INFLUENCE OF SLAB DEPTH SPATIAL VARIABILITY ON THE PROBABILITY AND RELEASE SIZE OF SKIER-TRIGGERED AVALANCHES

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ABSTRACT: The spatial variability of snowpack properties can create uncertainty when assessing avalanche hazards. We suggest a combined mechanical-statistical approach to investigate how changes in slab depth can influence the probability of a skier triggering an avalanche and the potential size of the release. We begin by creating multiple slab depth maps on a fictional slope using Gaussian Random Fields (GRF) with a particular set of mean, variance and correlation length. For each slab depth maps, we calculate the Skier Propagation Index SPI. We ran simulations of multiple skier tracks and calculated the probability based on the number of skiers who encountered a zone of SPI below 1. We used a Depth-Averaged Material Point Method to evaluate the potential size of an avalanche for a given slab depth variation. This analysis has revealed that a large correlation length and small variance lead to a lower probability of skier-triggered avalanches. Additionally, skiing style and skier group size have been shown to have an effect on the probability of skier-triggering. Furthermore, spatial variability can influence the size of an avalanche by introducing stress fluctuations that can cause early or late tensile failure. We illustrate the well-established relationship in avalanche forecasting between the likelihood and the consequence of an avalanche.

KEYWORDS: Snow spatial variability, skier-triggering probability, avalanche release size.

1. INTRODUCTION

Snow avalanches are a natural hazard for infrastructure and backcountry recreationists in mountainous regions. They can be classified into wet or dry avalanches and loose-snow or slab avalanches (Schweizer et al., 2003). Dry-snow slab avalanches are the most destructive and hard to predict. They are caused by the failure of a porous weak layer buried beneath a cohesive snow slab. This failure can be triggered by a skier, fresh snow, or explosives. If the size of the failed zone in the weak layer, or crack, exceeds a critical size, the crack may self-propagate across the slope, resulting in the release and sliding of the snow slab (Schweizer et al., 2016).

Statham et al. (2018) proposed a conceptual model to better predict the avalanche hazard for practitioners and backcountry recreationists. This model consists of two main components: the probability of an avalanche occurring and the size of the avalanche release. The combination of these two components gives the avalanche hazard in North America (Statham et al., 2018). However, predicting the likelihood and size of an avalanche is a difficult task, as practitioners and forecasters rely on parse and punctual observations of snowpack properties (Hägeli & McClung, 2004). The snow spatial variability at different scales adds complexity to this task, as it introduces uncertainty as to whether the properties measured in the field are representative of the slab and weak layer system (Schweizer et al., 2008). At a smaller scale, decision-making in avalanche terrain, such as the task of uphill and downhill route finding, is very complex due to the spatial variability of snow (Schweizer et al., 2008).

The concept of spatial variation of snow mechanical properties has been studied several times by the scientific community. Conway & Abrahamson (1984) conducted measurements of weak layer shear strength along an avalanche fracture line and identified deficit zones where the shear strength of the weak layer was notably lower than in the surrounding areas. This con-

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cept of weak zones or weak spots has been the focus of numerous studies over the past two decades (Schweizer et al., 2008). Kronholm & Schweizer, (2003) proposed a conceptual model to explain the effect of the stability variation on the overall slope stability. They suggested that short-range variation could have a stabilizing effect on the snowpack, while long-range variation could have a "knock-down effect" on the slope stability, but further investigation through mechanical models was needed. Research has been conducted to simulate artificial spatial patterns of the weak layer into mechanical models in order to understand the influence of the weak layer's spatial variability on the overall slope stability (Fyffe & Zaiser, 2004; Gaume et al., 2013). High shear strength disparities create more deficit zones and can lead to the entire slope's collapse, even with strong zones. Gaume et al. (2013) studied how stress redistribution, caused by the slab's elasticity, could reduce the weak layer's heterogeneity. They demonstrated that if the correlation length is smaller than the characteristic elastic length of the system, it behaves as if it was homogeneous. When the correlation length is larger than the elastic length, the smoothing does not take place and the system is more likely to fail, even for large slab depths, which is known as the knock-down effect (Gaume et al., 2014; Gaume et al., 2013). Gaume et al. (2015) employed the same method to evaluate the likelihood of tensile failure in the slab in order to determine the size of the avalanche release. Weak layer heterogeneity increases the probability of tensile failure in soft and shallow slabs, thus potentially leading to smaller avalanches. On the other hand, hard and thick slabs were not significantly affected by weak layer heterogeneity, which resulted in widespread crack propagation. These FEM studies focused solely on the spatial variation of the weak layer cohesion and its effect on natural avalanche release. It has been demonstrated multiple times, through surveys and modeling, that snow depth is highly variable in mountainous areas (e.g. Mott et al., 2011). The spatial variability of the slab depth should be related to the spatial variation of snow depth. Therefore, the spatial variation of the slab depth should influence the probability of skier-triggering across an entire slope. For homogeneous cases, the slab depth has an impact on the skier-triggering probability (Föhn, 1987) and the propensity for crack propagation (Gaume et al., 2017; Heierli et al., 2008). To the best of our knowledge, there is no study on the effect of slab depth spatial variation on the probability of skier-triggering and crack propagation.

Slab depth variability should also affect the avalanche possible size. Slab properties, mainly slab depth and density, are one of the main drivers for dynamic crack propagation (Heierli et al., 2008). Recent studies have shown that the crack speed during dynamic crack propagation could be related to avalanche release size (Bergfeld et al., 2021). Therefore, the spatial variation of the slab-weak layer system should affect the crack speed and either promote crack arrest caused by slab tensile failure or a full propagation of the entire slope. There is a need for further investigation on that matter in order to provide estimates of the avalanche release size which is crucial information for avalanche forecasting and risk management. Previous research has explored the impact of spatial snow variability on the release and size of avalanches, primarily using mesh-based approaches that can handle large deformations and fracture propagation at a significant cost of re-meshing and mesh refinement. The Material Point Method (MPM) - a hybrid Eulerian-Lagrangian technique - has been proposed as a promising tool for simulating solid-fluid transitions and crack propagation in geomaterials (Sulsky et al., 1994). Recently, Gaume et al., (2019) further developed this method by introducing an elastoplastic MPM with a new snow constitutive model, allowing them to simulate a range of mechanical processes in a snow slab avalanche, from weak layer failure initiation and dynamic crack propagation to slab tensile fracture and the eventual release and flow of the slab down the slope. Trottet et al. (2022) employed the method and full-scale measurements to demonstrate a transition from anticrack propagation (closing crack/ mode -I) to so-called ``supershear'' propagation, in which the fracture occurs in shear (mode II) at a speed higher than the shear wave speed (of the slab). They found that this transition requires a slope angle greater than the snow friction angle (~ 27°) and a propagation distance of at least 3-5 m. This implies that a pure shear interface model could be adequate to simulate large avalanche releases on an inclined slope. This discovery, combined with the high computational cost of 3D MPM simulations, motivated us to use the depth-averaged MPM (DAMPM) recently proposed and validated by (Guillet et al., 2023). DAMPM allows for a rapid computation time over large domains, enabling us to generate a large number of simulations to better comprehend the effect of the slab depth variation on the avalanche release size.

It is essential to understand how the spatial variation of slab depth impacts the probability of skier-triggering and the size of avalanche release. To gain a better understanding, we propose a combined mechanical-statistical approach to examine how the spatial variation of slab depth affects the probability of skier-triggering and the potential avalanche release size. To begin, a sensitivity analysis is performed to assess the probability of triggering skiers in relation to the spatial variation of the slab depth. Subsequently, DAMPM simulations were used to explore the connection between slab depth variations and the avalanche release size, by analyzing the propagation distance leading to the initial tensile fracture in the slab.

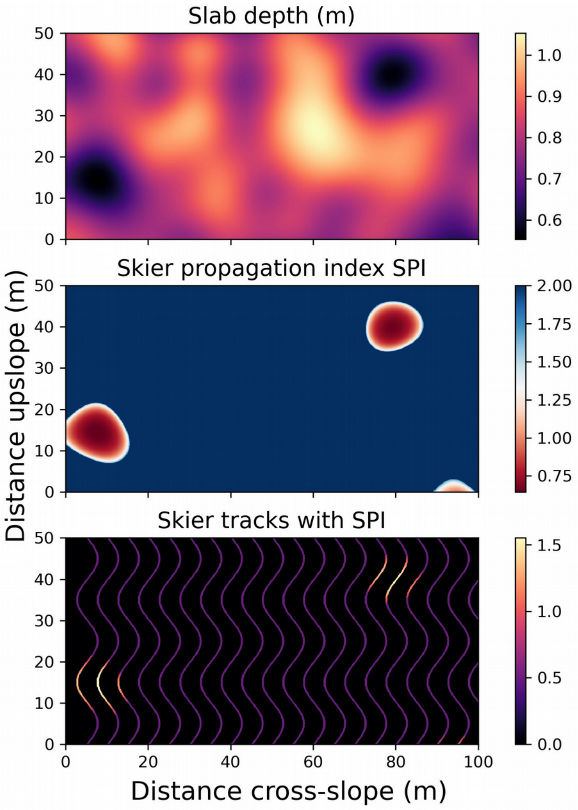

Figure 1: Example of one realization of a Gaussian Random Field GRF for slab depth, slab density, skier crack length, critical crack length ,skier propagation index SPI and skier tracks with SPI. The slope is reduced to 50 m by 100 m only for visualization purposes.

2. METHODS

Gaussian random fields were used to create artificial two-dimensional slab depth maps across a simulated slope of 100 m by 200 m. The GRF algorithm requires the mean slab depth, variance, and correlation length as input parameters. A sensitivity analysis was conducted on these parameters with 100 realizations per set of GRF parameters. Gaussian random fields were generated using the gstools v1.3 package in Python (Müller et al., 2022)

2.1 Skier-triggering probability

Generally, an increase in slab depth will also increase the snow density, elastic modulus, and shear strength of the weak layer. To obtain realistic snow values, we linked these snow mechanical properties to the slab depth with empirical power-law fits from the literature (McClung, 2009; Sigrist, 2006). The snow density and the elastic modulus were fitted to the mean slab depth of the GRF realizations, while the shear strength of the weak layer was fitted to the local slab depth variation to take into account the friction due to the weight of the slab. To assess the skier stability, we chose to use the skier propagation index (*SPI*) (Gaume & Reuter, 2017). This index is the ratio between two lengths, namely the critical crack length a_c and the skier crack length l_{sk}. For further information, refer to the publication of Gaume & Reuter (2017). To simulate the ski trajectory, we created sinusoidal ski tracks on the fictional slope, representing a "modern freeride" skiing trajectory, with a downslope turn radius of 10 m and cross-slope amplitude of 5 m (Figure 1). The spacing between the skiers was held constant at 5 m, with a total of 40 skiers. We recorded a hit if a skier track passed through a zone with *SPI* below 1. We calculated the probability of skier-triggering by comparing the number of skier tracks that recorded a hit to the total number of skier tracks on the slope.

2.2 Possible avalanche size

A different approach was required to calculate dynamic fracture propagation in a weak layer that would result in the release of a slab. Guillet et al. (2023) proposed the depth-averaged material point method to simulate the release of slab avalanches over complex topography. For a more detailed description of the method, please refer to Guillet et al. (2023). It is important to note that the model only simulates "super-shear" avalanches and propagation is only possible in mode II (shear) on a slope steeper than the typical snow friction angle of 27°. The tensile strength of the snow was linked to the snow density following the relation proposed by Sigrist (2006). This relation will represent thicker, and more dense slab will be stronger in tension.

The Depth-Averaged Material Point Method (DAMPM) is more computationally intensive and time-consuming than the analytical method. To obtain a statistical distribution for a GRF simulation of the slab depth, at least 50 simulations were required. We changed our approach and simulated a sinusoidal slab depth variation, reducing the number of simulations to one and providing a deterministic view. The variance parameter was changed to standard deviation (SD) to represent the amplitude of a sinusoidal function. We conducted very long propagation saw tests (PST) of 75 m in the up-slope direction and 0.30 m wide (Gauthier & Jamieson, 2008). Initially, the cohesion was numerically removed from the bottom of the slope to obtain the critical crack length that would initiate dynamic crack propagation across the slope. Finally, a tensile fracture in the slab was released from the slope, creating a slab avalanche. This type of slab fracture occurs when the tensile stress in the down-slope direction reaches the tensile strength of the slab. The distance from the first tensile fracture in the slab was noted for each simulation; we refer to this distance as the tensile length (L_t).

3. RESULTS

The probability of skier triggering decreases with increasing mean slab depth as expected. We observed that homogeneous cases with zero variance demonstrate a stable snowpack for skiers, from 0.6 m to 1 m mean slab depth. Two distinct regimes were identified: one for a mean slab depth of 0.5 m, where every skier triggered for both homogeneous and heterogeneous cases; and the second for a mean slab depth of 1 m, where no skier triggered except for the larger variance tested. An intermediate regime was observed for other mean slab depths, which was affected by both the variance and the correlation length. The probability of skier-triggering was seen to increase with the slab depth variance, as this allowed some areas of the fictional slope to have shallow slab depths and create propagation zones with SPI below 1. On the contrary, an increase in the correlation length decreased the skier-triggering probability, due to the reduction of the number of weak spots with SPI below 1 across the slope. A small correlation length created more weak spots with SPI below 1, while a large correlation length created fewer but larger weak spots with SPI below 1.

3.1 Influence of the skiing style

The initial analysis was based on a fixed skiing style, which was characterized by a 10 m down-slope radius Rdown and a 5 m cross-slope amplitude Across (as seen in Figure 1). However, these two parameters should be taken into account in the analysis as they have an effect on the trajectory of each skier and also affect the probability of the skier hitting a weak spot. We conducted a sensitivity analysis of two parameters, testing multiple values to create a linear down-slope trajectory and a trajectory that traverses the entire slope in the cross-slope direction. These two extremes are meant to simulate a freeride skiing trajectory (linear down-slope) and an up-hill skinning trajectory (cross-slope). Figure 2 shows that for a large A_{cross}/R_{down} ratio, the mean skier probability increases to one, meaning that a trajectory with a large cross-slope amplitude is more likely to hit weak spots and cause an avalanche. For a small A_{cross}/R_{down} ratio, the mean skier probability decreases to a value determined by the linear weak spot cross-slope ratio. This ratio indicates the minimum probability of a purely linear trajectory, which was 0.505 for 100 realizations with a mean slab depth of 0.7 m, variance of 0.0075 m^2, and 20 m correlation length.

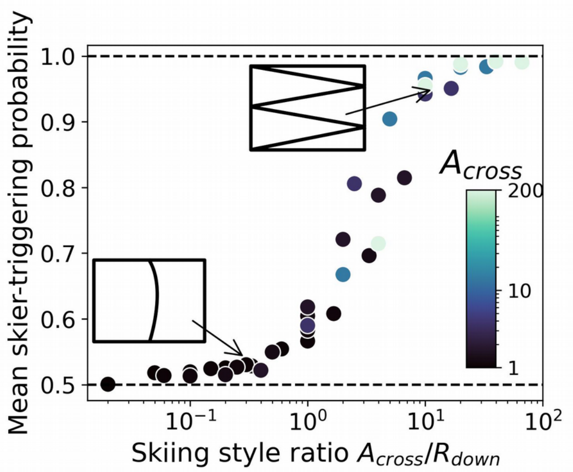

Figure 2: Mean skier-triggering probability from 100realizations for different skiing style ratios A_{cross}/R_{down} . A_{cross} represents the cross-slope amplitude and R_{down} represents the down-slope turn radius. A small skiing style ratio represents a linear down-slope trajectory and a large skiing style ratio represents a cross-slope trajectory. The probabilities are constrained by two values: the first is a probability of 1 where all skiers have triggered, and the second value is the linear weak spot cross-slope ratio set at 0.505, corresponding to the mean of the linear weak spot cross-slope ratio for 100 realizations for this set of GRF parameters: mean slab depth of 0.7 m, variance of 0.0075 m^2 ,and 20 m correlation length. The inlets represent schematic skiing style based on the skiing style ratios.

3.2 Influence of group size and terrain choice

We sought to investigate the effect of group size on the probability of triggering an avalanche. We hypothesized that skiing near a preexisting safe ski track would be safer than a completely random approach. To test this, we randomly chose a starting point at the top of the slope and added a skier 5 m apart until a trigger was recorded or the slope was skied in its entirety. This process was repeated 50 times for one realization and 100 times for a 0.7 m mean slab depth and 0.005 m2 variance, with four different correlation lengths (10 and 30 m). Figure 3 shows that for correlation lengths of 10 m, the random and structured approaches have a similar experimental cumulative density function (ECDF). The ECDF for the 10 m correlation length had a median of two additional skiers, indicating a slightly lower skier-triggering probability compared to the 30 m ECDF. For the simulation with a correlation length of 30 m, the ECDF of the structured approach was shifted from the random approach, towards more additional skiers before triggering. The ECDF began with two additional skiers for the 30 m distribution, meaning that a minimum of two additional skiers were needed before recording a trigger compared to the random approach. The difference was more pronounced for the median of the ECDF, with the random approach requiring 3 to 4 additional skiers before the trigger compared to the structured approach with 10 skiers (30 m).

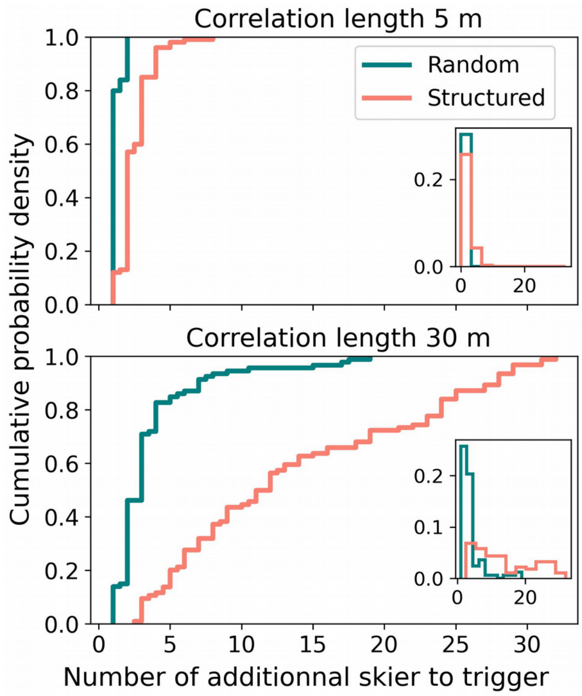

Figure 3: Experimental cumulative density functions (ECDF) of the skier-triggering probability from mid to low mean probability. All the distributions presented are from a GRF using a 0.7 m mean slab depth, 0.005 m^2 slab depth variance,and 5-30 m correlation lengths.

3.3 Tensile length and avalanche release size

We conducted a sensitivity analysis similar to the one in the skier-triggering section, but this time for the propagation distance of the first tensile fracture in the slab, which we refer to as the tensile length *Lt* from our numerical PST experiment. The homogeneous tensile length was obtained with a standard deviation of zero. This homogeneous tensile length increases with slab depth, although the theoretical quasi-static tensile length is not necessarily related to slab depth. However, in our model, the slab density and tensile strength are related to the mean slab depth, which explains the observed increase in the tensile length for our homogeneous cases. As the standard deviation increases, the tensile length decreases. When the correlation length increases, the tensile length increases and eventually converges to the same values as the homogeneous case.

3.4 Skier-triggering probabilities versus potential avalanche release sizes

Figure 4 presents both the sensitivity analysis of the skier-triggering probability and the potential avalanche release size. We estimated the potential size of the avalanche release by multiplying the tensile lengths by the mean slab depth. Our simulations did not take into account the cross-slope length of the potential avalanche. Figure 5 shows the probability of skier-triggering and the potential avalanche release size. It appears that the skier-triggering probability is inversely proportional to the mean depth of the slab since the force induced by a skier is inversely related to the depth. In contrast, the size of the potential avalanche release size increased with slab depth. However, the tensile strength in our simulations was parameterized based on the mean slab depth which also explains the longer tensile length values for thicker and stronger slabs. Figure 4 shows that the probability of a skier triggering an avalanche increases with an increase in the standard deviation for a given mean slab depth. However, one should be aware that the potential avalanche release size is smaller when the standard deviation is higher. This is evidenced by the heatmap, which shows that the maximum probability is associated with the minimum potential avalanche release size, and vice versa. For the same mean slab depth, a high variation leads to a high probability of a skier triggering an avalanche, but the potential size of the avalanche release is lower. As the mean slab depth increases, the probability of a skier triggering an avalanche decreases, and for 0.9 and 1 m mean slab depth, it is almost impossible to trigger an avalanche, except with a high slab depth variation. However, this trigger could still lead to relatively large avalanches. This scenario of low probability but high consequences with large avalanches is only possible with a slab depth spatial variation.

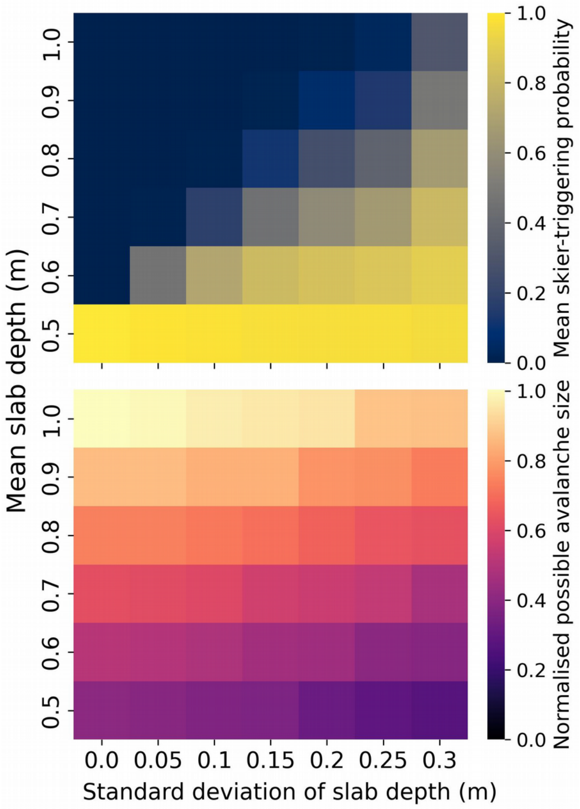

Figure 4: Probability of skier-triggering and normalized potential avalanche release size in relation to the mean slab depth and standard deviation of the slab depth. Potential avalanche release size is the combination of the tensile length normalized with the largest tensile length multiplied by the mean slab depth. We show the standard deviation slab depth values for visual purposes but the variance values used with GRF method yield approximately the same values as the standard deviation slab depth used with the sinus function.

DISCUSSION

The purpose of this research was to use the method to assess the common knowledge of avalanche professionals, which has been built over many years of working in the field. We realized that our method was highly dependent on the skier style of the simulated skier trajectory. We show that a linear trajectory with a high down-slope radius R_{down} and a small cross-slope amplitude A_{cross} significantly reduce the odds of triggering a weak spot. It is important to use caution when applying these results in practice, as they do not necessarily mean that skiing straight down the slope is "safer" in any sense of the word. Rather, they only indicate that the probability of triggering a weak spot that could lead to an avalanche is reduced. Additionally, the opposite trajectory was simulated with a very large cross-slope amplitude and a small down-slope radius, which can be interpreted as skinning up the slope with conversion (Figure 2). Backcountry recreationists should not base their decision to ski a particular slope on their skiing trajectory. Making decisions in avalanche terrain is a complicated endeavor that involves a variety of elements, including terrain characteristics, safety managements, and other mountain hazards (Harvey et al., 2023).

We wanted to test whether it was safer to ski closer to a pre-existing ski tracks. Figure 4 illustrates a comparison between a structured approach that closely follows a pre-existing ski track and a completely random approach. The ECDF with a 30 m correlation length had a median of 10 skiers on the slope before a trigger was recorded. It is noteworthy that in this method, the ECDF only accounts for cases where the first skier did not cause a trigger, and then additional skiers were added in both a structured and random approach. The use of a safe first skier track is important because it mimics the fact that preexisting ski tracks could give information to other skiers that this trajectory did not trigger. The long correlation length of spatial variation implies that, on average, the distance to the next weak spot is 30 m away. This could explain why many skiers, with a spacing of 5 m, can be on the slope before a trigger is recorded. These results confirm and quantify the common knowledge used by ski guides and in avalanche awareness communication (Harvey et al., 2023). The findings of our research indicated that the spatial variability of the slab depth adds a degree of randomness and unpredictability to skiing a avalanche-prone slope. A homogeneous slab creates a situation in which either all skiers set off the avalanche or none do. However, the spatial variability of the slab depth creates a third possibility in which some skiers trigger the avalanche while others do not on the same slope. The spatial variability of the slab depth creates weak spots on the slope which the skier's trajectory will determine the outcome. This randomness is a consequence of the arbitrary anisotropic trajectory (down-slope) of the skier towards a potential weak spot on the slope. Our results also showed randomness in the tensile length obtained from simulations. The variation of slab depth sometimes resulted in a shorter tensile length and sometimes the opposite effect. The slab depth variation influences the speed of the crack during propagation. An increase in crack speed was found to reduce the tensile stress that builds up on the slab, leading to a longer tensile length. The same phenomenon was observed when the variation in slab depth slowed the propagation of the crack, causing a sharp increase in tensile stress.

The last result presented in this study is the comparison between the skier triggering probability and the potential avalanche size. We show that it is more probable to trigger thinner and softer slabs compare to thicker and stronger slabs, but these thicker and stronger slabs could potentially create larger avalanche release sizes, also described and modeled by Gaume et al. (2015). The increase of the slab depth standard deviation has an ambiguous effect because it increases the skier-triggering probability but reduces the avalanche release size. This latter was also observed by Gaume et al. (2015) but regarding the variation of the weak layer cohesion instead of the slab depth on the avalanche release size. The relation between the likelihood to trigger by a skier compared to the propensity of propagation was initially described, through stability tests and field observations by van Herwijnen & Jamieson (2007). However, this study was focusing on fracture initiation and the propensity of propagation but not the potential avalanche size which refers to the dynamic crack propagation. Our statistical-mechanical provides a physically-based validation and includes the effect of spatial variability of this well-known relationship (Figure 4) which is the basis to describe the avalanche hazard in several countries (Statham et al., 2018; Techel et al., 2020).

4. CONCLUSION

This research examines the effect of spatial variability in slab depth on the likelihood of a skier triggering an avalanche and the potential size of the avalanche release area. We demonstrate that when the slab depth is not homogeneous, the probability of a skier triggering an avalanche is higher for thicker slabs than it would be in a homogeneous case. Additionally, we show that the spatial variability of slab depth can cause fluctuations in tensile stress, leading to smaller or larger avalanches depending on the scale of the variability. We used the tensile length as a potential indicator of crack arrest, but further research should focus on the dynamics of crack propagation and the factors that influence crack arrest.

This research provides quantification and scientific proof of the knowledge that practitioners have acquired over the years in the avalanche industry. We demonstrate the impact of skiing style on the probability of triggering an avalanche. We validate the concept with scientific evidence that skiing close to a pre-existing skier track could reduce the probability of triggering an avalanche compared to a random approach. This study also examines some processes during dynamic crack propagation in relation to the variation of slab depth along a 1D slope. However, further research is needed to understand which factors such as topography or strong snow heterogeneity could potentially stop this dynamic crack propagation, both for the anticrack propagation in flat terrain and the supershear regime on an inclined slope. Finally, this study shows, validates, and quantifies the well-known relationship between the likelihood and the consequence of an avalanche as well as the common safety guidelines in the avalanche community.

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