THE ROLE OF SLOPE ANGLE IN SKIER-TRIGGERED SLAB AVALANCHE RELEASE

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ABSTRACT: Slope angle is a key factor in dry-slab avalanche formation and central to avalanche education and terrain assessment. Combined with the avalanche danger rating, it is commonly used to estimate the release probability on a crux slope. Even small differences in steepness may therefore influence risk perception and decision-making. However, slope angle affects several interacting processes in slab avalanche formation, raising the question of how it influences triggering probability across the full range from flat to 45°, covering the terrain relevant for backcountry travel.

This study examines the effect of slope angle on slab-avalanche formation, from failure initiation and crack propagation to slab release. We synthesise current research, apply fracture-mechanical approaches and relate slope angle to skier-induced loading and dynamics. Additionally, we analyse slope angles at release areas and trigger locations of human-triggered avalanches in Switzerland.

Our findings show that slope angle has limited direct effects on failure initiation and the onset of crack propagation but influences skier loading and crack-face friction, thereby promoting dynamic crack propagation and slab release. Overall, loading type and snowpack properties often have a greater influence on release probability than small differences in slope angle. Particular caution is warranted on uniform slopes between 35° and 40°, where skier loading, crack-propagation propensity, and friction appear to combine favourably for avalanche release. Persistent weak layers have significantly lower friction angles and therefore require a more conservative approach.

KEYWORDS: slope angle, slab avalanche release, failure initiation, crack propagation, friction, skier triggering

1. INTRODUCTION

Slope angle is a key factor in avalanche formation and a central element of avalanche education and terrain assessment. Avalanches begin to slide when the slope angle exceeds the friction angle at the crack faces, which is approximately 30° (van Herwijnen and Heierli, 2009). Skier-triggered avalanches release mainly on slopes between 30° and 45°, with most starting between 35° and 40° (Schweizer and Lütschg, 2001; Harvey, 2002). By relating avalanche accidents to GPS tracks of backcountry recreationists, Degraeuwe et al. (2024) showed that slope angle substantially increases the relative frequency of human-triggered avalanches, particularly between 30° and 40°. This supports the long-standing rule of thumb that triggering becomes more likely as the avalanche danger level and slope angle increase.

Practitioners commonly begin assessing a crux slope by combining its slope angle with the current avalanche danger level. Simple tools such as the graphical reduction method, based on Munter's reduction method (Munter, 2003), provide an initial estimate of avalanche release probability (Harvey et al., 2022). In this scheme, a 5° difference in slope angle is equivalent to a change of one danger level. Thus, even a small difference, such as 33° versus 37°, can markedly affect how people assess release probability.

However, empirical evidence is inconsistent. Harvey (2002) found no differences in the slope angles of human-triggered avalanches among danger levels. Similarly, Birkeland et al. (2014) found no relationship between slope angle and compression test results, whereas Jamieson and Johnston (1993) reported a relationship between slope angle and Rutschblock score.

These inconsistencies raise the question: What effect does slope angle have on the probability of triggering a dry-snow slab avalanche across the range from flat to 45°, covering the relevant backcountry terrain, and in particular between 30° and 45°?

Although slope angle is easy to assess, its influence on avalanche release is complex. Its effects on skier-induced loading, failure initiation, crack propagation, friction, and potential consequences are seldom considered separately. We therefore examine how slope angle affects the different stages of slab-avalanche release. We review previous research, apply a fracture-mechanical model, consider snow properties and dynamic

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loading, and compare the findings with several datasets of human-triggered avalanches. For this purpose, we also compiled a new dataset of mapped avalanches from two contrasting winters.

2. REVIEW OF SLOPE ANGLE EFFECT ON AVALANCHE RELEASE

We first provide an overview on previous research on the influence of slope angle on the avalanche release processes.

2.1 *Slope angle and failure initiation*

A weak layer fails locally when the applied stress exceeds its strength. Reuter et al. (2015) found that failure initiation became more likely with increasing slope angle because of higher shear stresses, but the relationship was weak and not evident on every field day. Reiweger et al. (2015) and Schöttner et al. (2026) showed that weak layers are weaker in shear than in compression, implying that weak-layer strength decreases as the shear component increases with slope angle. Both concluded that failure initiation is a mixed-mode process involving compression and shear.

Thumlert and Jamieson (2014) measured dynamic loading from skiers and snowmobilers and concluded that slab structure controls the transmission of stress to buried weak layers: softer slabs allow stresses to penetrate deeper, while harder slabs distribute them laterally through bridging. They did not relate the measured loads to slope angle.

Supej et al. (2015) found that steeper slopes do not necessarily increase peak loading of slalom skiers but alter how and when loads are applied. Increasing slope angle from about 20° to 25° did not substantially raise average loading; instead, forces became more concentrated mid-turn, turns became tighter, and skiers adopted greater angulation and different techniques. Thus, slope angle affects loading mainly through technique changes rather than a direct increase in force. Although the study examined World Cup slalom skiers, whose style differs from backcountry skiing, we assume a similar technique adaptation with increasing slope angle despite differences in forces and speeds.

2.2 *Slope angle and crack propagation*

While failure initiation is primarily a local stress–strength problem, crack propagation depends more on the mechanics of the slab–weak-layer system. The onset of crack propagation is the transition from a localized failure to a self-sustaining crack, while dynamic propagation describes the crack's subsequent propagation. Gaume et al. (2017) found that the critical crack length decreased with increasing slope angle and concluded that the onset of crack propagation becomes easier on steeper slopes, whereas Reuter et al. (2015) found no significant relationship in natural snowpacks. Adam et al. (2024) showed that weak-layer anticracks involve mixed-mode fracture and that fracture resistance is greater under in-plane shear, mode II, than under compressive collapse, mode I. These findings likely differ because the studies examined different measures.

During dynamic propagation, slope angle appears to control the propagation regime. Trottet et al. (2022) and Bobillier et al. (2024) found that collapse-induced compressive stresses dominate below approximately 30°. Above the effective friction angle, shear stresses and the gravitational pull of the slab become dominant. This transition occurs after the crack has propagated over several metres. Video analyses by Simenhois et al. (2024) further showed that crack propagation accelerated with distance and was three to four times faster upslope and downslope than across the slope.

Overall, the effect of slope angle on crack propagation above approximately 30° remains insufficiently understood. Steeper slopes provide more available potential energy due to the geometric effect of relative slab thickness increasing in the gravitational direction. Yet, fracture resistance varies among loading modes. Adam et al. (2026), for example, showed that cross-slope loading, mode III, requires less energy than compressive mode I fracture and may therefore facilitate cross-slope crack propagation on steeper slopes.

2.3 *Slope angle, tensile failure and slide*

The greater the slope angle, the stronger the gravitational pull, which increases shear stress in the weak layer and tensile stress in the slab, potentially causing earlier slab fracture and crack arrest. This may explain why release areas sometimes do not extend across the entire slope, even when no distinct change in terrain is apparent (Pfister, 2016). However, Meloche et al. (2025) concluded that tensile stress does not increase as rapidly during fast dynamic crack propagation as predicted by a quasi-static force balance.

Crack-face friction is critical for slab release and varies with weak-layer type. Median friction coefficients are higher for non-persistent weak layers, at 0.75 or approximately 36°, than for persistent weak layers, at 0.57 or approximately 30° (Simenhois et al., 2012; van Herwijnen and Heierli, 2009). Accordingly, McCammon (2009) reported lower starting-zone angles for avalanches on persistent weak layers (~37°) than on decomposed fragments or new snow (~43°). Weak-layer type therefore affects crack-face friction and, consequently, crack propagation and slab sliding.

3. SKIER-LOADING MODEL AND HUMAN-TRIGGERED AVALANCHES

3.1 Dynamic skier loading model

Besides its direct effects on avalanche-release processes, slope angle may influence the load a skier exerts on the snowpack. To quantify this effect, we use a simplified mechanical model to calculate skier-induced loading for different slope angles and loading scenarios. We then compare these loads with the WEAC fracture-mechanical model (Rosendahl and Weißgraeber, 2022; Weißgraeber and Rosendahl, 2023), as implemented by Werner et al. (2026), to assess weak-layer failure across a range of slope angles and slab properties.

Skier loads during skiing, stopping, and uphill travel were modelled using only skier weight, speed, and gravity; snow properties and ski-snow friction were neglected. Results are intended for relative rather than absolute comparisons and represent surface loads, not weak-layer stresses. For each scenario, the peak vertical ground-reaction force F_z was converted to an equivalent skier mass $m_{\mathrm{eq}} = F_z/g$, where g is the gravitational acceleration. This is directly comparable to the WEAC critical skier weight for weak-layer failure. Calculations used an 80 kg skier and slope angles from 0° to 45°. Four loading scenarios were considered:

Skinning upwards is modelled as a lumped-mass step-up with the centre of mass rising by the angle-dependent step height $h = L\sin(\phi)$ per step, where L is the constant stride length. The push phase is modelled as a cosine-shaped displacement from which the peak acceleration is extracted and converted into a ground reaction force. This is an upper-bound estimate, not a spring-mass gait simulation.

Carved turns are modelled as a skier following a semicircular path of radius R in the slope plane, while retaining their velocity on curve entry. The problem reduces to a brake-only minimum-effort control problem with matching entry and exit speed v_0. Different configurations were calculated, including short turns ($R = 3$ m) and large turns ($R = 15$ m) at entry speeds of 4 to 15 m s⁻¹. The model assumes full contact and no ski–snow friction.

Hard stops are modelled as a constant-speed semicircular carve followed by a triangular force pulse that stops the remaining in-plane speed over a given duration t_{stop}. Vertical loading depends on the coupled fraction of along-slope speed, via a coupling factor k between 0 and 1.

Zig-zag hop is modelled as short jump turns with takeoff at speed v_0 lofted 10° above the snow surface; only the velocity change needed to resume coasting is absorbed at landing. Touchdown is absorbed by a hybrid of a triangular impulse and a work–energy stop over the leg compression distance d_{leg}, taking the more conservative peak.

Turn radii and speeds are order-of-magnitude anchors informed by alpine turn geometry and speed measurements (Supej et al. 2015; Federolf 2005), used as a sanity check rather than a backcountry calibration. Trend calibration against measured dynamic loading (Thumlert and Jamieson 2014) remains approximate.

3.2 Analysis of human-triggered avalanches

We examined slope angles of human-triggered avalanches at approximately 300 trigger locations and within 1268 release areas across Switzerland, calculated from a 5 m digital elevation model within segmented polygons. To compare weak layer types we compared two winters with contrasting snowpacks: 2023/24, dominated by storm snow with almost no persistent weak layers, and 2025/26, with below average snow depths and avalanches releasing widely on persistent, large faceted or surface hoar weak layers. The comparison comprised 140 reported, mapped and photographed avalanches from 2023/24 and 259 from 2025/26.

4. RESULTS

4.1 Dynamic skier loading

In general, skier-induced loads increased with both slope angle and speed. The effect of slope angle was quantified using relative load factors for the ranges 0° to 30° and 30° to 45° (Table 1). The largest increase from 0° to 30° occurred during fast, short-radius turns, reaching a factor of 2.16, whereas the increase from 30° to 45° was 1.25 (Table 1). Across all scenarios, loads increased by 6% to 33% over the latter range. In contrast, loads differed severalfold among loading types. At 35°, for example, loads ranged from about 1.5 times body weight (BW) during a large-radius turn at 8 m s⁻¹ to 5.5 times BW during an abrupt stop at 15 m s⁻¹ (Table 2).

The WEAC-derived critical skier load also increased between 0° and 45°, although less steeply than the applied loads. Accounting for this increase reduced the effect of slope angle on the load relevant to weak-layer failure. The resulting compensated factors, shown in parentheses in Table 1, were therefore lower than the corresponding factors for the load applied at the snow surface. Between 30° and 45°, the compensated factors remained close to one, ranging from 0.86 to 1.08, indicating that slope angle had little effect on failure initiation within this range, regardless of the loading type.

Table 1: Relative load increase from flat terrain to 30° and from 30° to 45°, respectively. Values in parentheses account for the WEAC-calculated critical load and indicate the effective load-increase factor for weak-layer failure. Bold values denote minima and maxima.

Loading type	***v (m s⁻¹)***	***Factor from 0° to 30°***	***Factor from 30° to 45°***
Large turn (R = 15 m)	15	1.85 (1.58)	1.23 (1.00)
Large turn (R = 15 m)	8	1.38 (1.18)	1.20 (0.98)
Stop (R = 8 m)	15	1.37 (1.17)	1.11 (0.90)
Stop (R = 8 m)	8	**1.16 (0.99)**	**1.06 (0.86)**
Short turn (R = 3 m)	4	1.42 (1.22)	1.20 (0.98)
Short turn (R = 3 m)	8	**2.16 (1.85)**	1.25 (1.02)
Zig-zag hop	2	1.19 (1.02)	1.26 (1.02)
Zig-zag hop	4	1.26 (1.08)	**1.33 (1.08)**
Skinning up	–	1.54 (1.32)	1.15 (0.93)
Mean weak layer capacity (WEAC)	–	1.17	1.23

Table 2: Load at 35° as a multiple of body weight (BW), with minima and maxima shown in bold.

Loading type	***v (m s⁻¹)***	***Factor of BW at 35°***
Large turn (R = 15 m)	15	2.00
Large turn (R = 15 m)	8	**1.47**
Stop (R = 8 m)	15	**5.51**
Stop (R = 8 m)	8	3.00
Short turn (R = 3 m)	4	1.51
Short turn (R = 3 m)	8	2.34
Zig-zag hop	2	2.39
Zig-zag hop	4	3.79
Skinning up	–	1.62

Figure 1 summarises the main findings and shows the ratio of skier-induced load to the critical load for failure initiation from WEAC for a slab thickness of 50 cm and varying density; when the load ratio exceeds the critical ratio of a given weak layer, failure is expected. At low density, all loading scenarios exceed the critical load. At high density only movements with high loading rates may initiate a failure in very weak layer scenarios. Overall, the effect of slope angle on skier-induced loading is minor compared with the differences between the loading types and the snowpack layering.

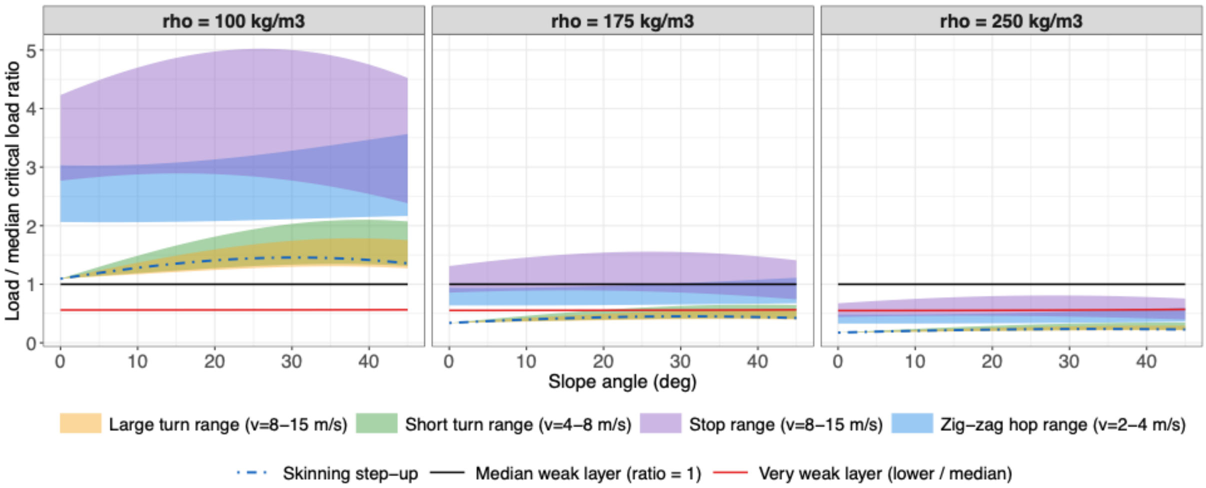

Figure 1: Skier-induced load relative to WEAC-calculated critical weak-layer capacity for a 50 cm slab at three densities. Coloured bands show loading types at two speeds, with the upper boundary indicating the higher speed. The black and red lines mark the critical ratios for a median weak layer, defined as one, and a very weak layer, respectively. Values above either line indicate failure initiation.

4.2 Human-triggered avalanches

Half of the observed human-triggered avalanches had median release-area slope angles within the narrow range of 35° to 40° (Figure 2, blue). Of the 1268 avalanches, 94% released in areas containing terrain steeper than 35°, and only 6% where slopes did not exceed 35° (Figure 2, violet). Similarly, 94% were triggered on slopes steeper than 25°, indicating that triggering from flat terrain was rare (Figure 2, orange).

Comparing the storm-snow-dominated winter of 2023/24 with the persistent weak-layer winter of 2025/26 revealed significant differences in release-area slope angles. The median and 10th and 90th percentiles differed significantly between winters (Wilcoxon rank-sum tests, all $p < 0.001$). In 2025/26, the median slope angle was 2.7° lower (95% CI: 1.9° to 3.5°) and the 90th percentile 3.9° lower (95% CI: 3.1° to 4.7°; Figure 3). Under pronounced persistent weak-layer conditions, 41% of release areas had median slope angles below 35°, more than twice the proportion under predominantly storm-snow conditions. The proportion with 90th-percentile angles below 35° was about four times higher, at 13% versus 3% (Table 3).

Table 3: Release areas with median and 90th-percentile slope angles below 35° during storm-snow (noPWL) and persistent weak-layer winters (PWL).

Winter	***N***	***Median < 35° (%)***	***90th percentile < 35° (%)***
2023/24 (noPWL)	140	18	3
2025/26 (PWL)	259	41	13

These findings align with previous studies reporting lower friction angles for persistent than for non-persistent weak layers (McCammon, 2009; Simenhois et al., 2012; van Herwijnen and Heierli, 2009).

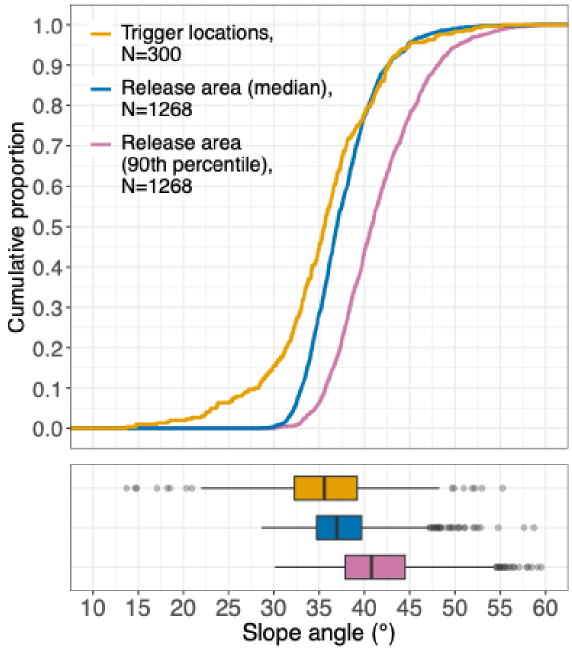

Figure 2: Slope-angle distributions for 300 approximate trigger locations (orange) and the median (blue) and 90th percentile (violet) within 1268 release areas of human-triggered avalanches all over Switzerland. Cumulative proportions (top) and boxplots (bottom).

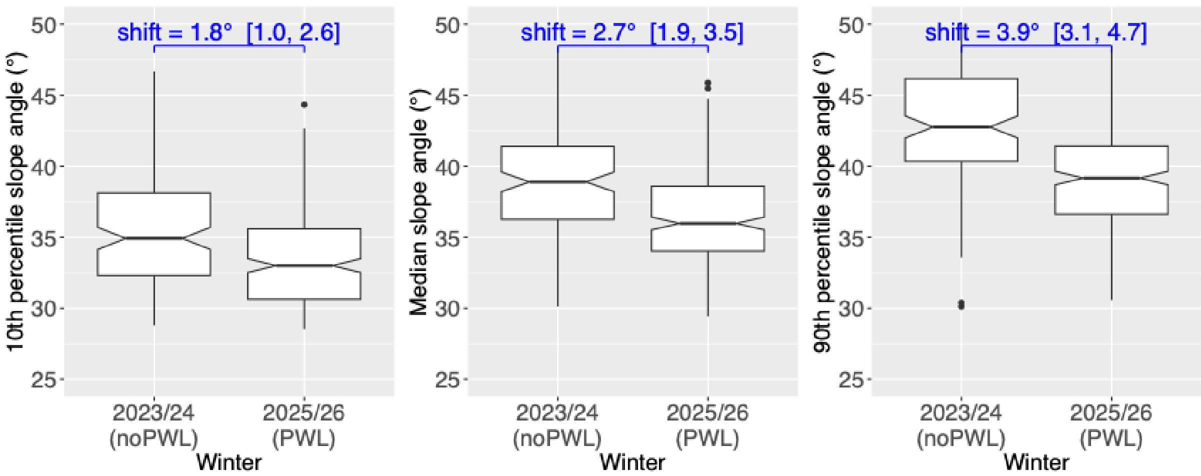

Figure 3: Release-area slope angles during storm-snow (2023/24) and persistent weak-layer (2025/26) winters: 10th percentile (left), median (middle), and 90th percentile (right). Blue indicates the shifts between the winters with 95% confidence intervals.

5. DISCUSSION ON EFFECT OF SLOPE ANGLE

General slope-angle statistics for avalanche release can mask the distinct effects of slope angle on slab-avalanche failure processes and consequences. We therefore examined its role in three key stages: failure initiation, crack propagation, and slab release. Our study combined a literature review, a comparison of skier-induced dynamic loads with WEAC-predicted critical loads, and an analysis of release-area slope angles for human-triggered avalanches during two winters dominated by contrasting weak-layer types. The highly simplified loading calculations are intended solely for relative comparison. We summarise the findings for each stage of the slab-avalanche failure process.

5.1 Failure initiation

Our simplified calculations showed that both the applied load and the critical load required to initiate failure increase with slope angle. Because these effects largely offset each other, slope angle alone has only a minor influence on failure initiation. From 0° to 30°, the load effect increased effectively by factors ranging from 0.99 to 1.85 across the snowpack scenarios considered. Between 30° and 45°, however, no loading type showed a consistent increase in relative loading, and the effect of some loading types decreased slightly (Table 1, values in parentheses; Figure 1).

In contrast, skiing style altered the applied load by factors of several. Relative to slow turns or skinning, fast zig-zag hops more than doubled the load, while abrupt stops at higher speeds more than tripled it (Table 2). Loading also increased with speed for every loading type, with the greatest increases occurring in skiing styles that already generated high loads.

Snowpack structure remains the primary factor governing failure initiation. Figure 1 shows that the critical load varies considerably with slab density, consistent with the importance of slab hardness reported by Thumlert and Jamieson (2014).

Although we did not investigate how slope angle affects skiing style, skiers may adapt their speed and technique as terrain steepens, consistent with observations of World Cup skiers by Supej et al. (2015). Skiers may move more slowly and smoothly on gentler terrain but use short turns and small jumps on slopes around 40°, generating loads equivalent to several times their body weight.

Schöttner et al. (2026) showed that surface hoar weak layers are generally 1.4 to 3 times stronger under compression than under shear. They also found that failure under combined loading can be described by an elliptical failure envelope. This criterion is implemented in WEAC and was therefore included in our calculations. Overall, weak-layer failure initiation depends much more strongly on snowpack characteristics and skiing style than on slope angle alone.

5.2 Crack propagation

As discussed previously, slope angle has only a minor direct effect on failure initiation and the onset of crack propagation. However, recent studies indicate that after a crack has propagated several metres, increasing slope angle can cause a fundamental transition in propagation dynamics. Once the gravitational driving force exceeds basal friction, propagation shifts from a collapse-dominated to a shear-dominated regime, characterised by higher propagation speeds and greater energy release (Trottet et al., 2022; Adam et al., 2024; Bobillier et al., 2024; Bergfeld et al., 2025).

The greater energy available in the shear-dominated regime is consistent with the concentration of avalanche release areas on slopes between 35° and 40°, where the gravitational driving force is more likely to exceed basal friction. Meloche et al. (2025) suggest that once a crack has propagated several metres on a steep slope, it becomes much more difficult to arrest than on low-angle terrain. This mechanism may also explain the pronounced decrease in remote triggering with increasing distance from terrain steeper than approximately 30° reported by Harvey et al. (2018).

Overall, slab and weak-layer properties are more important than slope angle in determining whether a crack propagates through its first few metres. Once the crack exceeds the supercritical length and gravitational forces overcome basal friction, however, slope angle promotes sustained, shear-dominated crack propagation.

How slope angle influences the different fracture modes across different snowpack stratigraphies, particularly cross-slope, remains poorly understood and needs further research.

5.3 Tensile failure and slide

Given the stronger gravitational driving force on steeper slopes, we hypothesise that upslope crack propagation may be limited by increasing tensile stresses, ultimately leading to slab fracture and crack arrest. Although slab tensile strength generally increases with density, denser slabs may also store more energy and develop greater tensile stresses as terrain steepens. Our qualitative observations of avalanche photographs support this hypothesis: where the upper slope exceeds 40°, crown fractures often extend only a short distance into the steeper terrain, even without a distinct terrain transition. However, slopes steeper than 40° are often rougher and contain more rocky outcrops, potentially increasing snowpack variability and promoting crack arrest. The interactions among slab properties, energy release, terrain, and tensile failure therefore remain insufficiently understood.

Basal friction along the crack faces is crucial for a slab to release. Friction angles are substantially lower in persistent weak layers than in new or storm snow, although the effects of slab density and thickness on friction remain unknown. Accordingly, median release angles were closer to 35° for avalanches involving persistent weak layers and closer to 40° for those involving non-persistent weak layers, although both groups included avalanches on slopes near 30°. Moreover, avalanches with a 90th-percentile slope angle below 35° were about four times more common for persistent than for non-persistent weak layers (13% vs. 3%; Table 3).

6. CONCLUSION

Slope angle is strongly associated with skier-triggered slab avalanche release, but this relationship arises from several interacting processes, including skier loading, failure initiation, crack propagation, and slab sliding. Our analysis suggests that slope angle has only a limited direct influence on failure initiation and the onset of crack propagation, which are controlled primarily by the mechanical properties of the slab and weak layer and by the loading type. Differences in loading scenario or slab properties can have a much greater effect than a few degrees difference in slope angle.

Slope angle nevertheless plays two important roles. First, it influences how a skier loads the snowpack, although the relationship between skiing behaviour and slope angle remains poorly quantified and cannot be inferred directly from the simplified loading scenarios considered here. Second, slope angle determines whether a detached slab can slide: below the crack-face friction angle, sliding is prevented, while above it avalanche release becomes possible. Existing measurements and our observations further suggest that this friction angle depends on weak layer type, with lower values for persistent weak layers. However, our qualitative observations indicate that crowns often do not extend far into extremely steep terrain, although it remains unclear whether this results from tensile failure or changing snowpack properties.

The concentration of skier-triggered avalanches on slopes of approximately 35° to 40° should not be interpreted as a simple increase in snowpack instability with slope angle. Rather, this range appears to provide a favourable combination of skier loading, propensity for crack propagation, friction, and terrain for triggering slab avalanches. Consequently, small differences in slope angle should be interpreted in the context of snowpack and loading conditions rather than as an isolated measure of triggering probability.

From a practical perspective, choosing lower-angle terrain remains beneficial, but its effect should not be overestimated. Measures that reduce dynamic loading, such as skiing slowly, making wide turns, and avoiding abrupt stops, may reduce triggering probability more effectively than selecting terrain only a few degrees less steep. Particular caution is warranted on uniform slopes between 35° and 40°. When persistent weak layers are present, lower friction angles are expected, calling for a more conservative approach.

These findings also have implications for simplified decision aids that combine slope angle and danger level, such as the graphical reduction method. Within such frameworks, differences in danger level may be more relevant than a 5° difference in slope angle. The slope-angle effect used in these methods is derived from aggregated statistics that implicitly combine multiple interacting processes. Similarly, danger level is a composite measure encompassing snowpack stability, the spatial distribution of instability, and expected avalanche size, but does not account for weak-layer type. Although valuable at the regional scale, these methods are therefore of limited use for decision-making on individual crux slopes (Schweizer et al., 2023). A detailed assessment of avalanche release probability should focus on the slab and weak-layer properties that affect failure initiation, crack propagation, and slab sliding, as well as on the nature of the applied load, rather than on slope angle to the nearest degree. A comprehensive risk assessment must also consider the potential consequences of an avalanche.

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