SLAB AVALANCHE TRIGGERING: A COMBINATION OF FOUR BASIC PHENOMENA IN SERIES.

Alain Duclos*
ALEA Sarl, France
François Louchet
Laboratoire de Glaciologie et de Géophysique de l'Environnement, UJF/CNRS, France

ABSTRACT: There is still a significant gap between models describing slab avalanche triggering mechanisms and practical field applications in terms of risk prediction and mitigation.

The present paper aims at "merging theory and practice", through a simple analysis i) of the basic processes responsible for initiation and expansion of fractured zones, and ii) of how they may be influenced by the various characteristics of the snow cover.

Slab avalanche triggering results indeed from four main steps occurring in series: i) nucleation of a collapsed zone in the weak layer, ii) expansion of this collapsed zone, iii) nucleation of a crown fracture, and iv) expansion of this crown fracture, leading to avalanche release. If a single of these steps is missing, avalanche triggering cannot occur. This is why many avalanches are not observed to occur, even if most of triggering criteria seem to be fulfilled.

The occurrence of any of these four steps is controlled by simple physical rules, which are described and discussed. More particularly, the 2^{d} step may occur in two very different modes, resulting in either small or very large starting zones. The transition between these two modes is very sensitive to both slab and weak layer properties and to the way skiers choose to cross the slope. Such a strong sensitivity of the expansion mode of the collapsed zone to these parameters is partly responsible for the large variability of avalanche sizes and locations. It accounts for instance for the possible and unpredicted occurrence of huge avalanches at places where much smaller ones are usually observed, or for a sudden release only after several skiers have successively (and safely!) traveled through the area, or for remote triggering events, etc...

KEYWORDS: avalanche triggering, crack propagation, avalanche program

1. INTRODUCTION

After a more comprehensive theory of slab avalanche release in terms of statistical physics, and based on an original cellular automaton [Faillettaz 2004, 2006], the present paper aims at "merging theory and practice", through a simple analysis of the basic processes responsible for initiation and expansion of fractured zones due to an external (artificial) action (skier or avalanche control), and of how they may be influenced by the various characteristics of the snow cover.

Each of the four steps leading to avalanche triggering are discussed and illustrated by figures. We subsequently report field observations that support such mechanisms, and finally suggest a few lessons that may be deduced from both the theory and the practice.

The figures presented here are used in many programs for mountain professionals education in France. They allow to explain why it is nearly impossible to predict if a slab will trigger or not, more especially when all the necessary conditions seem to be present.

2. BASIC PROCESSES RESPONSIBLE FOR INITIATION AND EXPANSION OF FRACTURED ZONES

2.1. A simple model system

The system can be schematized as an elastic/brittle slab lying on a brittle flat house of cards. The slab is represented as a series of elements linked by brittle springs, that can extend or contract depending on the stress they experience, or split into parts if the stress exceeds a threshold value. In a similar way, the slab is connected to older snow by elastic/brittle bonds (the weak layer),

Corresponding author address:
A. Duclos, ALEA Sarl – 73500 Aussois, France, a.duclos@wanadoo.fr

represented as some kind of flexible (i.e. elastic) and brittle flat house of cards, that may fail and collapse if the stress it experiences is large enough [Louchet F., Duclos A., 2006].

2.2. *Four steps toward the avalanche triggering*

Slab avalanche triggering results from four main steps occurring in series: i) nucleation of a collapsed zone in the weak layer, ii) expansion of this collapsed zone under the slab, iii) nucleation of a crown fracture in the slab, and iv) expansion of this crown fracture, leading to the avalanche release. The damage to the weak layer will be called “basal crack” and the damage to the slab itself will be called “crown crack” If a single of these steps is missing, slab triggering cannot occur. This is why many avalanches are not observed to occur, even if most triggering criteria seem to be fulfilled.

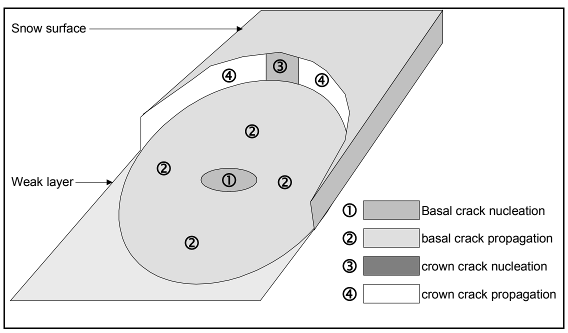

Figure 1. The four steps leading to the avalanche triggering are shown on a virtual slope, extending from the middle to the periphery.

The occurrence of any of these four steps is controlled by simple physical rules. More particularly, the potential spontaneous propagation of existing cracks obeys a specific law known as Griffith's criterion [Griffith 1920]. In spite of possible modifications related with snow geometry and stiffness, Griffith's criterion basically states that under a given stress, a large crack is more likely to expand than a small one. This is also the case for a sheet of paper, that tears off more readily if it contains a large crack. More quantitatively, spontaneous propagation takes place when the product of the stress by the square root of the crack size exceeds a threshold value K_c, called fracture toughness.

As a consequence, for a given load, spontaneous expansion (or growth) of the basal crack only occurs if the crack reaches a critical size. The larger the load, the smaller the critical size. Beyond this critical size, the energy release rate of the slab cannot be balanced any more by the resistance to crack propagation, resulting in much larger expansion velocities [Heierli 2005] [Johnson et al. 2004].

For this reason, the 2^d step may occur in two different ways, according whether the 3^d step starts or not before the critical size for spontaneous expansion is reached. This may result in either small or very large starting zones, corresponding to resp. gradual or spontaneous basal crack expansions. The transition between these two modes is very sensitive to both slab and weak layer properties and to how skiers choose to cross the slope. Such a strong sensitivity of the expansion mode of the collapsed zone to these parameters is partly responsible for the large variability of avalanche sizes and locations.

3. HOW THE PROCESSES ARE BE INFLUENCED BY THE VARIOUS CHARACTERISTICS OF THE SNOW COVER

3.1. *Nucleation of a collapsed zone in the weak layer*

3.1.1.Theory

On a slope, the weak layer experiences both the shear (parallel to the slope) and compression (perpendicular to the slope) components of the slab weight, that increase with its depth and density. The weak layer may be damaged when the load locally exceeds its mechanical resistance. The weight of a skier or a snowmobile does not significantly increase the total load experienced by the weak layer (about 10000 times smaller than that of the involved snow mass), but this load is applied on a very small surface (e.g. the base of skis), and results in a significant pressure that may locally participate to the damage of the weak layer. The local effect of the skier may significantly increase in dynamic conditions (additional pressure as the skier takes a sharp curve, or landing of a freerider after a jump). A similar effect is obtained with an explosive.

The resulting collapse of these zones reduces their shear resistance to almost zero, depending on the nature of the weak layer. The weak layer may also collapse on a flat ground: the whole slab weight is now along its compression component. Similar damage effects are expected, also resulting in basal crack nucleation.

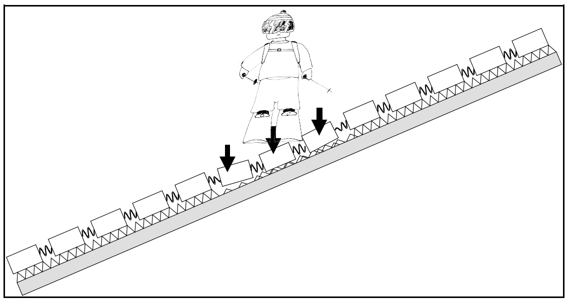

Figure 2. During the first step, the damage in the weak layer is only due to the skier’s action.

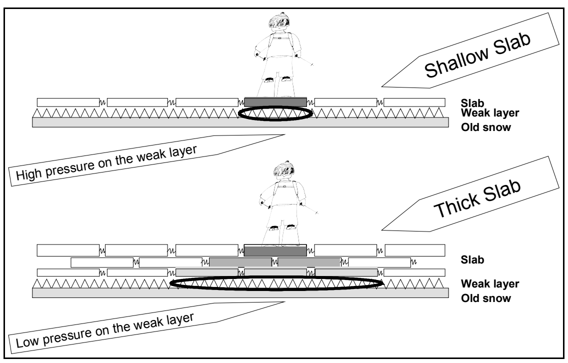

Figure 3. The thicker the slab, the smaller the skier’s action

3.1.2.Field observations

- When it is possible to spot out the place from which a fatal avalanche was initiated, we often observe that the slab is shallower in this place (0,30 m to 0,60 m). than elsewhere (more than 1 m).
- After unsuccessful explosions for avalanche control, we observed several times (by digging snow pits) that the slab was particularly thick (more than 1,5 m).at the place where the explosive had been thrown.

3.1.3.Possible lessons

- Recreationists, should be aware (and usually are) that staying in the middle of a wind slab is safer than reaching the border zones.
- Artificial avalanche triggering may become impossible if explosives are used too late (i.e. if the slab is too thick). But in the same time, due to its larger weight, such a huge slab will favour spontaneous release.

3.2. <u>Basal crack growth</u>

3.2.1.Theory

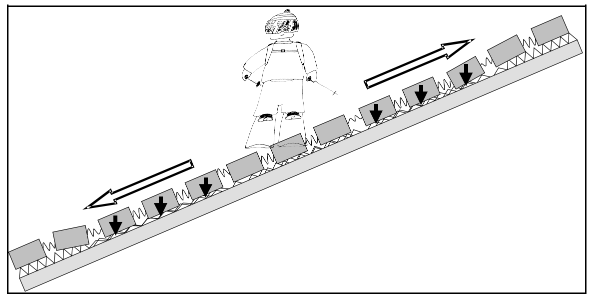

Figure 4. Beyond a critical size, the basal crack expands spontaneously at high speed. The skier cannot control any more the process at this stage.

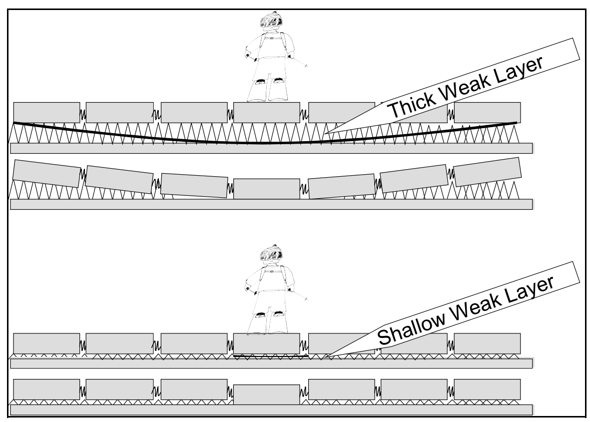

Figure 5. The thicker the weak layer, the larger is the initial basal crack size. As a consequence, the spontaneous growth of the basal crack is more likely to occur as soon as the skier arrives.

Owing to the gradual damage produced by the skier's additional and local pressure, the crack may expand step by step in an area around the skier's path. Sometimes, during such a gradual expansion, the basal crack may become large enough to allow slab triggering (steps 3 and 4). In this case, depending of his (her) skill, the skier, who is located at the boarder of the basal crack, has some chance to escape from the avalanche flow.

But the critical size for spontaneous expansion may be met before reaching step #3. In this case, the basal crack may rapidly expand over huge distances under the effect of the snow weight itself. In this last case, the driving force results from the energy release experienced by the slab as the weak layer collapses. The skier's weight has no more effect at this stage, as the involved snow mass is enormously bigger.

3.2.2. Field observations

- More and more videos of big avalanche triggerings show basal crack fast expansions appearing as a propagation of a slight discontinuity at the snow surface. Triggering from flat areas are frequents.
- Pictures and measurements made by scientists [Johnson B. 2000] provide many illustrations of the propagation phenomenon.

3.2.3. Possible lessons

- Recreationists should take into account the fact that the avalanche they can trigger may be sometimes much wider than what they are used to on a particular site. The size of the avalanche does not depend on the type of artificial initiation, but on the characteristics of the snow cover at a given time.
- We think that using explosives too often for avalanche control prevents triggering of big avalanches, more especially with exploders such as GAZEX or AVALEX. The slab must be thick enough to allow spontaneous propagation and wide slab triggering, and avoid the use of too narrowly spaced exploders.

3.3. Nucleation of the crown crack

3.3.1. Theory

As the basal crack expands along the slope, the slab weight that was balanced by the weak layer resistance is now transferred into the slab itself at the crack rims. It takes the form of a tensile stress at the top cross section of the slab, at which the freed part of the slab is hung. This stress turns into a compression stress at the bottom rim, and into shear stresses on both sides. These stresses obviously increase with the weight of the "hanging" part of the slab, i.e. with the basal crack size. The failure stress of snow is usually smaller in tension than in compression. Therefore, a crown crack nucleates at the top of the basal crack when the tensile stress in the slab reaches a threshold value.

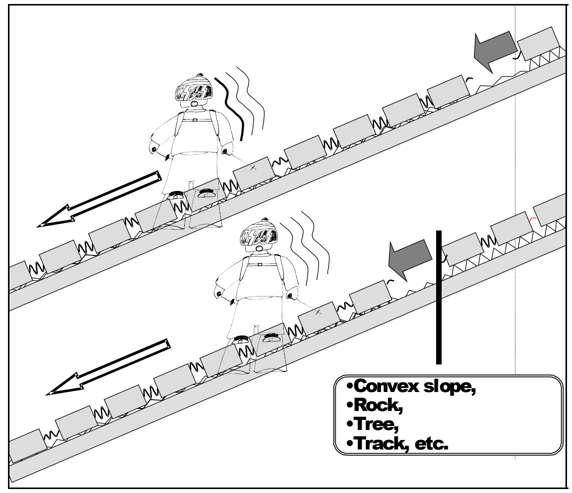

Figure 6. The more uniform the slab (no weakness), the wider the avalanche potential initial size.

3.3.2. Field observations

It is frequently observed that the crown crack starts opening (step 3) at an outcrop or a tree, or even on a ski or surf track. These features act as weak points in the slab, which help crown-crack nucleation. The same mechanism takes place at convexities.

3.3.3. Possible lessons

Such weak points play a double role: they facilitate slab triggering through crown crack nucleation, but they prevent large-scale propagation of basal cracks, which may have resulted in the release of very large slabs. In other words, large slab avalanches are likely to be found on wide and smooth slopes without weak points or field heterogeneity like trees, sparse rocks, or outcrops.

- Recreationists should ski first in heterogeneous terrain when they have a doubt about the stability: Slab avalanches will be easier to trigger in this case, but their limited size may allow skilled skiers to escape. Large and uniform slopes would probably be much more dangerous.

3.4. *Crown crack expansion and avalanche release*

3.4.1. Theory

Provided some modifications are made, Griffith's criterion may also apply to the crown crack. If the tensile load is large enough to nucleate an incipient crown crack, it will necessarily be large enough to propagate it, as the increasing crack size requires a decreasing propagation stress. The crown crack grows very rapidly (brittle failure), until the stress concentration at its tips reaches the shear failure stress on both sides. The bottom rim usually fails in turn at this stage, as the whole slab weight is now transferred to it, and the avalanche is released. As a consequence, in most cases, the nucleation of the crown crack is immediately followed by the avalanche release.

However, as for the weak layer, the slab rupture threshold may have scattered values. An incipient crown crack usually appears at one of the weakest places. Its subsequent propagation may meet a tougher zone, which may hinder its growth. In this case, the basal crack goes on extending up further.

3.4.2. Field observations

Although the topic of this paper is focussed on artificial triggerings, it can be mentioned that crown cracks are often observed to open spontaneously without being followed by slab triggering in the case of a thick and heavy snowpack, that may hinder brittle crown crack propagation. This usually occurs when the basal crack is located between the slab itself and the ground: the weakest layer is the interface between the snow and the ground.

Sometimes, crown crack nucleation occurs when the skier enters the hazardous zone, propagates only on a few meters as the scared skier stops, and expands very quickly when the skier starts moving again.

We also observed a crown crack expansion in a dry slab on a steep slope (around 38°), which was not followed by slab triggering. The expansion occurred while the sound of an explosion was heard (sudden stress relaxation), an the man with the snow shoes who initiated the phenomena doesn't understand yet why the slab didn't slide and bury him!

3.4.3. Possible lessons

Avalanches are very likely to slide on slopes steep enough as soon as the crown crack nucleates and begins to propagate. A crown crack that opens and then stops is not a guarantee that the avalanche will not be release a short time later.

Crown cracks which open in thick and homogeneous snowpacks (sometime wet) are usually spontaneous. Their expansion is slow and may not always lead to an avalanche release.

4. CONCLUSION

This approach in 4 steps allows a good understanding of the complexity that leads a skier or an explosion to trigger a slab release. It accounts for instance for the possible and unpredicted occurrence of huge avalanches at places where much smaller ones are usually observed, or for a sudden release only after several skiers have successively (and safely!) traveled through the area, or for remote triggering events, etc...

However, it does not yet allow to understand why so many avalanches are triggered within few days, and then do not slide anymore without noticeable change in the snowpack. Unfortunately, this happened one more time in France during the winter 2005-2006, and much too many people were killed. A possible explanation might be found in terms of damage percolation.

We hope that our approach will lead to further progress in both risk mitigation programs and educational sessions.

5. REFERENCES

Faillettaz J., Louchet F. and Grasso J-R. 2004. Two-threshold model for scaling laws of non-interacting snow avalanches, Physical Review Letters 93, n° 20, pp208001-1 – 208001-4.

Faillettaz J., Louchet F. and Grasso J-R. 2006. Cellular automaton modelling of slab avalanche triggering mechanisms: from the universal statistical behaviour to particular cases, this conference.

Griffith, A.A.., 1920. The phenomena of rupture and flow in solid,. Philos. Trans.R. Soc.London,Ser.A, vol 221, pp163-198

Heierli J.,2005. Solitary fracture waves in metastable snow stratification, Journal of physical research, vol 110, pp1-7

Johnson B. Jamieson B. Johnston C.2000, Field date theory for human triggering “whumpfs” and remote avalanches, ISSW Proceedings, pp 208-214

Johnson B.C., Jamieson B.,Stewart RR. 2004, Seismic measurements of fracture speed in a weak snowpack layer, Cold Regions science & Technology, vol 40(1-2), pp41-45.

Louchet F., Duclos A. 2006. Insight into slab-avalanche triggering: a combination of four phenomena in series, Avalanche Review, vol.24, n°3, pp 13-19