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Quantification of basal friction for glide-snow avalanche mitigation measures in forested and non-forested terrain

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Abstract

A long-standing problem in avalanche engineering is to design defense structures and manage forest stands such that they can withstand the forces of the natural snow cover. In this way glide-snow avalanches can be prevented. Ground friction plays a crucial role in this process. To verify existing guidelines, we collected data on the vegetation cover and terrain characteristics of 101 glide-snow release areas in Davos, Switzerland. We quantified the Coulomb friction parameter μ by applying a physical model that accounts for the dynamic forces of the moving snow on the stauchzone. We investigated the role of glide length, slope steepness and friction on avalanche release. Our calculations revealed that the slope angle and slab length for smooth slopes corresponds to the technical guidelines for defense structure distances in Switzerland. Artificial defense structures, built in accordance with guidelines, prevent glide-snow avalanche releases, even when the terrain is smooth. Slopes over 40 m length and 45° steepness require a ground friction of $\mu = 0.7$ corresponding to stumps or tree regeneration to assure protection. Forest management guidelines which define maximum forest gap sizes to prevent glide-snow avalanche release neglect the role of surface roughness and therefore underestimate the danger on smooth slopes.

1 Introduction

Full-depth, glide-snow avalanches are common events on the steep, smooth slopes of the European Alps (In der Gand and Zupančič, 1966; Höller, 2014). Although these slides have relatively small release areas, they endanger roads, railways and other infrastructure. Because glide-snow avalanches are difficult to predict (Dreier et al., 2014), hazard engineers rely on mitigation measures to stabilize the snow cover and prevent glide-snow avalanches from starting. These measures include both artificial defense structures and natural forests (Margreth et al., 2007; Höller et al., 2012). A critical problem for decision makers is to define potential release areas in real terrain and

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understand how terrain and vegetation characteristics influence release and can be managed to defend against glide-snow avalanche hazard.

The mechanics of glide-snow avalanches involves two principle components: the compressive strength of the stauchwall and the frictional properties of the ground (In der Gand and Zupančič, 1966; Häfeli, 1967; McClung, 1975; Bartelt et al., 2012). Glide-snow avalanches typically occur when water accumulates on the snow–soil interface either by melting (because of a warm soil surface) or by melt-water penetration through the snow cover (In der Gand and Zupančič, 1966; Mitterer et al., 2011). As the ground friction decreases because of the melt-water, the lost frictional forces must be taken up in the tensile or compressive zone of the snow cover, otherwise it begins to glide (Fig. 1). Typically, the snow cover breaks first in the tensile zone and a glide-crack (a so-called "Fischmaul") opens. This causes an additional redistribution of stress within the snow cover and leads to a fragile stability governed by the strength of the compressive zone. This zone is termed the stauchwall (Lackinger, 1987; Bartelt et al., 2012). The stauchwall is fixed to the ground, either because the basal surface is rough, or because the slope is flatter leading to large compressive stresses. Any obstacles, such as trees, will help stabilize the snow cover by consuming the additional stress. The distance between obstacles in large part determines the stress redistribution: if the distances are too large, the natural strength of the snow cover will be overcome and snow slides will result (de Quervain, 1979; Höller, 2004).

A key parameter in the mitigation of glide-snow avalanches is therefore the distance between defense structures and the allowable forest clearing size. Different approaches have been addressed to define distances between defense structures and maximum forest gap sizes. The Swiss guidelines on sustainable management of protective forests NaiS (Frehner et al., 2005) for example are based on a statistical evaluation of data mostly gained on a field campaign in Switzerland from 1985 to 1990 (Gubler and Rychetnik, 1991; Meyer-Grass and Schneebeli, 1992). Statements on possible avalanche formation as a function of slope angle and gap length could be drawn, taking ground roughness qualitatively into account (Frehner et al., 2005). These

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guidelines were successfully applied in the past by foresters. Leitinger et al. (2008) developed a spatial snow glide model based on data of two study areas in Austria and Italy. It takes slope angle, surface roughness, slope aspect, winter precipitation and forest stand characteristics into account. Likewise, the technical guidelines for avalanche prevention structures in release areas in Switzerland are based on calculations of the pressure that a slab exerts on a snow bridge (de Quervain and Salm, 1963; Margreth et al., 2007). Slope angle, snow height and the Coulomb friction of the snow on the ground are taken into account.

Although the relationship between slab length and slope angle at which glide-snow avalanches release is well understood (Fiebiger, 1978; Imbeck, 1984; Imbeck and Meyer-Grass, 1988; Gubler and Rychetnik, 1991; Meyer-Grass and Schneebeli, 1992; Leitinger et al., 2008), the important role of ground roughness remains an unknown parameter. Ground friction dictates the force redistribution and therefore the loading on the stauchwall (In der Gand and Zupančič, 1966; McClung, 1975; Höller, 2004; Bartelt et al., 2012). Vegetation can increase the ground roughness significantly (de Quervain, 1979; Fiebiger, 1978; Newesely et al., 2000; Höller, 2001; Leitinger et al., 2008; Schneebeli and Bebi, 2004; Weir, 2002). Although all authors agree that glide-snow avalanche activity is retarded by dense forest stands, the quantification of basal friction as a function of vegetation structure is missing.

In this paper we aim to combine a physical ground friction – stauchwall model with data on glide-snow avalanche release areas to quantify the role of artificial and silvicultural avalanche protection measures. To this end, we collected and analyzed data of the characteristic vegetation cover, terrain and snow characteristics of glide-snow avalanche release areas on the Dorfberg, near Davos, Switzerland. We compare the glide-snow avalanche data with model results and test if existing guidelines are in accordance with our measurements. As the glide-snow avalanche model includes the important role of ground roughness – which is strongly influenced by the vegetation cover – we are able to quantify the friction of the ground cover of our test site. Fi-

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nally we attempt to answer the questions where, when and what elements of terrain roughness are most appropriate for avalanche prevention.

2 Methods

2.1 Observed glide-snow avalanche release areas

Glide-snow avalanches are observed on the Dorfberg, above Davos, Switzerland every season and were documented via time lapse photography in the winters 2011/2012 and 2012/2013 (van Herwijnen and Simenhois, 2012). Their occurrence depends on meteorological conditions such as temperature, snow height, snow stratification and ground temperature (Dreier, 2013; Dreier et al., 2013) but their location in the terrain is almost similar each year. Dreier et al. (2014) mapped the release zones according to the photos (see Fig. 2). We performed a field campaign in autumn 2013 where we collected data on the characteristic vegetation cover, vegetation height h_v, distance to the next obstacle and terrain characteristics of 101 glide-snow avalanche release areas on Dorfberg. The compaction of vegetation due to the snow cover weight was documented on a second field campaign in February 2014.

The south to east facing slope below the Salezer Horn (2536 m) covers 200 ha. The elevation of the observed release areas ranges from 1700 m a.s.l. to 2300 m a.s.l. Grassy slopes, shrubs and forest alternate with stones and small rock walls. We calculated the mean slope angles α and slab lengths l_g of all avalanche release areas using ArcGIS. Release height was estimated with the snow height h_s measured at the meteorological station in Davos. The station is situated at a lower elevation (1560 m a.s.l.) but is not exposed to the sun. The snow height on Dorfberg and therefore the release height of the glide-snow avalanches resemble the snow height measured at the meteorological station in the investigated winters.

We documented the typical vegetation cover of the 101 release areas (Fig. 3) and found four characteristic types of vegetation:

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1. long grass (*Calamagrostis villosa*)
2. short grass (*Nardion* spp.)
3. low dwarf shrubs (*Ericaceae, Vaccinuium, Empetrum*)
4. strong lignified shrubs (*Rhododendron, Juniperus*).

No avalanches were observed in forested terrain. We recorded the dominating vegetation species, if more than one vegetation type was present on a single release area.

The vegetation height h_v was measured in November 2013 and February 2014 (Fig. 4). Our first field study took place in autumn, therefore this vegetation height represents the surface that the first snow fell on. In February 2014 the vegetation heights were measured below the snow cover at representative locations on Dorfberg. We observed a mean height of long compacted grass $h_v < 1$ cm, in contrast to short upright grass with $h_v = 3$ cm, low dwarf shrubs $h_v = 4$ cm and strong lignified shrubs 10 cm $< h_v < 20$ cm (Fig. 4). The snow cover of height $h_s = 0.5$ m compacted long grass to one tenth of the height in autumn. Short grass, low dwarf shrubs and strong lignified shrubs were compacted to one forth of their original height.

As topography contributes to roughness we assume the underlying terrain of the release areas to play an important role in glide-snow avalanche release. Therefore we documented the dominating terrain types and their height h_t for each release area. Typical features we found were smooth, steps, rocks and ridges. We performed a Mann–Withney U test in order to test for correlations between these different vegetation- and terrain types in release areas and other environmental variables.

We parameterized surface roughness using the measured terrain irregularity heights h_t and vegetation heights h_v. This allowed us to relate the observed heights to the calculated friction parameter μ. The heights h_v and h_t are assigned values characteristic to the observed vegetation and terrain types. This is necessary in order to transfer the model results to other field locations.

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2.2 Segregation of avalanches with stauchwall

We selected events where we assume the snow cover below the release area to be fixed to the ground, the so called stauchwall. The mechanical stauchwall model (Sect. 2.3) is applicable for these events. A flatter slope, higher surface roughness or an obstacle (Fig. 5) below the release area are cases where a fixed stauchwall is probable. Several events without stauchwall were neglected in further studies. In particular events with either a drop or with a steeper slope below the release area (Fig. 6) were disregarded. These events were found by comparing the slope angle of the release areas α with the slope angle of the areas below β. If $\alpha < \beta$ we assume no stauchwall to be present. Out of 101 glide-snow avalanches, 67 events were considered with stauchwall.

Vegetation cover and terrain both contribute to ground roughness. We defined three combined categories (see Sect. 3.1) to enable a simplified classification:

1. smooth terrain covered with long compacted grass

2. smooth terrain covered with short upright grass or low dwarf shrubs

3. rocky or stepped terrain covered with shrubs

Only avalanches with stauchwall were considered for this categorization. Long compacted grass always had smooth terrain underneath. We assume this combination of long grass and smooth terrain to form the surface with the lowest friction. Short grass or low dwarf shrubs on smooth terrain was defined as the second category. And the third category was shrubs on steps or rocks. On stepped terrain or on rocky slopes we did not find any grass dominated vegetation.

2.3 Mechanical stauchwall model

To predict glide-snow avalanche release we apply the two-dimensional visco-elastic continuum model of Bartelt et al. (2012). The model divides the snow cover into two

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regions: the sliding zone and the stauchwall (Fig. 7). The sliding zone has length l_m; the stauchwall has length l_s and is fixed to the ground. We assume a snow cover with height h_s and a homogenous density ρ. Therefore, the total mass per unit area of the slab is $m = \rho l_\mathrm{m}$. The snow cover starts to slide downwards once the frictional force on the ground can not withstand the gravitational force of the snow pack and a tensile crack opens at the crown. The tensile force at the crown is lost and must be transferred to the sliding zone and the stauchwall. It is possible that the lost force is balanced entirely by an increase in shear stress at the base of the snow cover. In this case no avalanche will release, but this scenario requires high friction to transfer the lost tensile force into the ground. Moreover, the driving force and the friction resistance are in balance:

$$mg_x = \mu m g_z; \tag{1}$$

where g_x and g_z are the gravitational accelerations in the slope parallel and normal directions, respectively. These depend on the slope angle α. When the interface balances the lost tensile force, it is seen as an increase in the friction μ. It is also possible that the lost force is taken up by the stauchwall. In this case there is an out-of-balance force σ that must be resisted by the stauchwall:

$$m\dot{u}(t) = mg_x - \mu m g_z - \sigma(t) h \tag{2}$$

where $u(t)$ is the displacement velocity of the slab. Because snow is a visco-elastic material, the stauchwall resisting stress σ is time dependent. A simple Burger's model is used to calculate the resisting action of the stauchwall:

$$\ddot{\sigma}(t) + \left[\frac{E_\mathrm{m}}{\eta_\mathrm{m}} + \frac{E_\mathrm{m}}{\eta_\mathrm{k}} + \frac{E_\mathrm{k}}{\eta_\mathrm{k}}\right]\dot{\sigma}(t) + \left[\frac{E_\mathrm{m}E_\mathrm{k}}{\eta_\mathrm{m}\eta_\mathrm{k}}\right]\sigma(t) = \frac{E_\mathrm{m}}{2l_\mathrm{s}}\dot{u}(t) + \frac{E_\mathrm{m}E_\mathrm{k}}{2\eta_\mathrm{k} l_\mathrm{s}}u(t). \tag{3}$$

The visco-elastic constants (E_m, E_k, η_m, η_k) are density and temperature dependent (Von Moos et al., 2003; Scapozza and Bartelt, 2003).

Equations (2) and (3) are a system of two coupled ordinary differential equations that can be solved numerically. Numerical solutions are presented in Bartelt et al.

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(2012). The model predicts the total strain and strain-rates in the stauchwall, $u/2l_s = \dot{\epsilon}$. When the strain-rates exceed a critical value, we consider the stauchwall to fail and an avalanche is released.

The guidelines specify the maximum allowable length between defense structures and the maximum allowable length of forest clearings. For clarity, we denote these allowable lengths l_d and l_f, respectively. The stauchwall is within these lengths. Both guidelines require knowledge of the ground friction, which we have designated μ. For example, the allowable defense structure distance l_d is calculated with friction values between $0.5 \leq \mu \leq 0.6$. Therefore $l_d(\mu,\alpha)$ and $l_f(\mu,\alpha)$ as both guidelines depend on the slope angle α.

Although the technical and forest guidelines are based on different approaches, the aim of both guidelines is similar: within the distance $l_d(\mu,\alpha)$ or $l_f(\mu,\alpha)$ no avalanche should release. On the Dorfberg we have measured the distance between fracture crown and stauchwall; we denote the observed lengths l_g. We have documented the terrain features and vegetation associated with each l_g. Furthermore we have quantified the mean slope angle of each slide observed in the field. That is, we have $l_g(\mu,\alpha)$. If the guidelines are correct, we should have

$$l_d(\mu,\alpha) \leq l_g(\mu,\alpha) + l_s \tag{4}$$

and

$$l_f(\mu,\alpha) \leq l_g(\mu,\alpha) + l_s. \tag{5}$$

where the stauchwall length is denoted l_s and added to the observed slab length l_g. These comparisons should also hold for the mechanical model. That is,

$$l_d(\mu,\alpha) \leq l_m(\mu,\alpha) + l_s \tag{6}$$

and

$$l_f(\mu,\alpha) \leq l_m(\mu,\alpha) + l_s. \tag{7}$$

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We calculated the critical slab lengths (the slab lengths at failure, l_m) for all slope angles mentioned in guidelines. Different friction parameters μ were applied in the model calculations. By comparison we could quantify the friction values we observed in the field. In the model calculations we tested different snow types and snow heights to investigate the role these parameters had on glide-snow avalanche formation.

3 Results and discussion

In this section we compare field data with model predictions and guideline recommendations and discuss our results.

3.1 Results of field observations, $l_g(\mu,\alpha)$

Most releases in the Dorfberg study area where found on long grass (45 avalanches) and on low dwarf shrub vegetation (49 avalanches), whereas only few avalanches released on the vegetation categories "short grass" and strong "lignified shrubs" (Table 1). The categories "short grass" and "low dwarf shrubs" had comparable vegetation heights h_v (Table 1). We subsequently combined these two categories in our data analysis. The mean vegetation height of long grass was 10 cm, whereas the mean vegetation height of short grass, low dwarf shrubs and strong lignified shrubs was 15 cm. These values were measured before the first snowfall. Below the snow cover (measurements taken in February 2014) the heights decreased to $h_v < 1$ cm for long grass, $h_v = 3$ cm and $h_v = 4$ cm for short grass and low dwarf shrubs and $10\text{ cm} < h_v < 20$ cm for strong lignified shrubs. We combined also different terrain types according to their measured irregularity heights h_t (Table 2). Irregularities of smooth terrain and ridges had a mean height of approximately 20 cm in contrast to stepped and rocky terrain with approximately 30 cm. We note that only 5 cm separates the vegetation types and 10 cm separates the two terrain classes. Below the snow cover the differences are even smaller. This is an indication that small height variations can lead to a large difference in surface friction.

The release of glide-snow avalanches on Dorfberg depended strongly on surface characteristics. Releases occurred in steeper terrain in areas with shrubs compared to areas with long grass (Mann–Whitney *U* Test, $p = 0.008$) and on areas with the terrain type “smooth” compared to other terrain types (79 events out of 101). The combination of vegetation- and terrain categories led to clear correlations between glide-snow avalanches and surface characteristics (Table 3). This suggests the importance of basal properties. For example, we found that glide-snow avalanches can release on relatively flat slopes and had the shortest slab lengths if the terrain was smooth and was covered with long grass. Higher slope angles and longer slab lengths were observed for the slopes covered with short grass or shrubs growing on smooth terrain. The highest slope angles and release lengths were necessary for cases where the terrain was rocky or stepped and covered with shrubs. In this case the mean slope angles and slab lengths increased.

We combined the terrain types with the vegetation cover and defined three surface categories shown in Table 3.

Snow height h_s (at the release) correlated only weakly with the slab length l_g (Fig. 8). But avalanches with a release length of $l_g > 50$ m where observed only for snow heights of more than one meter, $h_s > 1$ m. Note that slope angle α and snow height h_s could not be correlated. The mean snow height was slightly higher for short grass, low dwarf shrubs and strong lignified shrubs ($h_s = 94$ cm) than for long grass ($h_s = 84$ cm). Snow height has an influence on the mean vegetation height as vegetation is compressed by the snow mass (Table 1, Fig. 4). Long grass is already compressed with a relatively small load. However, shrubs need more weight for a similar effect. We observed glide-snow avalanche release on less steep slopes covered with low dwarf shrubs only for snow heights $h_s > 1$ m. No such effect was found for slopes covered with grass.

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3.2 Results of model calculations $l_m(\mu, \alpha)$

We performed a series of model calculations to establish a correlation between stauchwall strength, slab length, slope angle and ground friction. We studied the influence of ground roughness μ on slab length l_m and slope angle α by modeling the resistance and failure of the stauchwall (Sect. 2.3). We kept the material parameters of snow (E_m, E_k, η_m, η_k) constant and defined a critical strain rate in compression ($\dot{\epsilon} = 0.01\,s^{-1}$) which leads to the collapse of the stauchwall. Model results for different slope angles, slab lengths and friction parameter values are depicted in Fig. 9. We varied density ρ, snow height h_s and the stauchwall length l_s. We found friction values between $\mu = 0.33$ and $\mu = 0.81$ for a density $\rho = 300\,kg\,m^{-3}$, snow height $h_s = 1\,m$ and a stauchwall length $l_s = 2\,m$. The lowest values are necessary for a slope angle $\alpha = 30^\circ$ and slab length $l_m = 30\,m$ to prevent the stauchwall from failing. The highest values are necessary for a slope angle $\alpha = 45^\circ$ and a slab length $l_m = 60\,m$. Clearly, the calculated slab lengths and slope angles at failure depend strongly on the friction parameter μ.

We investigated the role of snow density ρ and snow depth h_s on the model results. We kept the slab length l_m and slope angle α constant. The model results revealed that a change in density of $\Delta\rho = 50\,kg\,m^{-3}$ needs a corresponding change in friction parameter $\Delta\mu$ of approximately 0.03. Therefore, we find that higher density snow-packs require higher surface roughness in order for the stauchwall to withstand the higher pressure. Moreover, the process of densification by snow settling coupled with melt-water (decrease of μ) could be a critical combination leading to glide-snow avalanche release. Thus, the process of densification, which can stabilize the high winter snow-pack, must not automatically lead to a reduction of glide-snow avalanche activity. For further studies we kept the density constant, $\rho = 250\,kg\,m^{-3}$.

The pressure on the stauchwall also depends on snow depth h_s. We assumed the stauchwall length to be twice as long as the snow depth. This assumption is based on observations, for example Fig. 1, in which the stauchwall length can be discerned as the zone with wavelike perturbations on the surface of the snowpack. No systematic

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measurements exist since the stauchwall is typically destroyed during an avalanche release. We therefore varied the snow depth h_s and the stauchwall length l_s respectively and found that an increase of approximately $\Delta\mu = 0.05$ is necessary to compensate for one additional meter of snow, $\Delta h_s = 1.0$ m. This result suggests that snow cover stability is relatively robust to changes in snow height. Moreover, the model results are in accordance with the observations which show a similar trend (Fig. 8). For example, we found very little correlation between avalanche release and snow depth: glide-snow avalanches can have both large and small fracture heights.

3.3 Comparison of guidelines, model results and field observations

We compared observed slab lengths $l_g(\mu,\alpha)$ from the Dorfberg with our calculated model results $l_m(\mu,\alpha)$ (Fig. 10). To be able to compare these to guidelines, the stauchwall length l_s was added to the observed slab length $l_g + l_s$ and modeled slab lengths $l_m + l_s$. We divided the observed release areas in the three different categories (1) smooth terrain with long grass, (2) smooth terrain with short grass or shrubs and (3) stepped or rocky terrain with shrubs (Table 3). Friction values between $0.1 \le \mu \le 0.5$ were tested. Observed terrain categories which are below stauchwall model calculation curves in Fig. 10 indicate lower ground friction than calculated. We found release areas with smooth terrain and long grass below the $\mu = 0.1$ curve, whereas smooth terrain with shrubs or short grass was always above the $\mu = 0.1$ curve. 92 % of rocky or stepped terrain with shrubs was above the $\mu = 0.4$ curve. The same analysis was performed for vegetation cover only. Whereas release areas with long grass are found even below the $\mu = 0.1$ curve, 89 % of all other vegetation types are above the $\mu = 0.2$ curve.

Guidelines on defense structure distances and forest gap sizes were formulated in Switzerland and Austria to prevent avalanches from releasing. We compared our observations with these guidelines to check on their performance. Guidelines on technical avalanche defense in Switzerland distinguish between different ground roughness and assume friction parameter values between $0.5 \le \mu \le 0.6$. For the same slope angle

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this variation leads to a change in allowable slab length of maximum three meters. The values for slab length and slope angle for small snow heights (1.5 m) are in the range of almost all events on Dorfberg of the winters 2011–2013 (Fig. 11). Deviations due to smooth or rough surface are small. Guidelines in Austria which do not distinguish between different snow heights recommend larger distances between defense structures.

In contrast most of the events on Dorfberg are below the guideline values for forest gap sizes. Lower slope angles and shorter slab lengths than proposed in the guidelines are sufficient to allow the release of glide-snow avalanches, especially if assuming a smooth surface.

We then compared the guideline values with the model results and found a good correspondence when comparing the technical guidelines for defense structures and stauchwall model results with low friction, i.e. for friction values $0.1 < \mu < 0.2$. This indicates that the guidelines assume low friction values, which is essential for the safe design of supporting structures. However, for higher friction values the stauchwall model is more sensitive to the slab length and slope angle. Thus, for high friction values, we can devise slopes that are stable for slope angles up to 35°. The technical guidelines are again conservative since they do not assume such high friction values. In comparison correspondence between the forest management recommendations and the model results was poor. This indicates that the guidelines are not consistent for the same ground roughness and slope angle (Fig. 12). The calculated maximum slab length for $\mu = 0.5$ and a slope angle $\alpha = 37^{\circ}$ corresponds to the guideline values for gap sizes in ideal conditions. However, the model results for lower slope angles overestimate the guideline values and underestimate the guideline values for high slope angles. Moreover, the forest guidelines are appropriate for low slope angles and high friction, but appear to miscalculate the acceptable gap length in steep terrain.

4 Conclusions

In this study we quantified the effect of ground roughness on glide-snow avalanche release with data on typical vegetation cover and topographical characteristics of 101 release areas. Additionally we employed a physical model which accounts for stauchwall mechanics and predicts failure or resistance depending on the slab length, snow height, snow density and ground roughness. We defined a critical strain rate which in turn defines the maximum slab length and slope angle allowable to prevent glide-snow avalanche release. The model results indicate a strong dependence of maximum slab length and slope angle on the Coulomb friction μ of the snow on the ground which we were able to quantify by comparing the model results with our observations.

Our field study revealed that glide-snow avalanches release on grass or shrubs and on smooth, stepped or rocky terrain. Slope angle and slab length depend on vegetation and terrain. We were able to distinguish between three roughness categories which have different characteristic heights. On the one hand smooth terrain with long grass has the least roughness and the release of avalanches is possible on relatively flat slopes with short slab lengths. On the other hand avalanches release on stepped or rocky terrain with shrubs only if the slope is steep and long. Snow height plays an important role as vegetation is compressed by the snow's weight and therefore the friction is lowered significantly. Whereas long grass is compressed with a small load, for shrubs to be pressed together a higher snow cover is needed.

We were able to draw conclusions on the Coulomb friction of the snow–soil interface by comparing the field data with stauchwall model calculations. Assuming stauchwall strength to be the crucial factor for glide-snow avalanche release only data of release areas was taken into account where the presence of a stauchwall could be expected. We defined approximate friction values μ for the categories "smooth terrain with long grass" ($\mu = 0.1$), "smooth terrain with short grass or shrubs" ($\mu = 0.2$) and for "stepped or rocky terrain with shrubs" ($\mu = 0.4$). These values represent the minimum Coulomb friction for a wet snow–soil interface that lead to glide-snow avalanche formation. They

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are slightly lower than the values Leitinger et al. (2008) found for abandoned meadows but in the same range as the values In der Gand and Zupančič (1966) estimated for wet grass. Assuming melt-water to be the crucial factor which lead to the gliding of these avalanches, the values are in good agreement with previous studies. In contrast the friction values proposed in the Swiss guidelines on artificial avalanche defense structures ($0.5 \leq \mu \leq 0.6$) are questionable if we assume snow gliding on wet smooth soil. We expect the friction μ to depend on terrain, vegetation cover and wetness of the snow–soil interface and to cover a wide range of values ($0.1 \leq \mu \leq 1.0$) that enable glide-snow avalanche formation.

Guideline values for the distance of technical defense structures are in accordance with the data and the model calculations for low friction ($0.1 \leq \mu \leq 0.2$). Our results indicate, that the release of glide-snow avalanches in between protection bridges appear to be unlikely. But the distance between structures depends strongly on the assumed maximum snow height. A larger snow height leads to larger distances which is not in accordance with our model calculations. The stauchwall model predicts a higher probability of glide-snow avalanches for a larger snow height. This fact is part of ongoing discussion (Matsushita et al., 2012). Austrian guidelines do not account for varying snow heights, therefore relatively large distances are recommended for small snow heights. Guidelines on maximum forest gap sizes in Switzerland fit our observations and calculations only if the ground roughness is relatively high. For $\mu \approx 0.5$ the guidelines ascertain safety for slope angles below 40°. To prevent avalanche formation on such slopes, we assume that a terrain roughness corresponding with stepped or rocky terrain and dwarf shrubs (e.g. Vaccinium vaccinium or Rodhodendron ferrugineum) is necessary in addition to the minimal required forest cover characteristica given in existing guidelines. Higher slope angles would even require a higher terrain roughness corresponding to strong lignified shrubs, stumps or piles of dead wood to hinder gliding. To leave logs of dead wood and high stumps in clearings is already often considered as safety measure in silvicultural management (Frehner et al., 2005; BAFU, 2008).

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This study underlines the importance of these measures, in particular for forest with protection against snow gliding and a low roughness of ground vegetation.

Surface roughness is one of the crucial factors governing glide-snow avalanche formation. We presented a model approach which takes stauchwall mechanics and ground friction into account. The friction values that we calculated could be confirmed with data of a field study where we distinguished various vegetation types and terrain characteristics on glide-snow avalanche release areas.

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Table 1. The observed vegetation types on Dorfberg. Mean vegetation height h_v in autumn and winter, slope angle α, slab length l_g and a photo of a typical example case are added.

Vegetation type	Long compacted grass	Short upright grass	Low dwarf shrubs	Strong lignified shrubs
Number of avalanches	45	6	49	1
Mean α [°]	35	36	39	35
Mean l_g [m]	26	42	28	38
Mean h_v [m] in autumn	0.10	0.13	0.14	0.5
Mean h_v [m] in winter	0.01	0.03	0.04	0.15
Photo				

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Table 2. The observed terrain on Dorfberg. Mean slope angle α, slab length l_g, terrain height h_t and a photo of a typical example case are added. Note the high number of smooth terrain cases.

Terrain	Ridge	Smooth	Steps	Rocks
Number of avalanches	1	79	9	12
Mean α [°]	36	37	38	40
Mean l_g [m]	40	26	36	34
Mean h_t [m]	0.15	0.19	0.31	0.32
Photo				

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Table 3. Vegetation and terrain combined in three categories. The least roughness was observed for smooth terrain with long grass and the roughest surface was observed when stepped or rocky terrain was covered with shrubs. The second category was smooth terrain covered with short upright grass or shrubs.

Terrain + Vegetation	smooth + long grass	smooth + short grass or shrubs	stepped or rocky + shrubs
Number of avalanches	31	23	13
Mean α [°]	35	39	40
Mean l_g [m]	27	27	42
Mean $h_v + h_t$ [m] in autumn	0.30	0.33	0.54
Mean $h_v + h_t$ [m] in winter	0.20	0.22	0.41

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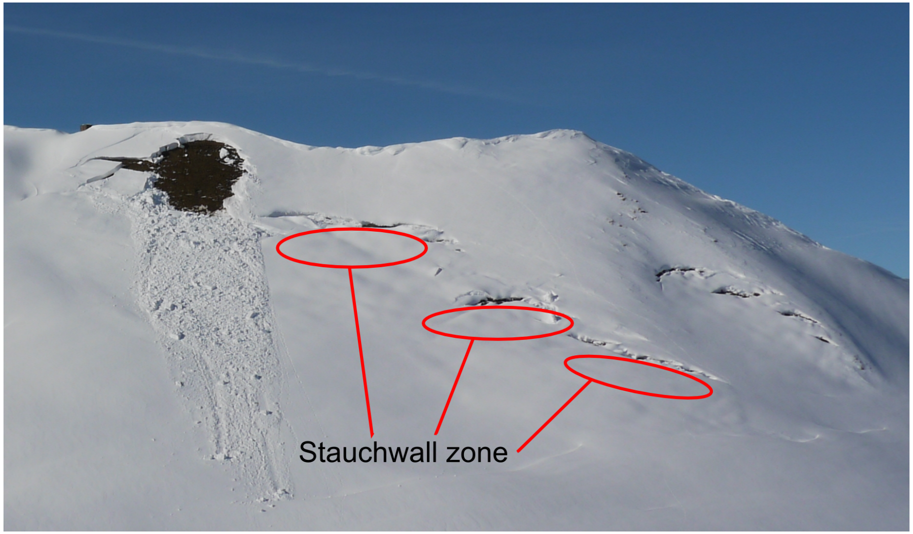

Fig. 1. Opening of glide-cracks (Fischmaul) near Davos. The left slope released, probably because the slope is steeper than the right part.

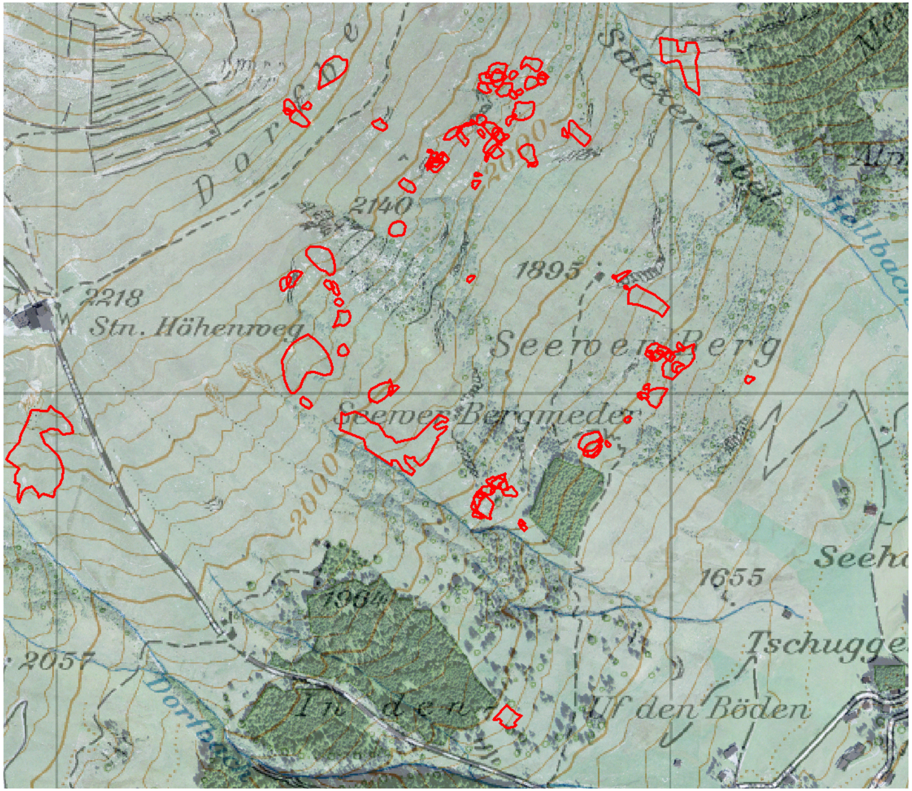

Fig. 2. Glide-snow avalanche release zones on Dorfberg, Davos. (Swissimage ©, DV 033594, 2013).

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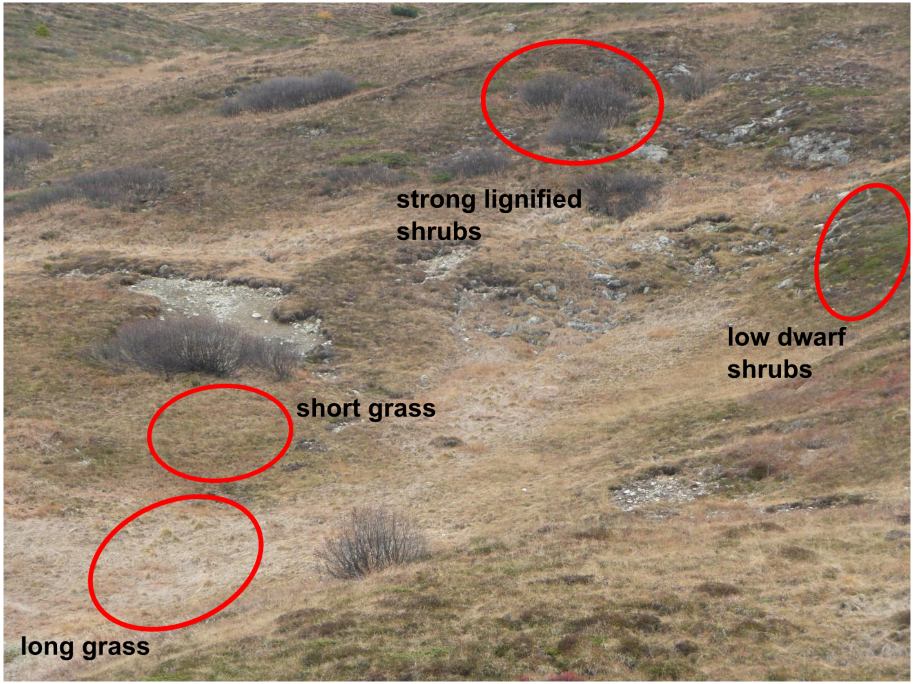

Fig. 3. Different vegetation types were observed at our field campaign. The main types were long grass, short grass, low dwarf shrubs and strong lignified shrubs.

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Fig. 4. Vegetation below the snow cover. Vegetation heights h_v are smaller in winter than in autumn: less than one centimeter for long grass, 3 cm for short grass, 4 cm for low dwarf shrubs and 10–20 cm for strong lignified shrubs.

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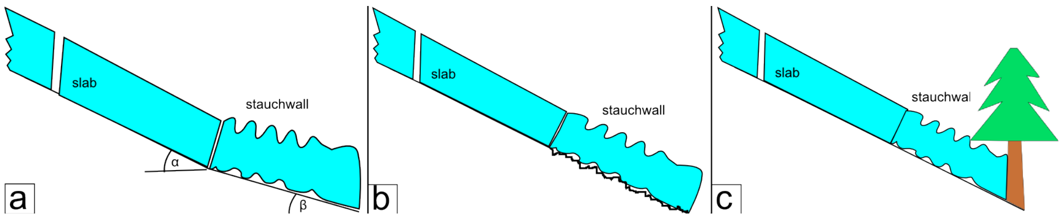

Fig. 5. Cases where a stauchwall forms: in **(a)** the area below the release zone is flatter, than the release area. Rougher surface below the release zone fixes snow to the ground **(b)** and a tree can be an effective obstacle stabilizing the snow cover below the release area **(c)**.

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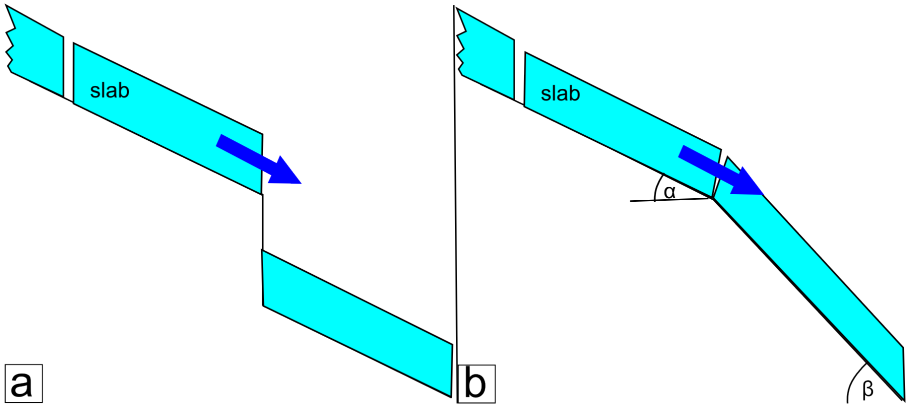

Fig. 6. Cases where no stauchwall forms: either there is a terrain drop **(a)** or the area below the release is steeper than the release area **(b)**.

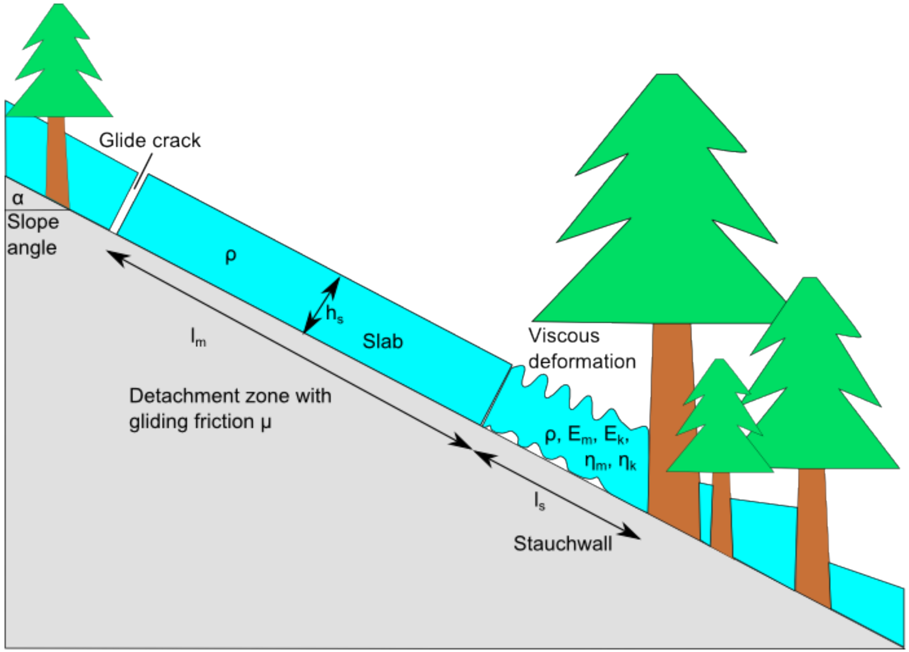

Fig. 7. Model description: a slab with length l_m, snow density ρ and snow height h_s starts to glide on a slope with angle α. A glide crack opens and the weight of the slab m is balanced by the friction of the snow on the ground μ and the stauchwall with length l_s, snow density ρ and material parameters E_k, E_m, η_k, η_m.

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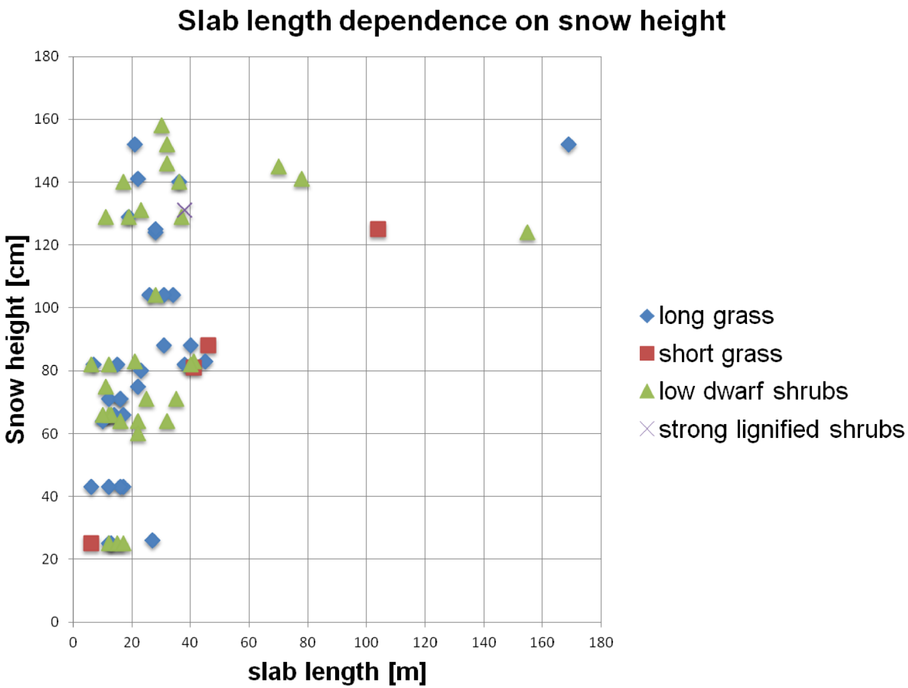

Fig. 8. Slab length and snow height correlate weakly ($R^2 = 0.11$). The longest slabs l_g were observed for snow heights of more than one meter. Whereas short release areas, (up to 50 m) are possible for any snow height, long slabs are characteristic for large snow heights.

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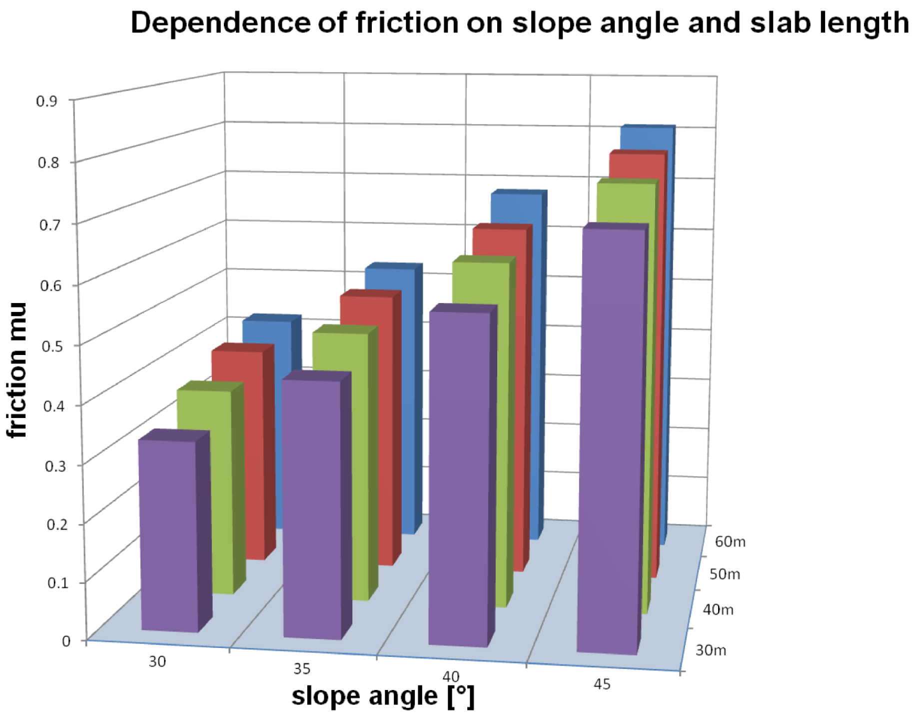

Fig. 9. Three-dimensional plot showing the dependency of friction μ on slope angle α and slab length l_m. The higher the slope angle, the higher the friction μ to prevent a failure of the stauchwall. The larger the slab length l_m, the larger the friction μ must be to prevent failure.

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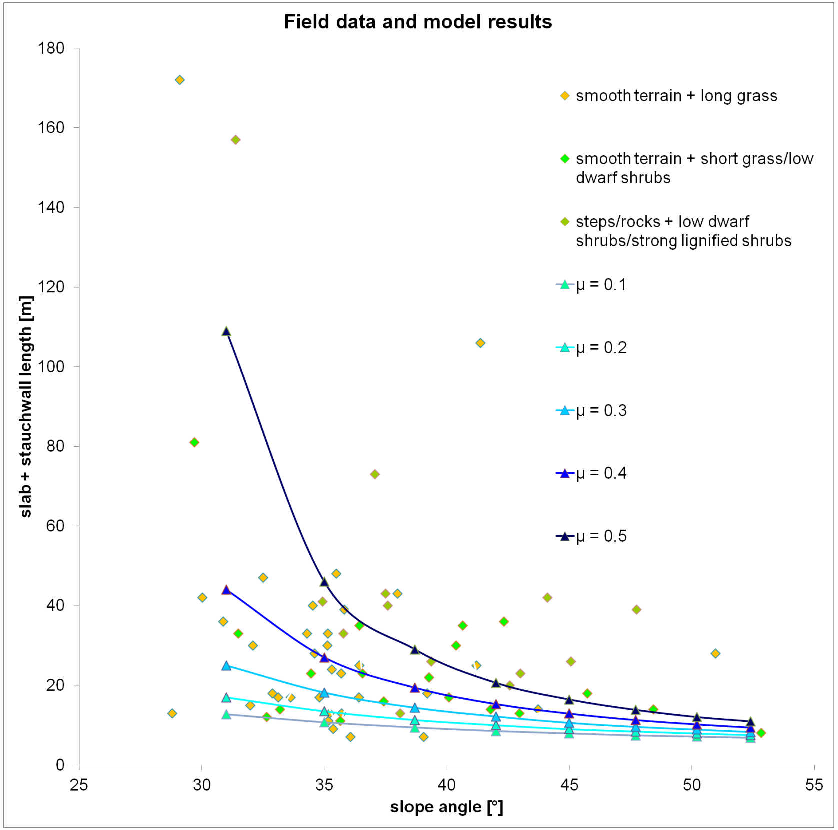

Fig. 10. Comparison of glide-snow avalanche release length and stauchwall $l_g + l_s$ from Dorfberg with model results. The graph shows slope angle against slab length of the 67 avalanches with stauchwall. We devided the data in three roughness categories: smooth terrain + long grass; smooth terrain + short grass or shrubs and stepped or rocky terrain + shrubs.

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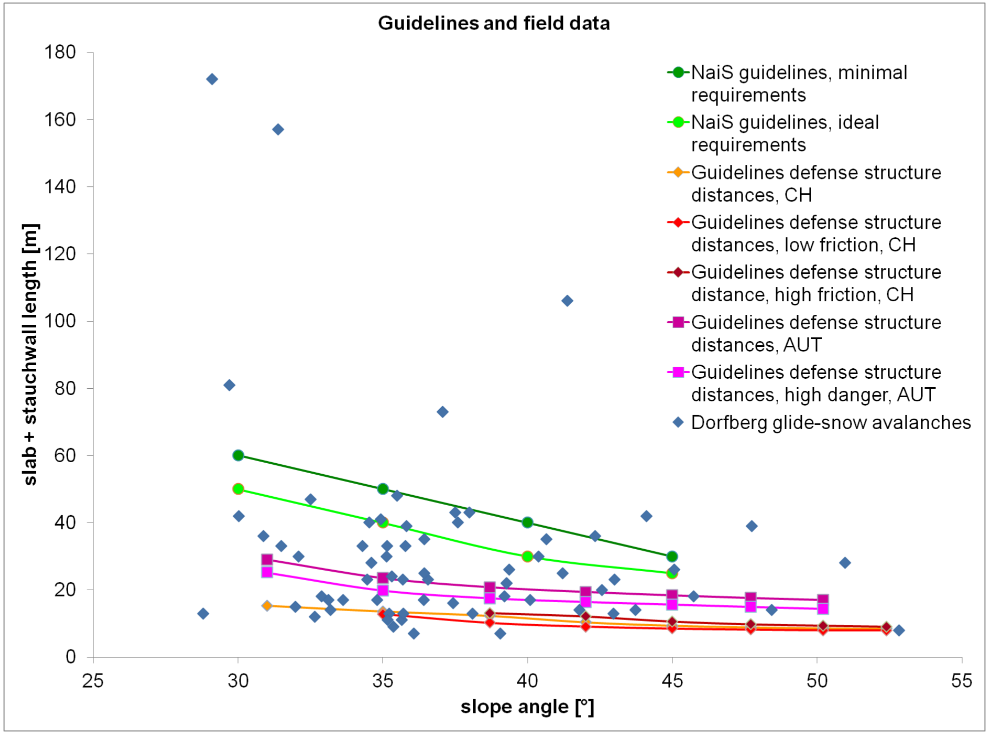

Fig. 11. Comparison of guidelines with Dorfberg data. Note that most of the Dorfberg glide-snow avalanches had longer slab lengths and released on steeper slopes than proposed by the defense structure guidelines of Switzerland. In contrast forest gaps with slope angles and lengths in accordance with the Swiss guidelines on sustainable management of protective forests NaiS would not have hindered avalanche formation in a lot of cases on the Dorfberg.

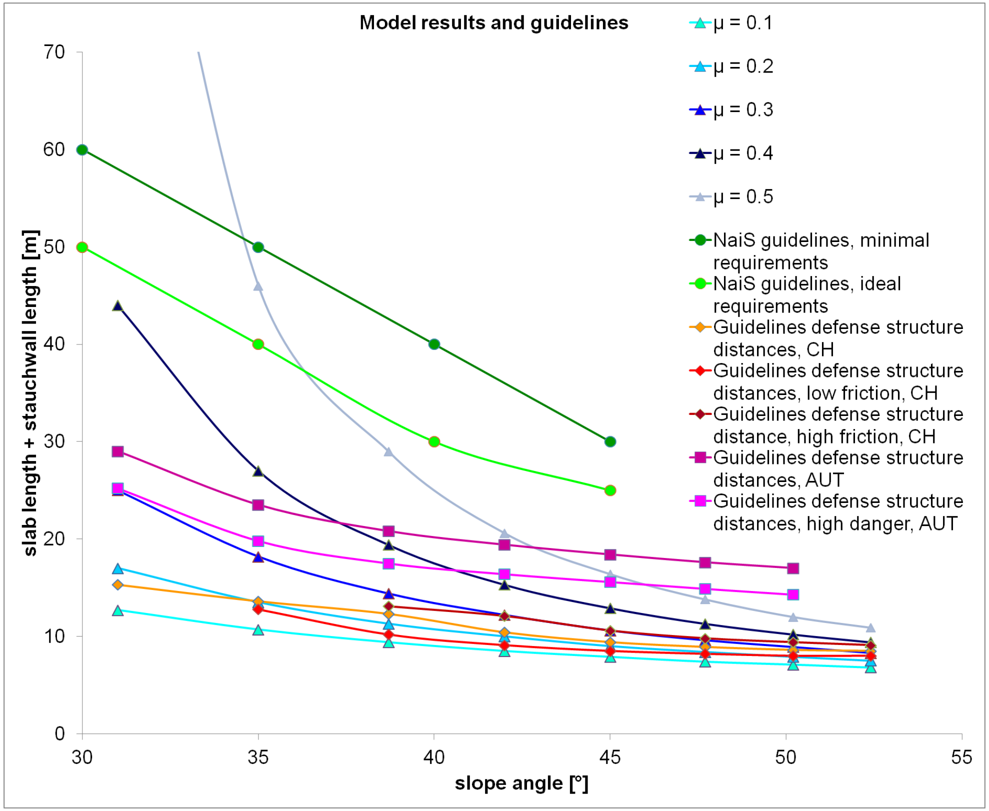

Fig. 12. Comparison of guidelines with model results. Model calculations with friction values between $0.1 < \mu < 0.2$ correspond to the technical guidelines for avalanche prevention bridges. Maximum forest gap sizes proposed by the Swiss guidelines on sustainable forest management (NaiS) are appropriate for low slope angles and high friction.