THE UNDERESTIMATED ROLE OF THE STAUCHWALL IN FULL-DEPTH AVALANCHE RELEASE

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ABSTRACT: During the winter 2011/12 the Swiss Alps experienced repeated cycles with high activity of snow gliding and full-depth avalanches. Up to 8 m deep glide cracks formed and full-depth avalanches caused significant damage to infrastructure. Long-standing questions reappeared: Are full-depth avalanches predictable? Are there optimal preventive measures? We use field observations to develop a model that divides the snowcover into a full-depth, gliding zone and a non-gliding deformable snowcover. We assume a glide crack opens and calculate how the lost tensile force is transferred to the non-gliding zone, the *stauchwall*. The model reveals how the interaction between the *stauchwall* and the instable gliding mass depends on the visco-elastic properties of the snowcover. We first demonstrate why the opening of a glide crack does not automatically lead to avalanching. However, under certain conditions material failure in brittle compression is imminent and full-depth avalanches can release. Failure depends not only on the snow properties of the *stauchwall*, but also on the frictional properties of the gliding interface. Even small length gliding zones can initiate avalanches, depending on the slope angle and the glide variability of the interface. The model underscores the importance of the *stauchwall* and reveals why the formation of full-depth avalanches is depth invariant (although the consequences are not). We use the model to draw conclusions concerning the forecasting and mitigation of full-depth avalanches. The conclusions stress the difficulties and limitations of forecasting as the necessary and relevant data will seldom be available.

1. INTRODUCTION

Full-depth glide avalanches are a concern for local and regional avalanche forecasting because they are difficult to predict and can pose significant and prolonged hazard to highways, railroads, housing and ski runs (Peitzsch et al., 2012). During winter 2011/12, Switzerland experienced a rare snow glide situation - it is estimated to have had at least a 30-year return period. A dry and extremely warm fall season preceded extreme snowfall during December and January. This led to snow glide activity from December till spring in most areas of the Swiss Alps. Repeated cycles of high activity of full-depth avalanches in combination with almost record snow depths (Figure 1) posed a challenge to maintain mountain roads and ski runs open during the main tourist season.
From January till March 2012 there was more or less continuous activity of full-depth glide avalanches with six cycles of high activity. Two people died in full-depth avalanches and there was considerable direct and indirect damage from them. At least every fifth avalanche causing damage was a full-depth glide avalanche during the winter 2011/12.

Fig. 1: Record snow fall in December and January led to massive full-depth cracks, as below the peak “Hoher Wasserbergfirst” (2341 m) at Muotathal, canton Schwyz, Switzerland (photo: S. Bürgler, 07.02.2012).

The Swiss forecasting service issued special danger maps and safety authorities had to keep roads and ski runs closed frequently and for extended time periods. Still, traffic routes were hit by full-depth avalanches (Figure 2) and objects such as skilift pylons were destroyed by gliding

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snow (Pielmeier et al., 2012). Questions arose about improved local forecasting: When does the gliding snow mass release or on the other hand, what are the conditions where the snowcover remains stable? Also questions arose about efficient short-term preventive measures: When and where is avalanche control work useful, for example with explosives?

Fig. 2: During the New Year's holidays, a cycle of high wet and full-depth avalanche activity caused damage to traffic routes and endangered or buried skiruns, as at Gros Van, Col des Mosses, canton Waadt, Switzerland (photo: Patrick Mesot, 01.01.2012).

In this paper we reinvestigate the mechanics of full-depth avalanche release with the goal of trying to develop a better understanding of the release. At present we are primarily interested in the mechanics of gliding snow after an initial crack has opened. This attempt is based on observations of snow glide and full-depth avalanche release. A well compacted snowcover is typical for winters with increased snow glide. Such a snowcover typically lacks weak layers. Therefore, the standard avalanche formation processes do not apply. A model of the mechanical system is presented. It describes the mechanical failure or non-failure of the snowcover in glide and reveals the crucial role of the *stauchwall,* which is the snowcover zone below the glide zone. From the model, we draw some conclusions about avalanche forecasting and avalanche control work but also show the limitations due to missing measurements of physical snow properties.

2. FULL-DEPTH AVALANCHE RELEASE

2.1 Gliding slab, compression zone and stauchwall

Our model ideas are based on observations of full-depth avalanches such as those depicted in Figure 3. We divide the snowcover into three regions: a gliding slab, the compression zone and the stauchwall. We assume that a tensile crack has opened. The crack opens due to reduced friction at the ground. This system might fail within seconds, or, it might find a new quasi-stable equilibrium. A feature of this new quasi-stable equilibrium is that the crack might widen, but the gliding slab does not overcome the stauchwall. Full-depth avalanche release is therefore divided into an *immediate* release and a *delayed* release.

When the crack opens, there is a redistribution of the stress from the crown to the stauchwall. The stauchwall is located at the lower end of a region where the snowcover glides. By definition, we assume that the stauchwall is fixed to the ground and therefore carries all the weight of the gliding slab in shear; that is, there is no longitudinal displacement at the ground as the stauchwall cannot glide at the bottom. The stauchwall is often located at terrain discontinuities, such as footpaths that transverse the slope or large rocks. Interestingly, after the release of a slab, the overrun remnants of a stauchwall are often visible as snowcover patches that remain fixed to the ground (Figure 3). Located immediately above the stauchwall is the *compression zone*, a region of primarily longitudinal deformation. This zone deforms under the loading of the slab. We associate the mechanics of this zone with the slab as this region also glides at the bottom, while the stauchwall is fixed to the bottom. The two defining features of the compression zone are that (1) it is located at the end of the gliding zone, and therefore must carry the most axial load (higher stress) and (2) it is located immediately before the stauchwall, which does not deform. The compression zone must therefore accommodate the largest gradients in deformation and deformation rates (strains and strain rates).

The start of full-depth avalanches is associated with the interplay between these three mechanical regions: the gliding slab (which defines the load), the compression zone (the failure region) and the stauchwall, the region of the snowcover which must transfer the excess or free load of the slab to the ground. Theoretically, the stability problem would be well posed (and simple to solve) if we would know the lengths of each region. In reality, this is seldom the case and probably the greatest problem for avalanche forecasters. Although we can consider that the snowcover to have no variation in mechanical properties both along the length and throughout the cross-section of the snowcover, variations in frictional properties at the ground are absolutely necessary to cause failure. Specific knowledge of these variations is therefore necessary to forecast the release.

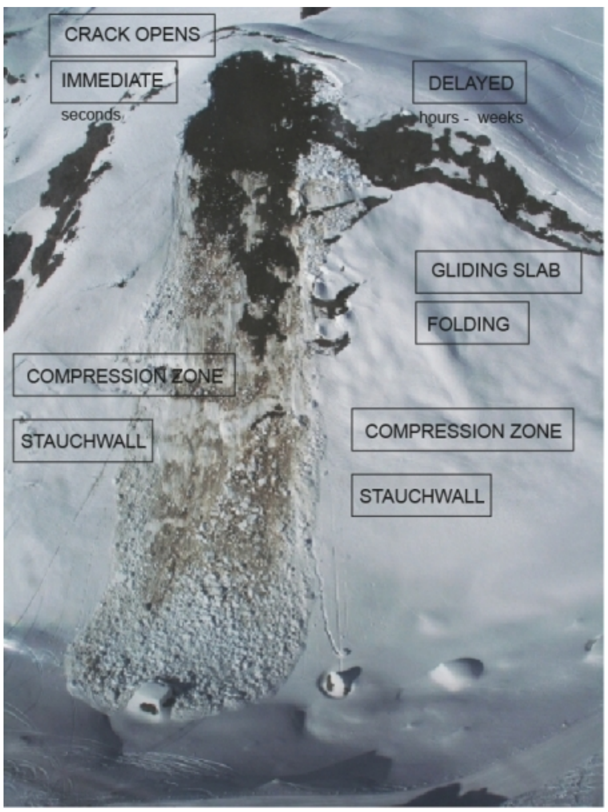

Fig. 3: After an initial tensile crack opens the avalanche may release immediately or delayed. The stauchwall is located at the lower end of a region where the snowcover glides and is compressed (photo: F. Meyer 20.02.2008).

An interesting variation to this mechanical model arises when the slope of the gliding zone is not constant (it seldom is in reality). This causes an eccentric longitudinal loading of the snowcover, primarily in the compression zone (Figure 4). This facilitates buckling and viscous folding in the gliding slab. Such folds are often visible prior to an avalanche release. The role of the folds is striking as the primary mode of deformation is no longer compression, but bending. The bending deformations serve to raise the center of mass of the snowcover, making it easier for the slab to overcome the stauchwall. It also accelerates the glide process as the snowcover is raised from the ground, reducing the contact area and thus the frictional force taken up by the ground. As the snowcover bends, the shear deformations at the stauchwall are exacerbated as the snowcover must rotate at the stauchwall to accommodate the bending deformations. The large shear rotations at the stauchwall often cause material to be extruded upwards, forming bulges of snow, that help identify the location of the stauchwall and the end of the gliding zone (Figures 3 and 4). If the bending moments at the stauchwall and the folds are unequal, it is possible that the vertical reaction at the stauchwall will change sign, causing a sudden uplift of the snowcover, which helps to displace the slab over the stauchwall.

2.2 Mechanical model

To mechanically model the stability of the gliding zone, compression zone and stauchwall we apply the full-depth avalanche release model developed in Bartelt et al. (2012). With this model we must first assign lengths to two regions of variable basal friction (Figure 4). The first is the length of the gliding zone l and the length of the compression zone l_s. The snowcover height h and density ρ are constant. We assume that the compact snow slab begins to move as the tensile region (the crown) releases. At initiation we consider the slab to be a block moving as a rigid body. Coulomb friction at the ground (parameter μ) prevents the slab from accelerating fully. At the lower end of the slab, the stauchwall experiences an axial compression and therefore an increase in stress σ. Denoting the downslope velocity of the slab u and the acceleration $\dot{u}$, the momentum balance of the slab is:

$$m\dot{u}(t) = mg_x - \mu m g_z - \sigma(t)h \qquad (1)$$

where m is the total mass of the slab with unit width, $m = \rho h l$, with ρ the density. For simplicity, we assume a homogenous density from the bottom to top of the snowcover. This is a realistic assumption especially for full-depth, wet snow gliding snowcovers (McClung and Schaerer, 2006). The angle of the slope θ determines the slope parallel component of the gravitational acceleration $g_x = g\sin\theta$, with g the gravitational acceleration. The slope normal component

$g_z = g\cos\theta$ defines the normal stress N acting on the ground $N = \rho g_z h$ and together with the gliding Coulomb coefficient μ the frictional shear stress at the gliding surface $S = \mu N$.

Snow is a visco-elastic material, see overview works of Mellor (1974) or Salm (1982). The total compressive strain rate $\dot{\varepsilon}$ can therefore be split into elastic (reversible) and viscous (irreversible creep) parts. Triaxial tests with snow show that at strain rates $\dot{\varepsilon} \approx 10^{-2}$, snow will fail in brittle compression (Scapozza et al., 2003). We compute the relationship between strain rate $\dot{\varepsilon}$ and stress σ below this failure limit using a Burger's viscoelastic model (Mellor, 1974). This general model was first proposed by Salm (1974) to model the viscoelastic response of snow under stress loading and also applied by von Moos (2003) to model the visco-elastic behavior of snow under different strain rates in triaxial tests. Burger's model divides the stress response of snow into Maxwell and Kelvin spring (elastic) - dashpot (viscous) elements in series. The governing differential equation relating stress σ and strain rate $\dot{\varepsilon}$ is (Mellor, 1974):

$$\ddot{\sigma}(t) + \left[\frac{E_m}{\eta_m} + \frac{E_m}{\eta_k} + \frac{E_k}{\eta_k}\right]\dot{\sigma} + \left[\frac{E_m E_k}{\eta_m \eta_k}\right]\sigma = E_m \ddot{\varepsilon}(t) + \frac{E_m E_k}{\eta_k}\dot{\varepsilon}(t) \qquad (2)$$

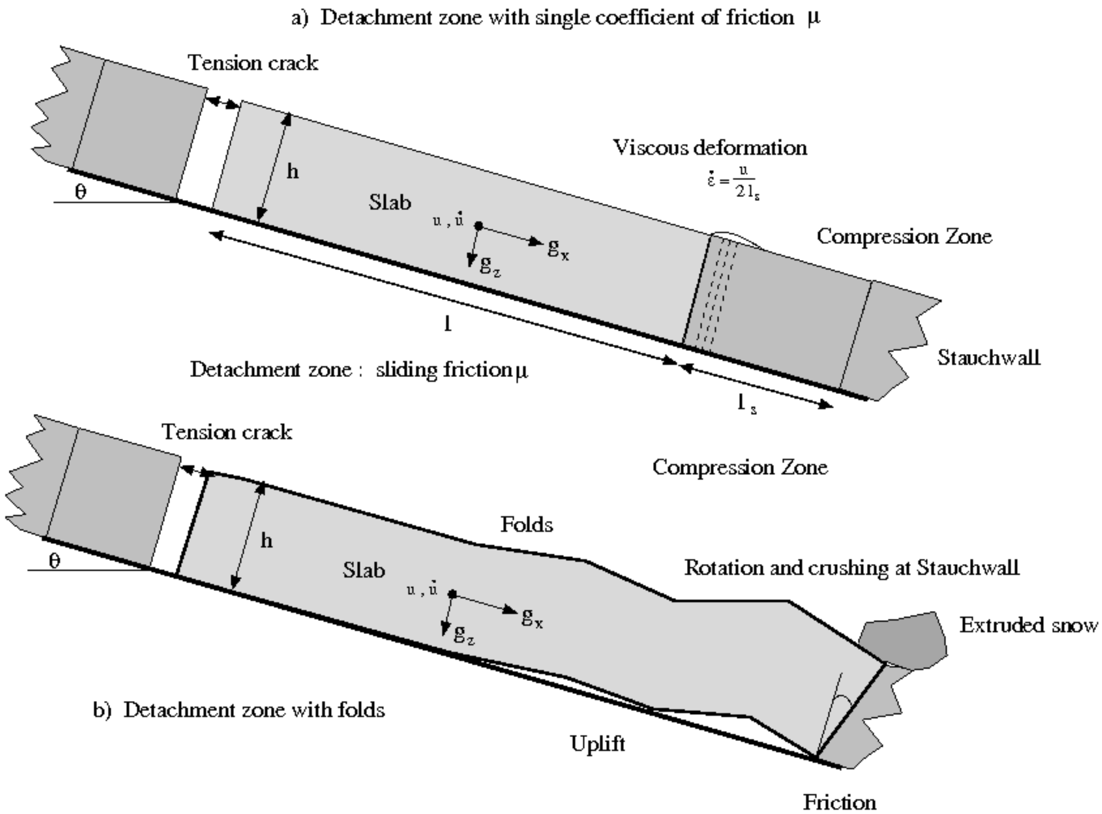

Fig 4: A rigid avalanche slab of height h and length l releases spontaneously on a slope of angle θ at time t=0. The slab accelerates with $\dot{u}(t)$ and deforms the compression zone over the length l_s. We consider two cases: a) a detachment zone with constant sliding friction μ; b) the detachment zone with folds. Note the rotation at the stauchwall.

which contains the four material constants E_m, E_k, η_m and η_k, the Maxwell (subscript m) and Kelvin (subscript k) elasticity and viscosity, respectively. Values for different snow densities can be found in von Moos (2003).

At the instant of release the slab is motionless, but as it displaces, it deforms the compression zone.

The axial deformation of the compression zone and the motion of the rigid slab must fulfil the continuity constraint: $\dot{\varepsilon} = u / 2l_s$ and $\ddot{\varepsilon} = \dot{u} / 2l_s$. The mechanical model consists of two coupled ordinary differential equations (Eqs. 1 and 2 with primary unknowns slab velocity $u(t)$ and compression zone stress $\sigma(t)$). As a weak basal interface is necessary to initiate the tensile failure, the slab may have an initial velocity that causes the initial fissure. We consider t =0 to be the time the fissure has completely developed. In the following, we solve the two equations numerically with the boundary conditions: $u(t=0)=0$ and $\sigma(t=0)=\dot{\sigma}(t=0)=0$. The model can also be applied to determine the stability of snowcovers with variable gliding zone friction (Bartelt et al., 2012).

Theoretically, the tensile force that is no longer carried by the crown could be taken up by an increase in frictional force at the ground, retaining the slab in static equilibrium. In this case, the lost tensile force is balanced by an increase in basal shear stress. This can happen; however, we assume this does not occur: the gliding friction coefficient is constant and therefore the tensile force results in an increase in stress σ at the stauchwall. For this to happen, the friction on the ground must vary between two regions: (1) the detachment region l where the sliding friction is lower than the tangent of the slope angle and (2) the stauchwall, which is fixed rigidly to the ground. The difference in surface friction could be caused by a variation in surface roughness; for example, changes in surface properties e.g. small scale terrain undulations (Conway, 1998), meltwater accumulations (McClung and Clarke, 1987), vegetation or natural or man-made obstacles. We also admit the possibility that the gliding slab can smooth the surface, decreasing the friction of the surface. Mathematically, these changes in surface properties divide the snowcover into the gliding region with length l and length l_s.

3. RESULTS

A mathematical feature of the coupled solution of equations 1 and 2 is the existence of a steady equilibrium point (ε_s, σ_s), see Figure 5. This is just a mathematical way of saying that the system can find the quasi-stable equilibrium that we observe in nature. This steady-state point represents the refound equilibrium of the gliding slab. However, the new snowcover equilibrium is not found immediately, but requires several stress and strain rate oscillations with decreasing amplitude (Figure 5). To visualize this result imagine the shock absorbers in your mountain bike. In reaction to an intense loading there is a damped swinging response before equilibrium is reached or new shock occurs.

The counter clockwise spiral depicted in Figure 5 stipulates that the stauchwall will experience strain rates and stresses *greater* than the final, refound equilibrium. On our mountain bike we would experience a shock, but one that is damped depending on the properties of our shock absorbers. If large enough, these excess displacements (strain-rates) can cause failure of the compression zone. Thus, the model predicts both stable and failed snowcover states. Avalanche release is possible under the shock loading, but depends on the interplay between slope angle, basal friction, length of gliding slab (load) and the visco-elastic material properties of the compression zone (shock absorber).

In general a stauchwall zone with lower density will experience larger deformation rates and therefore are "weaker", in the sense that they will be loaded more closely to the critical brittle strain rate, approximately 10^{-2} 1/s (Figure 5a). Such critical strain rates were found by Scapozza (2003) in triaxial tests for a wide range of snow densities. The strain rate depends on the magnitude of the sliding friction coefficient μ (Figure 5b). Varying the sliding friction coefficient reveals another significant feature of the relationship between strain rate and ground conditions: even glide regions with high sliding friction can induce deformation rates near the critical strain rate. For example, there is no difference between the maximum calculated strain rate for the μ = 0.2 and μ = 0.4 cases (Figure 5b). This result suggests that gliding snow avalanches can form even on rough gliding surfaces. The two most important components are the strength (density) of the compression zone (the shock absorber) and the length of the gliding zone. Full-depth, gliding snow avalanches are therefore best mitigated, by reducing the length l of the gliding zone, creating "artificial" stauchwalls (berms) (Margreth, 2007).

The new snowcover equilibrium is found relatively slowly, compared to the time required for a stress wave to reach the stauchwall, which depends on the speed of sound in the snow-ice matrix. When the tensile crack opens at the crown, a tensile pressure wave will be transmitted to the stauchwall at an approximate speed of 1000 m/s (ice). For a slab length of l = 20 m, 0.02 s are required to propagate the disturbance to (and past) the stauchwall whereas the new visco-elastic snowcover equilibrium will be reached within 0.5 s to 1.0 s.

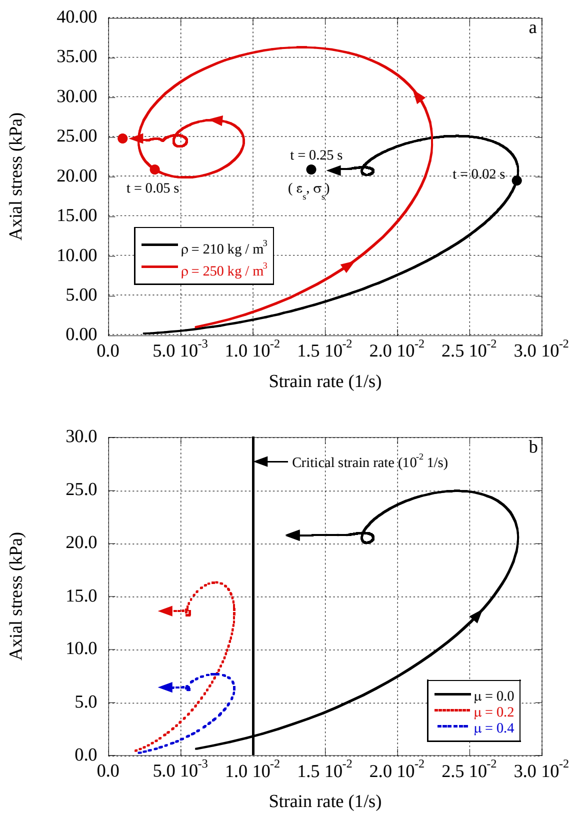

Fig. 5: Response of the compression zone/stauchwall to a sudden stress distribution when a tensile crack opens. a) Influence of stauchwall density on strain rate. The larger the density the smaller the strain rate and fewer stress oscillations are required to find equilibrium. b) Influence of gliding friction μ on strain rate. Without gliding friction μ=0, the maximum strain rate increases significantly. There is little difference in strain rate between the μ=0.2 and μ=0.4 cases.

Another result concerns the absence of the snow cover height in the model equations. This occurs because of our assumption of depth invariance in the downslope x-direction; the height of the stauchwall is the same as the snowcover height in the detachment zone. If this is the case, our results indicate that gliding snow avalanches are mechanically height invariant: the response of the stauchwall to the stress redistribution does not depend on the height, rather the frictional properties of the substrate. Gliding snow avalanches can occur for all snowcover heights. Of course, the damage potential very much depends on h. The likelihood of an avalanche releasing depends on the length l of the detachment zone and the friction μ of this zone. Once these are given, the start of full-depth avalanches depend on the properties of the compression zone (l_s and ρ).

4. CONCLUSIONS

Instead of asking the question why a full-depth avalanche starts after a crack has opened, we asked the reverse question: why does the gliding slab reach a new quasi-stable equilibrium. The model predicts that immediate failure is possible, but delayed release as well. Stability depends on the ability of the compression zone to absorb the sudden stress change from the crown to the stauchwall.

Unfortunately, the mechanics of this process are governed by the length and properties of the gliding zone (Lackinger, 1987) as well as the visco-elastic properties of the snowcover. This information is seldom (never) available to avalanche forecasters. Perhaps our investigations serve only to demonstrate (again) why it is difficult to forecast the occurrence of immediate full-depth avalanches. The model may be helpful in developing better permanent mitigation methods, such as delimiting the length of gliding zones.

A method to mitigate full-depth avalanche release after crack opening was to remove the slab using snow removal machines (Figure 6). Mechanically, this is effective method since it removes the load from the stauchwall. However, it is often both impossible and dangerous and therefore cannot be recommended in all cases. It is possible to blast the stauchwall and force the release of the slab. The effectiveness of this method depends on the gliding properties of the slab, which might vary during the course of the day. If there is no danger from the slab runout, it can be (but not always) an effective method. However, a negative blast result will weaken the stauchwall which may increase the chance of an uncontrolled, delayed release. Mechanical removal of the stauchwall is obviously dangerous as it places snow removal devices and personnel in harm's way. Reports of introducing water into glide cracks showed no clear result. It is not clear if this method works by decreasing the friction coefficient or increasing the length of the gliding zone. If the latter is the case, much water will probably required, the result uncertain and the logistics immense. The water might not spread evenly, but be concentrated in terrain gullies and therefore only locally erode the snowcover on the bottom without affecting the overall stability.

Fig. 6: Lungern-Schönbühl, canton Obwalden, Switzerland in January 2012: to reduce the danger from a full-depth avalanche, the slab was partially removed by snow removal machines.

Once the new quasi-stable equilibrium has been found, it is possible to identify the length of the gliding zone and the location of the stauchwall, as well as the stressed state of the compression zone. Folds and variations in glide speed become indicators of the frictional variations at the base. Extruded material at the stauchwall is an indicator of large bending stresses and deformations associated with increased glide. Without change of the external boundary conditions, the quasi-stable equilibrium should remain: there is no reason for the stauchwall to fail as long as the strain rates are well below the critical. This implies that delayed release avalanches require external factors such as temperature changes and/or precipitation that intensify gliding rates. At this stage, observations of glide rates are helpful. For example, the optimal time for blasting might be when the glide rates are relatively high. When the glide rates are smaller, blasting might not function and worsen the problem. Even if the observed glide rates decrease, indicating the secondary equilibrium is stable or becoming stable, the external parameters might change, leading to eventual failure.

In future, it might be possible to apply the model to predict whether a delayed avalanche release is imminent. That is, the model can be used to calculate slab gliding speeds. For this purpose, an understanding how the visco-elastic properties of the compression zone change as a function of temperature, or any other time dependent variable, is required.

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