Interpretation of prevalent avalanche scenarios on the basis of the anticrack model

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ABSTRACT: Each winter the build-up of snow conditions is unique and distinctive, but a wide variety of avalanche situations can be attributed to a relatively small number of typical scenarios. Such scenarios can be of great value to practitioners, in particular to characterize avalanche situations, to increase the transparency of the decision-making process or for the purpose of teaching and training. In the present contribution, three types of scenarios are explored in the light of the anticrack model for avalanche release: new snow situations, wind slab situations and persistent weak layer situations. In order to investigate the cause of snowpack failure in each case, characteristic snow stratifications are assumed. The scenarios are analysed case by case on a theoretical basis by studying the stability to anticrack formation and anticrack propagation. The results are judged from a practitioner's point of view by using empirical rules. The aim of the study is to show new ways of detecting the critical moments and critical configurations in avalanche situations of one of the above types. The better the cause for failure can be identified, the more specific one can be in communicating the hazard and in taking decisions to mitigate the risk.

KEYWORDS: avalanche scenarios, anticrack model, avalanche formation.

1 INTRODUCTION

Avalanche forecasting and related decision making in the terrain is usually done by assessing and weighting key factors of avalanche formation. Precise and purposeful observations are as necessary as expert knowledge and rules of thumbs to figure out the current avalanche situation. Practical methods such as pattern recognition and physical methods such as fracture mechanical models can be very valuable in helping practitioners to characterise the type and perhaps the locus of the danger and improve the focus on the main avalanche problem (Harvey 2008). The severity of an avalanche problem is often challenging to determine: Are spontaneous avalanches to be expected? Is the settled new snow overlaying some surface hoar more critical or less critical than the hard wind slab overlaying a layer of depth hoar? Until now, to answer such questions, the emphasis has been laid on the examination of the weak layer. The roles of the slab and especially of the bed surface have often been overlooked.

Recent experimental studies (van Herwijnen and Jamieson 2005, van Herwijnen et al. 2008) and a new physical model based on anticracking of snow (Heierli et al. 2008, Heierli 2008) provide a new approach to the causes of snowpack failure. The model incorporates the collapse in volume of the weak layer and identifies the respective roles of slab, weak layer and bed surface in the criterion for fracture propagation. The anticrack model is not merely an improved mathematical description of previous slab avalanche release models (Birkeland et al., 2009), but a new approach involving new results. Even though the mathematical development of the anticrack model is complicated in parts, some of its results are simple and can be applied by practitioners to understand slab avalanche release. In the present contribution we show what type of results can be obtained by applying the new model. We indicate how the results may help practitioners and forecasters in their respective work.

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2 METHODS

The anticrack model uses the concept of energy barrier for fracture propagation to calculate the stability of the snowpack. The energy barrier can be overcome either by an increase in size of a damaged portion of weak layer (as in PST tests, Gauthier and Jamieson, 2008) or by applying an additional point load on the slab (as in ECT tests, Simenhois and Birkeland 2006).

In the first case, the critical crack size r_c at which fracture propagation is initiated can be accurately calculated (Heierli et al. 2008). Unlike in previous shear models in which critical lengths were predicted to be of the order of a few meters to several tens of meters, the critical lengths of an anticrack are of the order of a few centimetres to a few tens of centimeters, in accordance with PST test results (e.g. Gauthier and Jamieson, 2008). This means that spontaneous snowpack failure can result from the presence of small, cm-scale defects in the snowpack. Mathematically, the critical crack size r_c is calculated by maximizing the crack energy

$$V(r) = 2w_f r + V_0(r) + V_1(r) \qquad (1)$$

The maximisation is carried out over $r \geq 0$. Here, V(r) is the crack energy for a crack of length r and w_f is the fracture energy per unit surface of the weak layer. The contributions $V_0(r)$ and $V_1(r)$ come from eqs. (1) and (2) as calculated by Heierli et al. (2008).

In the second case, the critical line load p_c at which a crack forms from nil under the action of the skier can be calculated. As no pre-cracked area or so-called "super-weak spot" of strength zero must be assumed, the anticrack model proposes a solution for the fundamental problem of crack formation in an intact snowpack under the action of a skier. Mathematically, for a vertically applied line load, the skier instability criterion can be formulated as follows: Fracture is initiated if the line force p the skier applies to the snowpack, e.g. during a turn, is larger than the critical line force p_c expressed by

$$p_c = \left(\frac{8 w_f E h}{\sin^2\theta + 3\cos^2\theta} \right)^{1/2} \qquad (2)$$

where E and h are the elastic modulus and thickness of the slab respectively, and θ is the slope angle (Heierli 2008). To obtain this result we have not considered dissipative processes. Therefore we must keep in mind that the effective value of p_c is likely somewhat larger than calculated. In practice, it is useful to express p and p_c in units of the line force p_0 induced by an immobile skier on the weak layer. In this work we use p_0 = 200 N/m.

For practitioners, the interpretation of r_c and p_c is most simple: The smaller the value of r_c, the larger the likelihood of a spontaneous avalanche release. The smaller the value of p_c/p_0, the easier a skier or snowboarder can trigger a slab and vice-versa.

In the present study, to apply eqs. (1) and (2) to avalanche scenarios, characteristic snow profiles are decomposed into slab, weak layer and/or bed. Each layer is assumed to be homogeneous. The various causes for instability of a large number of snowpack situations are explored by combining a slab, chosen from Table 1 with a weak layer/bed chosen from Table 2. For example the combination of slab "NA0" and weak layer/bed "a" correponds to 60 cm of fesh snow (PP/DF) overlaying a thick layer of facets (FC). This situation is denoted by "NA0a". Each of these situations is then subjected to three types of changes: (i) a settlement of the slab by 25 % (denoted "NA1a" in our example), (ii) a rapid warming of the top three quaters of the slab (denoted "NA2a") and (iii) an additional snowfall of unbonded new snow loading the slab with an additional 30 kg per square meter (around 30 cm of new snow, this scenario is denoted "NA3a"). In the end, two hundred and twenty-four different snowpack situations are thus obtained and calculated.

Table 1: Assumed characteristics of the slabs for the different initial situations, coded "N" for new snow, "T" for wind slab and "A" for old slab. The second capital letter indexes a subcategory (e.g. a different grain or density). D: Grain size, F: Grain type, K: Hand hardness, h: depth of slab, ρ: Density, wf: specific fracture energy of weak layer, E: E-modulus.

code	D	F	K	h	ρ	wf	E
	[mm]			[m]	[kg/m3]	[J/m2]	[MPa]
NA0	2	PP/DF	1	0.6	100	0.08	0.63
NB0	1	DF	1	0.6	150	0.14	2.3
TA0	0.4	RG	1-2	0.6	150	0.14	3.5
TB0	0.4	RG	1-2	0.6	200	0.24	8.1
TC0	0.4	RG	3	0.6	300	0.47	27
AA0	1.5	FC	1-2	0.6	250	0.07	9.6
AB0	0.4	RG	2-3	0.6	250	0.35	16
AC0	0.5	RG/FC	3-4	0.6	350	0.35	36

Table 2: Applied bed layers. The categories a,b, g and h consist of a thick weak layer (more than 20cm). The other ones are thin weak layers (decomposed fragments or surface hoar) which lay on a consolidated substrate. D: Grain size, F: Grain type, K: Hand hardness, h: depth of slab, ρ: Density, wf: specific fracture energy of weak layer, E: E-modulus.

code	D	F	K	ρ	wf	E
	[mm]			[kg/m3]	[J/m2]	[MPa]
a	1.5	FC	1	250	0.07	9.6
b	3	DH	1	300	0.07	15
c	0.5	DF/RG/FC	2	200	0.08	6.9
d	0.3	DF/RG/FC	3	300	0.08	36
e	0.5	SH/RG/FC	2	200	0.04	6.9
f	0.3	SH/RG/FC	3	300	0.04	36
g	0.5	RG/FC	2-3	300	0.27	23
h	2	PP/DF	1	100	0.08	0.63

Some of the above scenarios are investigated in more detail by following the evolution of the snowpack in time and computing a sequence of critical crack lengths and critical loads. The first sequence we investigate consists in a gradual increase of new snow depth during snowfall, once with and once without taking into account slab settlement. In the second sequence we investigate the effect of the settlement of new snow after snowfall. The third sequence consists in a rapid warming of the slab in which the elastic modulus of the slab deteriorates down to a certain depth h_t due to rapid, continuous warming of the snow to about -1°C, starting from the surface (Schweizer and Camponovo, 2002). In this sequence we increase h_t in steps of 25 % from 0 % to 75 % of the slab thickness.

The fracture energies w_f listed in Table 1 and Table 2 have been estimated by assuming eq. 4.15 in Sigrist (2006) for faceted grains and eq. 4.6 in Sigrist (2006) for other types of grain. The use of these equations for mixed-mode cracking is justified by Kirchner et al. (2004) who have shown that the fracture energy of snow is independent of fracture mode. In presence of two different grain types (e.g. RG/FC) we average the fracture energy according to a mixing ratio of 50:50. For each scenario, the effective fracture energy used in the calculation is taken as the minimum of the slab value in Table 1 and the bed value in Table 2. This simply assumes that the snowpack fractures in the weakest layer (usually in the bed, but in some cases in the slab).

The elastic moduli E listed in Tables 1 and 2 for various types of snow have been estimated in terms of snow density ρ and grain size D according to $E(\rho,D) = E(\rho)\cdot f(D)$, where $E(\rho)$ stems from eq. 4.8 in Sigrist (2006) and f(D) is a dimensionless factor taking into account the effect of grain size, estimated according to data computed by Schneebeli (2004). We remark that the assumptions regarding the fracture energy and elastic moduli are not part of the anticrack model, but separate assumptions that can be chosen differently or adjusted as the database of snow measurements is developed. Finally we note that, unless mentioned otherwise, all slabs are assumed to be bonded throughout their entire thickness.

All calculations are done for a slope angle of 35 degrees and a Poisson's ratio of 0.25.

3 RESULTS

The critical crack size r_c and critical load p_c calculated for the fifty-six meaningful combinations of a slab chosen from Table 1 and a bed chosen from Table 2 are shown in the log-log plot in Figure 1. New snow scenarios are shown in green, wind slab scenarios in blue and old slab scenarios in red. According to the interpretation that a situation with small r_c is prone to spontaneous avalanche activity and a situation with small p_c/p_0 is prone to skier triggering, the results show that, having the smallest p_c/p_0-values, the new snow situations are amongst all scenarios the most prone to skier triggering. As the r_c-values of the new snow situations are, with one exception, all lower than 10 cm, these situations are at the same time critical for spontaneous avalanching. Further, the model results show that some of the wind slab situations (but not all of them) are the most dangerous scenarios for spontaneous avalanche activity, as indicated by the very small r_c-values. Interestingly, these same situations are in general more difficult to trigger for skiers or snowboarders than the new snow situations. This is indicated by the somewhat larger p_c/p_0-values. The old slab situations finally, having on average the highest r_c-values and the highest p_c/p_0-values, are the least prone to spontaneous avalanches and skier triggering. While the results generally indicate instability for new snow situations, the model differentiates between stable and unstable wind slab and old slab situations. Both high and low r_c-values and p_c/p_0-values are obtained especially for wind slab situations. The cause for this apparent unpredictability of wind slab scenarios is due to the elastic mismatch $\alpha = (E_{slab}-E_{bed})/(E_{slab}+E_{bed})$ between slab and bed (Heierli 2008).

The first scenario involving the settlement of the slab by 25 % of its initial thickness indicates a stabilizing effect for both spontaneous activity and skier triggering, but the effect is stronger on spontaneous activity. Indeed, spontaneous avalanches release during or just after a snow fall. Once the freshly fallen snow has settled, spontaneous release is unlikely.

The second scenario involving a rapid warming is shown in Figure 2. The points in grey show the r_c-values and p_c/p_0-values for the snowpack before the warming begins (i.e. as in Fig. 1). The points in color show the r_c-values and p_c/p_0-values after the elastic modulus has deteriorated in the top ¾ of the slab. Both the r_c-values and p_c/p_0-values decrease (making the situation more unstable for both spontaneous and skier triggering), but the decrease is more marked for p_c/p_0-values, i.e. for skier triggering. These theoretical results are in line with and explain experimental studies by Wilson et. al. (1999).

The third scenario involving an additional snowfall of 30 kg/m^2 of unbonded new snow indicates an increase in spontaneous avalanche activity, indicated by a substantial decrease of the r_c-values. According to the model, skier triggering is not affected by the additional load until the new snow bonds. From a practitioner's point of view spontaneous avalanches are more likely after additional load. As practitioners know, unbonded snow can hardly be triggered. However, it is necessary to know if there is a triggerable slab beneath.

The scenarios which we investigated in more detail and for which we computed time sequences can be examined in Figures 3 to 5. Fig. 3 shows the effect of new snow precipitation on stability: with increasing slab thickness, the r_c-value decreases (A>B>C>D>E). The decrease is smallest for small amounts of new snow and largest when the slab thickness increases from 30 cm to 50 cm. This indicates that small precipitations are not as critical as heavy precipitations. At the same time the p_c/p_0-value increases with increasing precipitation (A<B<C<D<E). At first this may surprise, but close examination shows that all values are very small ($p_c/p_0 < 2$) and therefore skier triggering is not unlikely in all these cases. If however the slab thickness become very large (e.g. 1.50 m), then the p_c/p_0-value becomes too large for skier triggering. Fig.4 shows the effect of slab settlement after new snow precipitations ceased. The settlement decreases both the possibility of spontaneous avalanches and skier triggering (A<B<C<D). The effect is larger on the r_c-values than on the p_c/p_0-values, especially at the beginning of the settlement process. Indeed, a settled new snow laying on a weak layer, like depth hoar, can be triggered by a skier for quite a while as practitioners know. This persistent avalanche problem for skier triggering results also in Figure 4 from the calculation of a sequence of a settling new snow. Fig. 5 shows the effect of rapid warming. The deeper the heat penetrates into the slab, the smaller the r_c-values and the p_c/p_0-values. The effect is small on r_c and more effective on p_c/p_0. This is precisely the opposite result as we encountered for slab settlement.

Altogether the model results show a fascinating complexity of the interacting factors. But this complexity is only apparent as it results from the mechanics of the anticrack model.

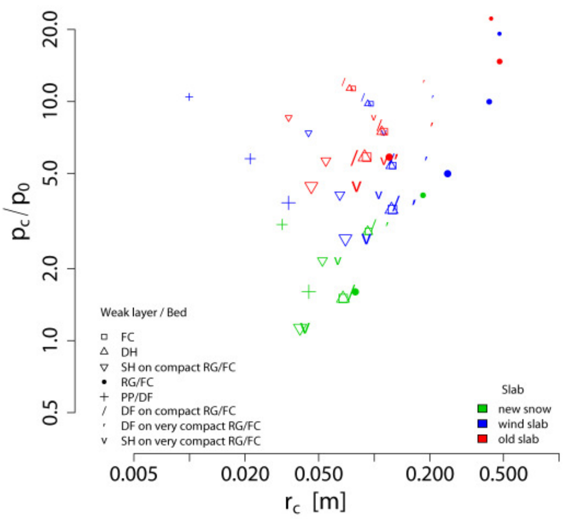

Figure 1: Calculated r_c-values (critical crack length) and p_c/p_0-values (critical skier loading) for the initial situation of a cold slabs around -5 to -10℃ (e.g. NA0b in Table 1). The smaller the symbols of each category, the denser or harder the slab. E.g. the green "+"-symbol means new snow slab on a weak layer with stellar dendrites. The larger "+"-symbol illustrates the less dense slab NA in Table 1. For new snow situations we considered two types of slabs, for wind slab and old snow situations tree types.

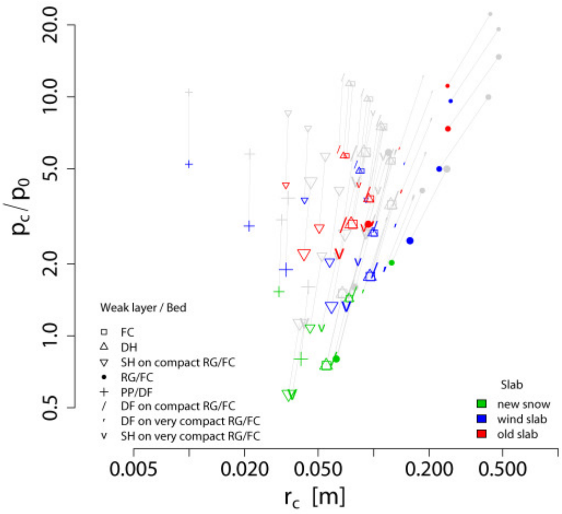

Figure 2: Effect of a rapid warming of the slab reaching ¾ of its thickness. The likelihood of skier triggering increases more than the likelihood of a spontaneous release. Symbols as in Fig.1. Points in grey show the values before warming.

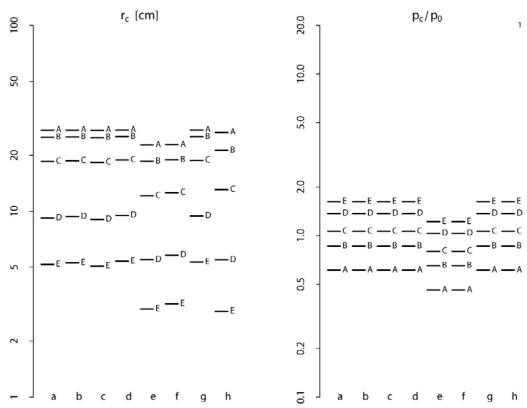

Figure 3: Calculated critical crack length (r_c) and critical skier load (p_c/p_0) for a sequence of increasing amount of bonded new snow. A=10 cm, B=20 cm, C=30 cm, D=50 cm, E=70 cm. a-h: weak layer type according to Table 2.

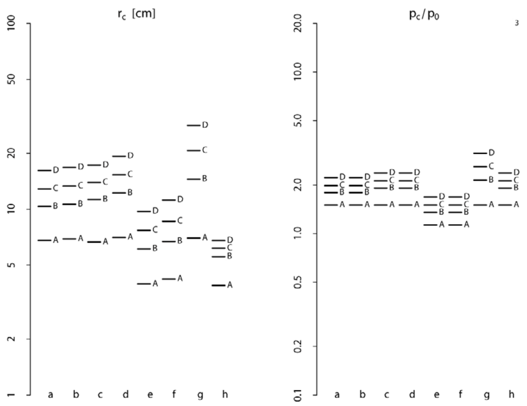

Figure 4: Calculated critical crack length (r_c) and critical skier load (p_c/p_0) for a sequence of a settling new snow slab in absence of precipitations. Slab thickness: A=60 cm, B=50 cm, C=45 cm, D=40 cm.

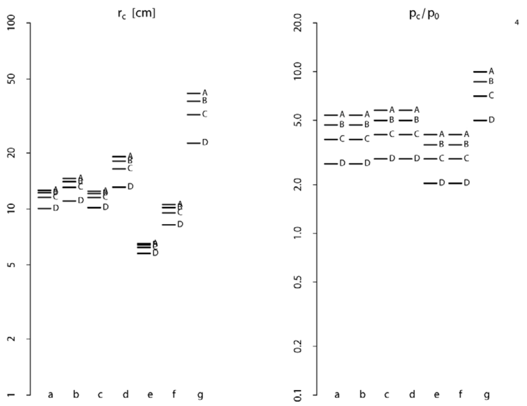

Figure 5: Calculated critical crack length (r_c) and critical skier load (p_c/p_0) for a rapidly warming slab. Percentage of affected thickness: A=0%, B=25%, C=50%, D=75%.

4 DISCUSSION AND CONCLUSION

In this study we examined a large number of avalanche scenarios on the basis of the anticrack model by evaluating separately the stability of the snowpack for spontaneous slab release and for skier triggered slab release. From a practitioner's point of view, the results are consistent with field experience.

Judged from practical experience, a critical crack length around 10 cm and below appears to indicate that spontaneous avalanches are possible or even likely. Concerning skier triggering, the threshold seems to be 4 to 5 times p_0, indicating why smooth skiing or snowboarding can prevent accidents (Camponovo and Schweizer, 1997).

The scenarios involving no weak layer clearly differ from the other scenarios with various types of weak layers. As expected, their r_c-values are the largest amongst all scenarios, indicating that spontaneous activity can be excluded. The p_c/p_0-values, while generally large, do not exclude in some cases, the possibility of skier triggering, especially in the case of a rapidly warming slab.

Among the situations with typical weak layers, buried surface hoar and buried stellar dendrites resulted to be the most critical. The calculations indicate that the harder and denser the slab, the more difficult the situation becomes for a skier to trigger failure. Importantly, we remark that hard slabs (e.g. wind slabs) overlaying weak layers and substrates with low stiffness generally lead to critical situations. This is due to the large positive elastic mismatch, which strongly reduces the critical crack length (Heierli, 2008).

The settlement and rapid warming scenarios showed a reasonable sequence of results. On the other hand, wind slab and old slab scenarios are not as distinct as we would have expected. In our calculations the specific fracture energy of a weak layer (w_f) was always kept constant regardless of the amount and the duration of loading. In practice w_f probably increases with age due to sintering. This means that the stability of especially the old slab situations is probably higher than modelled.

Some of the results presented in this contribution are known by practitioners, so why the effort of using physical models to reproduce something which is already known? Practitioners know the various factors which increase or decrease the hazard, but not the intricate mechanics by which these factors interact. Practitioner's therefore resort to rules of thumb or intuition to weight these factors in particular scenarios. Not so the model, which balances opposing and reinforcing factors according to the underlying mechanics when the input variables are available. For example practitioners know the rule of increasing avalanche danger with rapid warming. The computation with the anticrack model helps to differentiate at what kind of situations avalanche release may increase by rapid warming. The model results reveal a great complexity in the interplay of the avalanche factors which would be difficult to tackle without using the physical model. In this respect the use of the model can be of great assistance to forecasters and practitioners. The effort is therefore justified.

The distinction by the anticrack model of the type of hazard (spontaneous activity and skier triggering are treated differently) and its ability to track changes in snowpack stability when snow conditions change, make it a useful and objective tool for avalanche forecasters to consult. Besides the computational benefits, the model gives the opportunity to compare scenarios in time and in space. For example, wind slabs are especially dangerous on soft beds, and much less so on harder beds. This explains for example why wind slabs are the most hazardous when accumulating on freshly fallen snow and why the danger rapidly decreases within 24 or 36 hours: Less because the wind slab or the bonding with the bed changes, but mainly because the bed settles rapidly and thus decreases the initially dangerous elastic mismatch between slab and bed. By digging a snow pit, a practitioner can follow the state of the bed under wind slabs and thus evaluate the change of hazard. We note that the anticrack model also implies that the hazard is conserved longer under thin wind slabs than under thick ones. Indeed, under heavier loads, the bed settles quicker and affects the elastic mismatch faster.

Further progress along the lines proposed in this contribution can be made by increasing the database of fracture mechanical and elastic properties for all types of snow, including new snow.

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