GLIDE-SNOW AVALANCHES: THE INFLUENCE OF SPATIAL VARIATION IN INTERFACIAL FRICTION AND SNOW COVER ON AVALANCHE RELEASE

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ABSTRACT: Glide-snow avalanches typically release in well-known avalanche paths due to a loss of friction at the ground-snow interface which is related to the presence of liquid water. However, the spatial distribution of liquid water and its influence on mechanical snow properties and the progression of local failures is unknown. As a result, predicting glide-snow avalanches and their release area remains difficult. We therefore built a model that captures mechanical snow interactions and investigated the impact of spatial variations in liquid water content (expressed as loss in interfacial friction) on glide-snow avalanche release probability and release area. In this threshold-based mechanical model, the snow cover is represented with hexagonal columns. The columns interact through compressive, shear and tensile bonds. Interfacial friction between the ground and the snow cover was implemented as a proxy for the liquid water content. The results suggest that our modeling framework can emulate the power-law release-area distribution of glide-snow avalanches as observed in 14 years of georeferenced time-lapse photographs at our field site. A sensitivity analysis showed that the homogeneity of the basal friction was the main influence on avalanche release area and the power law exponent while the spatial variation in snow cover properties was of second order influence. In the future, the implementation of additional model parameters such as snow loading, and local topography will improve our understanding of release probability and release-area size. This knowledge will help to assess crititcal conditions for large glide-snow avalanches and improve forecasting capabilities.

KEYWORDS: glide-snow avalanche, power law distribution, statistical modelling

1 INTRODUCTION

Glide-snow avalanches release at the ground-snow interface which can result in large snow volumes that endanger infrastructure in alpine regions (Clarke and McClung, 1999; Mitterer and Schweizer, 2012). These avalanches pose a threat which is difficult to mitigate due to limited forecasting capabilities (Simenhois and Birkeland, 2010) and unreliable mitigation measures (Sharaf et al., 2008). Observations have shown that glide-snow avalanches mostly release in well-known avalanche paths which are typically characterized by a slope angle greater than 28 degrees (Ancey and Bain, 2015) and a smooth ground surface (in der Gand and Zupančič, 1966). It is generally accepted that the loss of friction between the snowpack and the ground is caused by liquid water at the ground-snow interface. The potential sources of liquid water include melt water percolation (Lackinger, 1987; Clarke and McClung, 1999), geothermal heat (McClung, 1987; Newesely et al., 2000; Höller, 2001), and capillary suction (Mitterer and Schweizer, 2012). Whether the loss in friction causes the formation of a tensile crack or a full-depth avalanche release also depends on the stauchwall, which is the snow cover located at the lower limit of the gliding zone. The stauchwall stabilizes the gliding snowpack if it can withstand the strain-rates that occur af- ter tensile failure (Bartelt et al., 2012). There have been several attempts at modelling glide- snow avalanches (Haefeli, 1939; McClung, 1981; Bartelt et al., 2012). However, it remains unclear how snow and soil properties and their spatial variation influence avalanche size, location and release timing.

While the details of the processes causing glide-snow avalanche release are not yet fully understood, their behavior should be similar to that of other gravitational mass movements. Gravitational mass movements such as landslides (Lehmann and Or, 2012), rockfalls (Dussauge et al., 2003) or slab avalanches (Kronholm and Birkeland, 2005; Faillettaz et al., 2004) exhibit characteristic scale-invariant statistics. This means that the probability distribution $p(x)$ of event sizes follows a power law with an exponent α (Bak, 1996). Often the power law only applies to the tail of a distribution where values are greater than a minimum value ($x_{\min}$) (Equation 1; Sornette (2006)).

$$p(x) \propto \left(\frac{x}{x_{\min}}\right)^{-\alpha} \quad \text{with } x > x_{\min}, \alpha > 1 \qquad (1)$$

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These heavy-tailed power law distributions have been associated with self-organized criticality (SOC). Self-organized criticality refers to the spontaneous organization of an externally driven system into a (marginally) stable state. Models that replicate this behaviour consist of many interacting components that show a non-linear threshold response while they are externally driven with a constant rate (Sornette, 2006). SOC con- cepts have been applied successfully to model landslides (Lehmann and Or, 2012) and slab avalanches (Kronholm and Birkeland, 2005; Faillettaz et al., 2004).

We show that the tail of the release area distribution of glide-snow avalanches on Dorfberg (Davos, Switzerland) follows a power law. This power law exponent was then reproduced with a threshold-based mechanical model that was based on the idea of self-organized criticality (e.g. modeling of the mechanical interaction and failure propagation between elements). The aim of the model was to investigate the influence of spatial variation in basal friction and snow properties on the avalanche release area and the power law exponent.

2 RELEASE AREA MODEL

In this model for glide-snow avalanche release areas (motivated by the landslide triggering model (Lehmann and Or, 2012)), the snow is discretized into hexagonal columns (apothem r, snow height h, snow density ρ, see Figure 1). The column height is parallel to the direction of gravity and the columns are placed on a homogeneous hill- slope with a slope angle β. The friction ($\mu \in [0, 1]$) between the hillslope and the snow columns is modelled as a spatial random field with an exponential covariance function (parameters: variance, mean and length scale). Note that this is a simple proxy. We do not include any assumption on how the coefficient of friction is linked to processes like liquid water infiltration or environmental variables like ground roughness. The total mass (m) of a soil column and its force ($F_G = mg$) due to gravity (g) can be devided into two components: the down-slope directed force ($F_H = F_G \sin\beta$) and the counteracting normal frictional force ($F_N = \mu F_G \cos\beta$). Dividing the forces with the effective hexagonal cross section (cross section: $A_H = 2\sqrt{3}r$) results in the normal stress (σ_N) and the shear stress (τ).

$$\sigma_N = \frac{F_N \cos\beta}{A_H} = \mu\rho g h \cos^2\beta \tag{2}$$

$$\tau = \frac{F_H \cos\beta}{A_H} = \rho g h \sin\beta \cos\beta \tag{3}$$

During model initialization, the random friction field is scaled such that all hexagonal columns are initially stable ($\tau < \sigma_N$). The reduction in frictional strength due to liquid water, is mimicked through a homogenous and step-wise reduction in friction across the entire slope. If, somewhere in the model domain, the shear stress exceeds the normal stress ($\tau > \sigma_N$), the corresponding column base fails and the column's basal friction is set to a residual friction ($\mu_{res} << \mu$). After failure, the column can be stabilized by its neigh- boring columns through tensile, shear and compressive bonds. The strength of the compressive bonds is scaled based on the snow density (Mellor, 1975) and the bond-strength ratio (compressive:shear:tensile) is set to 10:2:1 (Mellor, 1975). The load of the column is initially distributed equally onto all neighbors. If the load onto a neighbor exceeds its bond strength, the bond fails and the load is redistributed amongst the remaining intact bonds to other neighbors until the column is stabilized or all bond strengths are exceeded. The latter causes a column to fail and the column is removed from the system. To implement a partial failure of the stauchwall, a column can also fail if its compressive bond strength is exceeded by the load exerted by a neighboring column. Failed and subsequently removed columns cannot support neighboring columns any longer which can cause a cascading chain reaction that results in an avalanche of failures. Note that the model does not describe the dynamics of avalanche release. If a column fails, it is removed from the system and is not tracked further.

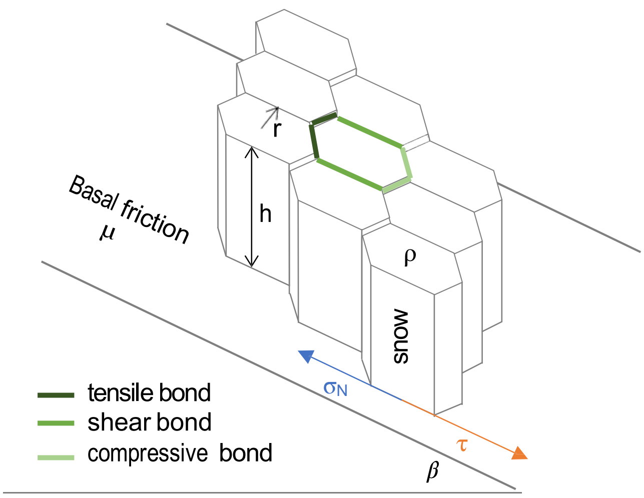

Figure 1: Visualization of model parameters with the bond interactions (green) visualized for the center column.

3 RESULTS

3.1 Measured release area distribution

The glide-snow avalanche release areas were extracted from time-lapse photographs which were taken continuously on Dorfberg (Davos, Switzerland) through seasons 2008/09 to 2022/23 as described by Fees et al. (2023). The 488 detected release areas follow a power law distribution with $x_{\min} = 633$ m^2 and $\alpha_{\text{field}} = 2.4 \pm 0.1$ (Figure 2).

3.2 Model evaluation

The preliminary sensitivity analysis of the initialization parameters (Table 1) indicated that the power law exponent and release area size were dominated by the basal friction (friction variance, friction length scale and the step size of the reduction of the friction). A more homogeneous basal friction (large friction length scale and low friction variance) caused larger release areas and a decrease in the power law exponent (Figure 2). A friction length scale of 350 and a friction variance of 0.0001 resulted in a power law exponent ($\alpha = 2.5 \pm 0.3$) within the range of uncertainty of the Dorfberg field data ($\alpha_{\text{field}} = 2.4 \pm 0.1$). An in- crease in the step size of the reduction of friction resulted in larger possible release areas, but did not show a systematic influence on the power law exponent.

The implementation of the snow density as an exponential random field and the variation in its spatial parameters (density length scale and density variance) did not result in substantial influence on the power law exponent or on release area size.

Table 1: Initialization parameters for the release area model.

Parameter	Value
Number of hexagons	100 x 100
Number of simulation runs	30
Hexagon apothem	0.54 m
Slope angle β	35
Snow height h	1 m
Snow density ρ	250 $\frac{\text{kg}}{\text{m}^2}$
Minimum analyzed release area	4 m^2
Compressive bond ($\rho = 250 \frac{\text{kg}}{\text{m}^2}$)	100 Pa
Compressive bond outer elements (constant boundary condition)	10^{50} Pa
Residual friction μ_{res}	0.01
Friction variance	0.0001
Friction length scale	50-500
Friction step size	0.005

4 DISCUSSION AND OUTLOOK

The distribution of glide-snow avalanche release areas on Dorfberg show a power law distribution for release areas larger than 633 m^2.

The glide-snow avalanche power law exponent $\alpha_{\text{field}} = 2.4 \pm 0.1$ is close to the exponent of observed slab avalanches ($\alpha_{\text{slab}} = 2.2 \pm 0.1$, Faillettaz et al. (2004)). However, the release areas are limited to Dorfberg and local limitations in topography can impact the distribution. Additionally, the extraction of release areas from time-lapse photographs is inherently limited in resolution. The minimum detectable release area depends on the topography and the orientation of the release area towards the camera (Fees et al., 2023). As a result, the number of very small avalanches may be underrepresented in this dataset. More field data from varying locations would be necessary to determine if large glide-snow avalanche release areas exhibit scale-invariant power law behavior. Larger field datasets may also allow for the separation of avalanches based on the suspected source of interfacial water (surface-generated interfacial water vs. interface-generated interfacial water (Fees et al., 2023)) which would permit a more process-based investigation.

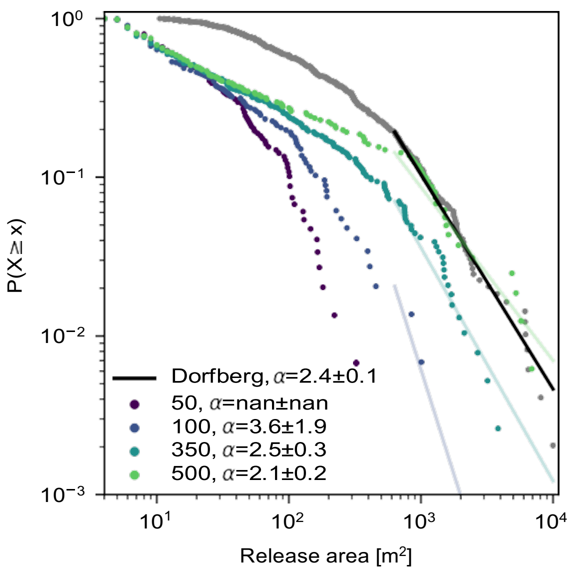

Figure 2: Complementary cumulative distribution function $P(X \geq x) \propto x^{-(\alpha-1)}$ for glide-snow avalanche release areas on Dorfberg and for sim- ulations with varying friction length scales (50, 100, 350, 500). For Dorfberg, the optimal parameters $x_{\min}$ and α were determined with a maximum likelyhood fit and according to Clauset et al. (2009) using Alstott et al. (2014). For the simulation fits $x_{\min}$ was set at 633 m^2.

The model is built on our current understanding of glide-snow avalanche release and translates it into a simple, threshold-based model. One model assumption is, that the basal friction decreases homogeneously across the entire slope. This assumption may hold well for avalanches in spring when melt water percolation can cause liquid water across the entire slope. For avalanches in early winter this assumption may be less suited. Another model assumption is the ratio between compressive, shear and tensile bond strengths, which was retrieved from experiments with dry snow (Mellor, 1975). This assumption may hold well for avalanches in early winter when the snow cover is predominantly dry but less so in spring when the snow cover is wet. As of today, there are no reliable measurements on the mechanical properties of wet snow (Yamanoi and Endo, 2002). The lack of knowledge on wet-snow mechanics and the formation and influence of liq- uid water currently prevents the connection of more model parameters. The basal friction, snow density, and bond strengths could potentially all be connected to the liquid water content at the ground-snow interface. Linking more parameters is an important step towards driving the model with a physical quantity like the snow liquid water content.

Although the model is built on numerous assumptions and simplifications, it reproduces the power law distribution of glide-snow avalanche release areas as observed in the field (Figure 2). A first sensitivity analysis suggested, that the spatial variation in basal friction dominated avalanche release size and the power law exponent while variations in the snowpack were of second order influence. This hypothesis has yet to be verified through field measurements. In general, the simulated power law exponent depends strongly on the set of initial parameters (Table 1).

In the future, a thorough sensitivity analysis and the implementation of topography are needed to investigate the influence of parameter combinations on the power law exponent. This information may help to form new hypotheses regard- ing the cause and size of avalanche release tak- ing into account the spatial variability of the fric- tion and snow cover properties. This would allow for more targeted field observations to (dis)prove these hypotheses. The model can grow in complexity, for example through linked parameters, as our knowledge on avalanche release processes and on wet-snow properties grows. This will help to identify potentially dangerous conditions and improve glide-snow avalanche forecasting in the future.

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