. Bebi, M. Teich, Y. Bühler, M. Christen, K. Thuro, and P. Bartelt, 2014: Observations and modeling of the braking effect of forests on small and medium avalanches. *Journal of Glaciology*, **60**, 124–138.

Grosser, D., and W. Teetz, 1985: Einheimische Nutzhölzer. Centrale Marketinggesellschaft der deutschen Agrarwirtschaft GmbH (CMA), Bonn, und Arbeitsgemeinschaft Holz e. V., Düsseldorf.

Häfeli, R., 1967: Kriechen und progressiver Bruch in Schnee, Boden, Fels und Eis. *Schweizerische Bauzeitung*, **85**, 1–9.

In der Gand, H., and M. Zupančič, 1966: Snow gliding and avalanches. *IAHS-AISH Publ.*, **69**, 230–242.

Indermühle, M., 1978: *Struktur-, Alters- und Zuwachsuntersuchungen in einem Fichten-Plenterwald der subalpinen Stufe*. Ph. D. thesis, Eidgenössische technische Hochschule Zürich.

Johannesson, T., P. Gauer, P. Issler, and K. Lied, 2009: *The design of avalanche protection dams. Recent practical and theoretical developments*, Chapter 12, pp. 95–107. European Commission.

Johnson, E.A., 1987: The relative importance of snow avalanche disturbance and thinning on canopy plant populations. *Ecology*, **68**, pp. 43–53.

Margreth, S., 2007a: Lawinenverbau im Anbruchgebiet. *Technische Richtlinie als Vollzugshilfe. Bundesamt für Umwelt, Bern*.

Margreth, S., 2007b: Snow pressure on cableway masts: Analysis of damages and design approach. *Cold regions science and technology*, **47**, 4–15.

Mattheck, C., and H. Breloer, 1994: *Handbuch der Schadenskunde von Bäumen: Der Baumbruch in Mechanik und Rechtsprechung*. Rombach.

Mayhead, G., 1973: Some drag coefficients for british forest trees derived from wind tunnel studies. *Agricultural Meteorology*, **12**, 123–130.

McClung, D., and P. Schaerer, 1985: Characteristics of flowing snow and avalanche impact pressures. *Annals of Glaciology*, **6**, 9–14.

Norem, H., 1991: Estimating snow avalanche pressures on towers. In: *Proceedings of a Workshop on Avalanche Dynamics*.

Peltola, H., and S. Kellomäki, 1993: A mechanistic model for calculating windthrow and stem breakage of scots pines at stand age. *Silva Fennica*, **24-31**.

Peltola, H., S. Kellomäki, H. Väisänen, and V.P. Ikonen, 1999: A mechanistic model for assessing the risk of wind and snow damage to single trees and stands of scots pine, norway spruce, and birch. *Canadian Journal of Forest Research*, **29**, 647–661.

Salm, B., 1978: Snow forces on forest plants. In: *Mountain Forests and Avalanches*, pp. 157–181.

Salm, B., A. Burkard, and H. Gubler, 1990: *Berechnung von Fliesslawinen: eine Anleitung für Praktiker mit Beispielen*. Eidgenössische Institut für Schnee-und Lawinenforschung.

Sovilla, B., M. Kern, and M. Schär, 2010: Slow drag in wet-snow avalanche flow. *Journal of Glaciology*, **56**, 587–592.

Sovilla, B., I. Sonatore, Y. Bühler, and S. Margreth, 2012: Wet-snow avalanche interaction with a deflecting dam: field observations and numerical simulations in a case study. *Natural Hazards and Earth System Sciences*, **12**, 1407–1423.

Teich, M., P. Bartelt, A. Grêt-Regamey, and P. Bebi, 2012: Snow avalanches in forested terrain: influence of forest parameters, topography and avalanche characteristics on runout distance. *Arctic, Antarctic, and Alpine Research*, **44 (4)**, 509–519.

Thibert, E., D. Baroudi, A. Limam, and P. Berthet-Rambaud, 2008: Avalanche impact pressure on an instrumented structure. *Cold Regions Science and Technology*, **54**, 206–215.

Vera, C., K. Wikstroem, Y. Bühler, and P. Bartelt, 2014: Release temperature, snowcover entrainment and the thermal flow regime of snow avalanches. *Journal of Glaciology*, **submitted**.

Weir, P., 2002: *Snow avalanche management in forested terrain*. B.C. Government Publication Services.