

GLIDE-SNOW AVALANCHE MECHANICS: VELOCITY-DEPENDENT SNOW-GROUND INTERFACIAL FRICTION

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ABSTRACT: Glide-snow avalanches occur when the entire snow cover slowly slides downslope and suddenly releases and forms an avalanche. The physical processes controlling glide-snow avalanche initiation remain poorly understood, making their prediction and mitigation difficult. Although liquid water at the snow-ground interface is recognized as a key precursor of glide-snow avalanche release, its role in controlling snow-ground interfacial friction and glide dynamics remains largely unknown. To investigate how liquid water affects snow-ground interfacial friction, we conducted direct shear tests of snow over a temperature-controlled slate surface across a wide range of normal stresses and shearing velocities. Under dry conditions, the interface exhibited strain-softening behaviour described by a Mohr-Coulomb model with a time-dependent cohesive contribution, while shear velocity had no significant effect. Under wet conditions, the amount of measured liquid water did not systematically affect interfacial shear strength; instead, velocity became the dominant control. Slow sliding involved low friction, whereas faster sliding produced higher peak and residual shear resistance. We describe this behaviour using a velocity-dependent Mohr-Coulomb law. Peak strength increased through both cohesion and friction, whereas during sustained sliding the residual cohesion remained approximately constant and rate strengthening is mainly carried by the frictional term. The kinetic friction angle increased strongly with velocity and approached a plateau above approximately 2 mm s⁻¹. This rate strengthening provides stabilizing feedback during gliding: a steady sliding velocity can exist when basal resistance balances the driving stress, whereas no equilibrium is possible once the maximum basal resistance is exceeded, leading to accelerated sliding. These results provide a constitutive description of the wet snow-ground interface that can be implemented in slope-scale models of glide-snow avalanche initiation.

KEYWORDS: glide-snow avalanche, snow-ground interface, rate-dependent friction

1. INTRODUCTION

Glide-snow avalanches (a type of full-depth avalanches) involve significant volumes of moving snow. Glide-snow avalanches are a concern for operational avalanche forecasting because they are difficult to predict and represent a considerable challenge for the protection of roads, railways, and ski resorts (Höller, 2014; Ancey and Bain, 2015). Because the timing and size of glide-snow avalanche release cannot be anticipated, control services may need to keep exposed infrastructure closed for extended periods.

Glide initiation is assumed to start with a loss of friction along the snow-ground interface due to the accumulation of liquid water (McClung and Clarke, 1987). Recent field monitoring has quantified how much interfacial water is present and where it comes from, reporting liquid water contents of 3–7 % at the interface before release (Fees et al., 2025a). What monitoring cannot provide is the mechanical counter-

part: how interfacial water modifies shear resistance, and under which conditions. Once the snowpack glides, stresses build up within the snowpack, and a tensile fracture may open through the entire depth of the snowpack (glide crack). After a glide crack has opened, the snow can continue to glide and stresses increase at the lower end until the compression (retention) zone fails and the avalanche is released (Bartelt et al., 2012). However, not every visual sign of gliding results in an avalanche, and the time between glide-crack opening and release ranges from hours to weeks (Fees et al., 2025b).

Although glide-snow avalanche activity has been studied since the 1930s, the mechanical response of the snow-ground interface, particularly under wet conditions, remains poorly constrained (Höller, 2014; Ancey and Bain, 2015). There is no real consensus on how liquid water affects resistance, or if this resistance depends on the sliding speed; there is not even agreement on the friction model that should be adopted: dry Coulomb friction (Bader et al., 1939), viscous shear of a lubricating water film (In Der Gand and Zupančič, 1966; Salm, 1977), snow creep over a rough bed (McClung, 1981), and a Mohr-Coulomb criterion with velocity-dependent cohesion

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(Lackinger, 1987). These laws were inferred from measured glide rates rather than from direct measurements of the interface.

In a previous cold-laboratory study, we sheared snow over glass and sandpaper at a single shearing rate and found no dependence of the friction angle on liquid water content (Bobillier et al., 2024). Here we use the direct shear test and cover a wide range of normal stresses and shearing velocities on a natural glide surface (slate rock) to determine the constitutive response of the wet snow-ground interface and ask whether it can be described by a single friction law.

2. DATA AND METHODS

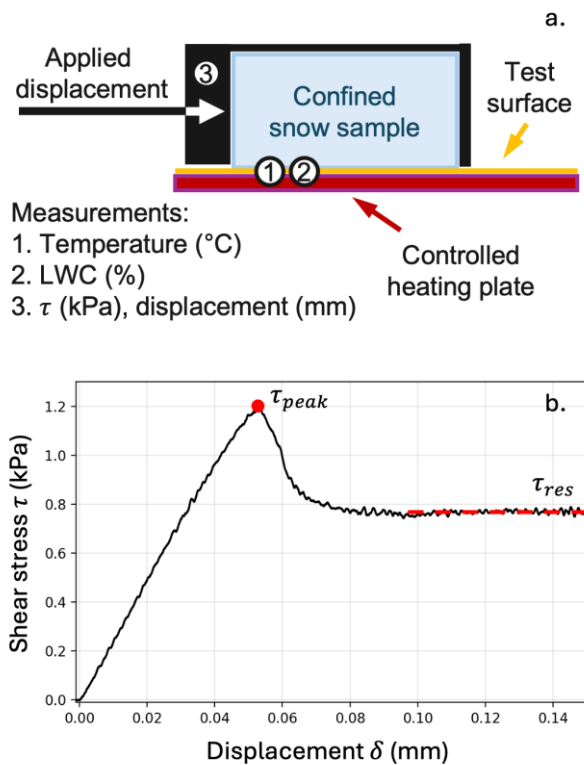


Figure 1: a. Experimental setup: a confined snow sample is sheared over a substratum mounted on a temperature-controlled heating plate, with measurements of (1) interface temperature, (2) liquid water content, and (3) shear stress and displacement. (b) Typical shear stress-displacement response under dry conditions, defining the peak shear stress τ_{peak} and the residual shear stress τ_{res} .

2.1 Sample preparation and setup

Snow was produced in a cold laboratory at -25°C and stored at -5°C until it reached thermal equilibrium. It consisted of dry, decomposing and fragmented precipitation particles (DF; Fierz et al., 2009). For each slab, 1.7–2.0 kg of snow was sieved through a 3 mm mesh into a 30 cm x 40 cm mold and

compacted under a vertical load of 60 kg for 10 min, yielding slabs 4.5–6.5 cm thick with a density of 220–320 kg m^{-3} . Cylindrical specimens with an 8 cm diameter were extracted using a ring pressed vertically into the slab, so that no additional compaction was induced.

Tests were performed with a mobile shear-compression unit (MSCU) at -5°C room temperature. Each specimen was placed on the shear surface, and a confining box was positioned on top, the normal load was applied on the confining box. The MSCU tip pushed the guide box along the shear surface at a prescribed velocity while recording force and displacement at 2000 Hz, over a total displacement of about 10 mm. The substratum was slate sourced locally in the Davos region, chosen as representative of a natural, impermeable glide surface. A geotextile surface was tested in parallel; because it showed the same trends, only the slate results are reported here.

Normal stresses ranged from 0.1 to 5.3 kPa, corresponding to snow depths of roughly 0.03–1.8 m for a snowpack of 300 kg m^{-3} . Shearing velocities ranged from 0.06 to 8.68 mm s^{-1} , covering reported field glide rates (Maggioni et al., 2019). About 350 tests were performed, with at least three replicates per condition.

2.2 Dry and wet conditions

Under dry conditions, no liquid water was present at the interface, and all components were kept below 0°C . Contact (idle) times of 0, 600 and 1500 s between the positioning of the sample and the start of shearing were imposed to analyse interfacial sintering.

Under wet conditions, a temperature-controlled heating pad kept the shear surface at $+2^{\circ}\text{C}$, which produced liquid water at the interface for all samples. LWC was varied by leaving the sample on the heated surface from seconds to several minutes before testing. LWC was measured immediately after each test with a dielectric sensor (SLF SnowPro-17), five times per sample with a rotation of about 72° between measurements.

2.3 Data processing

Force signals were normalized by the contact area (Figure 1). Two quantities were extracted from each curve: the peak shear stress τ_{peak} taken as the maximum shear stress, and the residual shear stress τ_{res} , taken as the mean shear stress beyond 1 mm. The apparent friction angle of an individual test is:

$$\varphi = \tan^{-1}(\tau / \sigma_n)$$

with the apparent static friction angle φ_s and the apparent kinetic friction angle φ_k obtained from τ_{peak} and τ_{res} , respectively.

3. RESULTS

3.1 Influence of liquid water content

When the material was sheared at a constant shearing velocity of 0.06 mm s^{-1} , the apparent friction angle decreased markedly between dry and wet conditions but showed no systematic trend within the wet regime (Figure 2). Mean values in the wet regime remained between about 21° and 26° for the static angle and between about 20° and 23° for the kinetic angle over the full range of measured LWC (0–11 %), with the scatter of the 1 % bins comparable to the scatter within a single bin.

Under dry conditions, the apparent friction angles were both higher (about 41° and 29° on average) and considerably more scattered, consistent with the large, contact-time-dependent cohesive contribution.

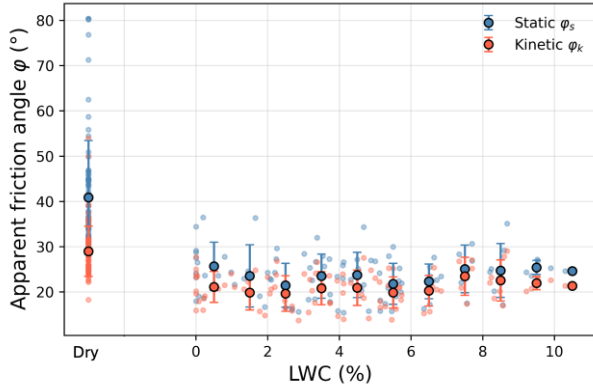


Figure 2: Apparent static (φ_s , blue) and kinetic (φ_k , orange) friction angles as a function of liquid water content at $v = 0.06 \text{ mm s}^{-1}$. Faint symbols are individual tests; solid symbols are mean values per 1 % LWC bin with standard deviation. The dry reference is shown on the left.

3.2 Shear stress-displacement behaviour

Under wet conditions, the shape of the stress-displacement curve depended strongly on the shearing velocity (Figure 3). At the lowest velocity (0.06 mm s^{-1}), the shear stress increased non-linearly towards a plateau, with no pronounced peak: peak and residual stresses differed by less than 10 %. At the highest velocity (8.68 mm s^{-1}), the stress rose to a sharp peak and then dropped by about 60 % to the residual level.

Under dry conditions, all curves exhibited the classical peak-residual response irrespective of velocity (Figure 1). Increasing the contact time from 0 to 1500 s raised the cohesion from 350 to 600 Pa without modifying the friction angle, consistent with sintering reported by Szabo and Schneebeli (2007). A global Mohr-Coulomb fit over all dry tests yielded $\varphi_s = 24.2^\circ$ with $c = 364 \text{ Pa}$ for zero contact time, and $\varphi_k = 23.7^\circ$.

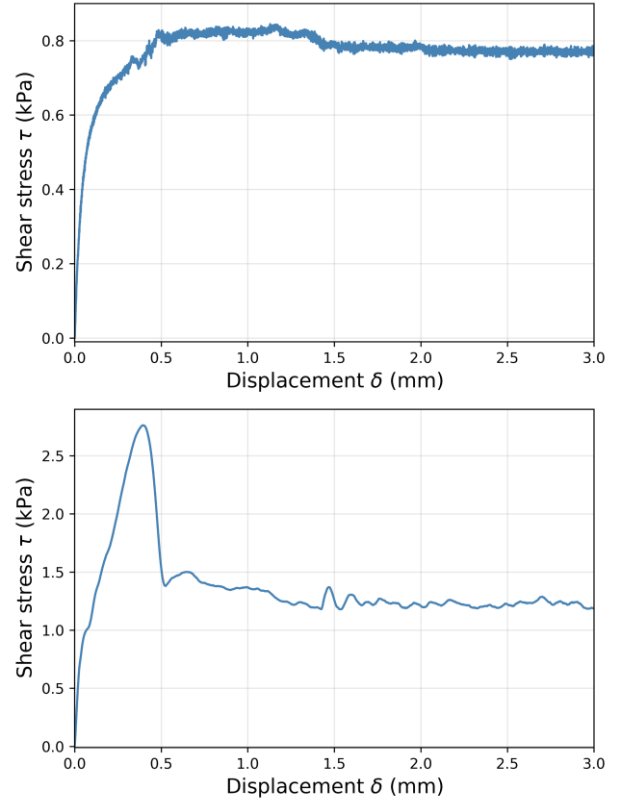


Figure 3: Shear stress as a function of shear displacement under wet conditions for two shearing velocities: $v = 0.06 \text{ mm s}^{-1}$ (left), $v = 8.68 \text{ mm s}^{-1}$ (right). Peak (τ_{peak}) and residual (τ_{res}) shear stresses are indicated. Note the different axis scales. Normal stress $\sigma_n = 1.73 \text{ kPa}$, LWC = 3.2 %.

3.3 Rate dependence and interface law

The apparent friction angles measured under wet conditions increased strongly with velocity and saturated above about 2 mm s^{-1} (Figure 4). At the lowest velocity, the static and kinetic values converged to about 22° , consistent with the absence of a distinct peak in the corresponding stress-displacement curves. At the plateau, they diverged by roughly 20° , reaching about 55° (static) and 36° (kinetic).

We extended the Mohr-Coulomb criterion by making both the friction angle and the cohesion functions of the sliding velocity v :

$$\tau_{peak}(v, \sigma_n) = c(v) + \sigma_n \tan \varphi_s(v)$$

$$\tau_{res}(v, \sigma_n) = c_0 + \sigma_n \tan \varphi_k(v)$$

with exponential saturation laws fitted to the internal friction angles obtained from the $\tau - \sigma_n$ envelopes,

$$\varphi_i(v) = \varphi_0 + (\varphi_{\infty,1} - \varphi_0)[1 - \exp(-a_i v)],$$

$$i = s, k$$

and to the cohesion,

$$c(v) = c_0 + c_\infty [1 - \exp(-a_c v)]$$

Both friction angles share the same low-velocity limit φ_0 , which indicates a common frictional mechanism as the sliding rate approaches zero.

The modelled apparent friction angles are shown as solid lines in Figure 4 ($R^2 = 0.8$ and $R^2 = 0.6$ for the static and kinetic angle, respectively); the largest deviations occurred between 0.7 and 2.2 mm s⁻¹, where the transition towards the saturated regime was most rapid.

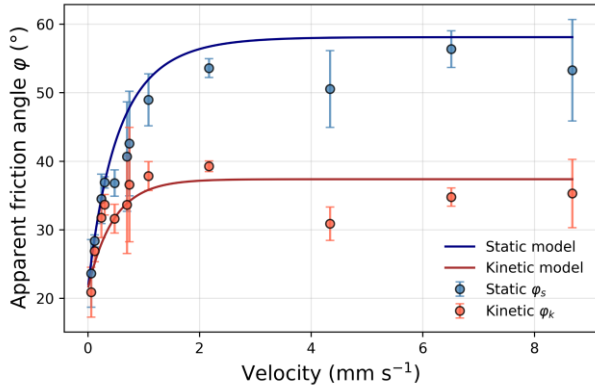


Figure 4: Apparent static (φ_s , blue) and kinetic (φ_k , orange) friction angles as a function of shearing velocity under wet conditions. Markers are mean values over all wet tests at a given velocity; error bars indicate the standard deviation. Solid lines show the rate-dependent Mohr-Coulomb law model.

4. DISCUSSION

Within the partially saturated regime, the measured liquid water content (LWC) had no systematic effect on the interfacial shear strength, consistent with our earlier tests on glass and sandpaper (Bobillier et al., 2024). The main transition occurred between dry and wet conditions: the dry interface showed no significant rate dependence, whereas the wet interface became strongly rate dependent.

Under wet conditions, the stress-displacement response changed markedly with velocity. For velocities close to 60 $\mu\text{m s}^{-1}$, deformation was gradual, and peak and residual stresses were similar; at higher velocities, a sharp peak developed, followed by weakening. We interpret this as a transition in the interfacial failure mode: at low rates, bonds fail progressively while capillary contacts reform, allowing creep-like deformation; at higher rates, contact healing becomes too slow relative to loading, stress accumulates, and many bonds fail almost simultaneously. This interpretation remains a hypothesis; the observed change from creep-like to brittle-like behavior is analogous to a ductile-to-brittle transition (Narita, 1980).

Under wet conditions, the Mohr-Coulomb envelopes show that the peak stress components do not evolve identically. For strength, both the interface friction angle and the cohesion increase with velocity, from 13°

and 344 Pa at 0.06 mm s⁻¹ to 41.4° and 805 Pa at 8.68 mm s⁻¹. During sustained sliding, a residual cohesion remains close to 230 Pa while the kinetic interface friction angle increased from 13.6° to 29.1°. The envelopes therefore fan out as the speed increased rather than shifting in parallel: rate strengthening therefore scales with normal load, suggesting a contact-scale frictional origin. This contrasts with classical glide laws, which carry the velocity dependence in a viscous or cohesive term while keeping the frictional term either fixed or absent (In Der Gand and Zupančič, 1966; Salm, 1977; Lackinger, 1987). Those laws assume a resistance that increases linearly with velocity, whereas our measurements show a strongly nonlinear, saturating response.

This has direct consequences for glide dynamics. An imposed load increment produces a slip-rate increment, to which the wet interface responds by strengthening; basal slip is therefore unlikely to be initiated by a sudden load increase alone, and motion should emerge progressively at low velocity. This is consistent with the resistance of glide-snow avalanches to artificial triggering and with new snow loading acting as the sole trigger in only one of the 21 events documented by Lackinger (1987). Once sliding has started, the residual resistance $c_0 + \sigma_n \tan \varphi_k(v)$ is self-regulating: an increase in velocity raises the basal resistance and slows the motion, whereas a decrease lowers it and allows the snow to accelerate again. A steady velocity is reached where the basal resistance balances the driving stress, and because c_0 does not scale with normal stress, this equilibrium depends on both slope angle and snow load. If the friction angle tends to be constant at high velocity, a second threshold appears: beyond the maximum basal resistance, no steady solution exists and sliding accelerates. Predicted steady velocities encompass reported field glide rates (Maggioni et al., 2019), and tilt tests (not shown) reproduce the three expected regimes: 1. no sliding, 2. steady sliding and 3. accelerated sliding.

These conclusions apply to a freely sliding block and cannot be transferred directly to glide-snow avalanche release. A natural snowpack is retained downslope by a compression zone and laterally by the surrounding snow, while internal deformation redistributes stresses. The interface law can therefore control the onset and the rate of gliding, but release requires failure of the retaining zone (Bartelt et al., 2012). The next step will be to incorporate the measured interface law in a slope-scale snow model using the material point method (Gaume et al., 2018). The present results are limited to snow consisting of decomposing and fragmented precipitation particles and an impermeable slate substrate; future work should quantify the effects of substrate roughness and permeability.

5. CONCLUSIONS

Direct shear experiments showed that wet snow-ground friction is strongly velocity dependent, whereas the measured liquid water content within the wet regime had no systematic effect on interfacial shear strength. Both peak and residual resistance

increased with sliding velocity and approached a plateau at high velocities. This rate strengthening provides stabilizing feedback during snow gliding and can be described with a velocity-dependent Mohr-Coulomb law. The proposed interface law provides a basis for investigating how basal friction controls glide dynamics in slope-scale models.

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