Scale invariance of snow avalanche triggering mechanisms

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Abstract: Field data on more than 5000 avalanches confirm that avalanche size distributions are scale invariant, in a same way as a number of other geophysical phenomena. They also suggest that this particular behaviour may reflect a scale invariant indepth distribution of snow shear resistance. In order to better understand the origin of this scale invariant behaviour, we ran two different cellular automata representing the interface between the substrate and the snow slab, and loaded in shear. In the first one, each cell is in a binary state (0 if failed, 1 otherwise), depending on its neighbours states. It reproduces quite well the release scale-invariant statistics. The second one is based on a gradual evolution of the cell states (between 0 and 5, depending on the number of the failed first neighbours), and may include tensile rupture. Interesting results show a very good qualitative behaviour of basal crack propagation followed by tensile rupture. Slab avalanche release morphology is also nicely reproduced.

Keywords: avalanche triggering, scale invariance, critical phenomena, cellular automata,

1. Introduction

Slab avalanche release has been studied for a long time using mechanics of defect-free continuum media. More recently the role of defects was introduced through basic fracture mechanics approaches (McClung 1981, Louchet 2000). Though, the main problem that arises in the study of such natural phenomena is twofold: i) numerous parameters are involved, each of them being hardly accessible with a reasonable accuracy, and ii) the initial state of the system is not exactly known: snow packs never stop evolving owing to meteorological conditions, snow drift, etc. It therefore appears that a deterministic approach is probably not the best way to investigate such a complex problem.

The aim of this work is to study slab avalanche triggering on a different basis, using a probabilistic analysis. It has been shown recently indeed that snow avalanche release statistics exhibit a scale invariant behaviour, for both the avalanche size (Schweizer 1995, Louchet et al. 2001, Birkeland and Landry2002) or the amplitude of the acoustic emission associated with the avalanche release (Louchet et al. 2001).

In the last case, since it was not possible to record several events in the same gully, data were taken in several gullies of the same mountain range. Yet, the data aligned quite well on a unique straight line, with a critical exponent of about 1.6. This observation suggests that the very nature of the release mechanism is independent of the average slope and morphology of the gully. In the present paper, we report new results on avalanche size distributions that confirm such a critical behaviour. Cellular automata simulations are set up and run in order to reproduce avalanche triggerings and the associated critical behaviour.

2. Field data analysis

In order to study slab avalanche release in a probabilistic way, we used a database of more than 5000 avalanches recorded on the La Plagne and Tignes ski resorts during 3 winters. These data contain lots of valuable informations such as avalanche triggering mode (artificial, accidental or natural), crown crack length, crown crack height, location, etc.

In the following, the avalanche starting zone size will be defined using either the crown crack length, or the surface of the crown crack step (crown crack length × slab height).

All available avalanche data were plotted

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on the same diagrams, whatever the triggering mode, the mountain range, or the gully they start from. Fig. 1 (top) shows that length distributions obey an approximate power law, but without any roll-off at large scales. By contrast, crown crack surface distributions (fig. 1, bottom) follow a nicer power law, but with a roll-off at large scales. This result suggests that the maximum avalanche sizes are limited by the maximum available snow depth rather than by the corridor width. It also suggests that the scale invariant distribution of avalanche sizes may be ascribed to a scale invariant distribution of snow shear resistance as a function of depth, rather than to a particular scatter in corridor geometry. This might also be an explanation for the observation that data from different paths, mountain ranges, *etc.*, align on the same scale invariant plot.

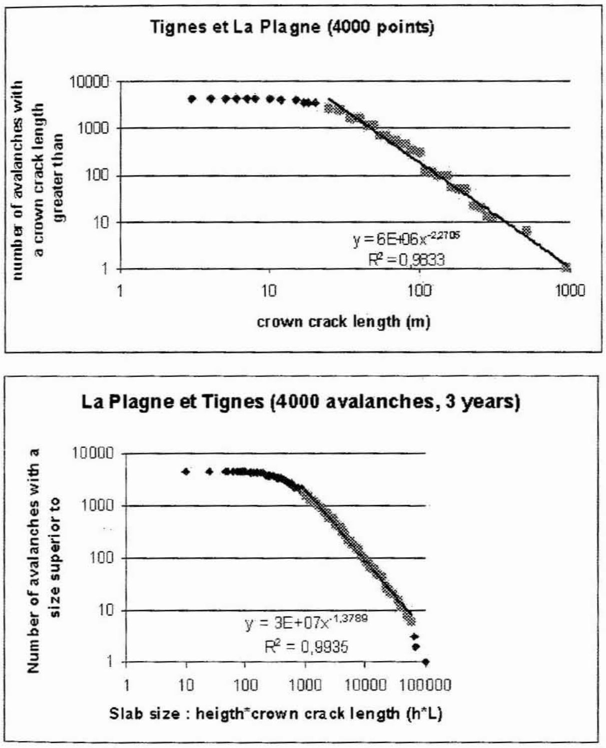

Figure 1: Statistical cumulative distributions of avalanche sizes obtained from field data. Sizes can be represented by the crown crack height (top) or the crown crack surface (height × width) (bottom). The corresponding slopes are -2.27 and - 1.38.

3. Simulations

In order to better understand the origin of a possible scale invariant behaviour for snow avalanches, we independently simulated avalanche release using both by discrete elements simulations and cellular automata.

Discrete elements simulations dealt with a population of spheres on a slope, experiencing both a gravitational stress, interactions with the substrate, and mutual contact interactions. A gradual increase of the slope or a gradual change in contact forces (accounting for thermal snow microstructure evolution) eventually result in avalanche release. The conditions were adjusted until the avalanche frequency-magnitude distribution aligns in a log-log plot along a straight line characteristic of a scale invariant critical distribution (Faillettaz et al. 2002).

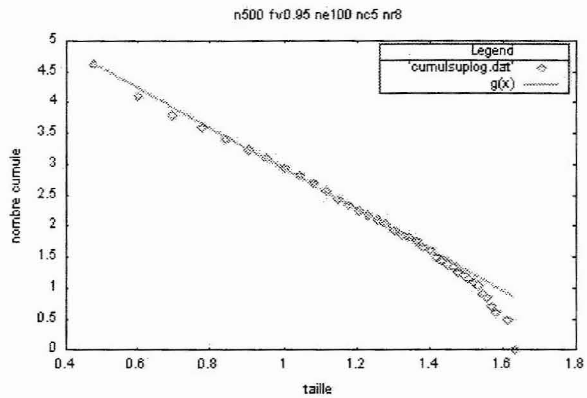

Figure 2: Example of cumulative distribution of avalanche starting zone sizes obtained by a binary cellular automaton: ln(number of events with an area larger than x) vs ln (x) (arbitrary units). The slope is close to -3. The roll-off at large sizes is related to the size of the system.

In the present paper, we shall focus on another type of simulations: cellular automata. This type of simulation is more or less similar to the so-called game of life: a 2-d grid of boxes represents the interface between the substrate and the snow slab, loaded in shear by the slab weight. Each box can be found in one among two states labelled 0 and 1, according whether the slab/substrate interface is locally cracked or not. The mechanics of basal crack growth are taken into account through a local load transfer between a damaged box and the non damaged first-neighbour boxes: the state of a box can be changed depending on the number of neighbours that are in the 0 state or in the 1 state. The model is rather crude, in that long range direct elastic coupling is not taken into account. The automaton is run from various randomly generated initial box populations in 0 and 1 states. A group of adjacent boxes in the 0 state represents a basal crack. Basal cracks of various sizes are obtained at the end of each run. The local rules are adjusted until the final basal crack frequency-size distribution aligns in a log-log plot along a straight line characteristic of a scale invariant critical distribution, as shown in fig. 2. However, we have to keep in mind that the size we deal with in this type of simulation represents the total area of damaged boxes at the end of a run and not the length nor the surface of the crown step. It is therefore difficult to relate the critical exponent

(-3 in the present case) to field data shown in figure 1. In addition, the scatter in snow shear resistance is taken into account in a very crude manner in these simulations, through both a binary choice of box states, and a planar random distribution of weak zones. Finally, tensile rupture, that determines the starting zone size, is not considered.

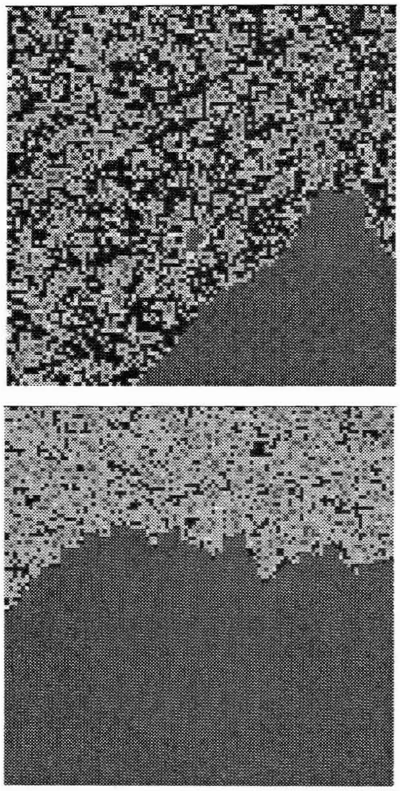

Figure 3: Natural avalanches simulated by a gradual cellular automaton. Box states vary from dark blue (undamaged) to bright red (totally cracked). The conditions are similar in both figures, except for the tensile rupture threshold which is small in the top figure and large in the bottom one. The starting zone corresponds to the uniformly red area.

This is the reason why we developed a second and more sophisticated type of cellular automaton: in this case, each box may be found in one among 6 different states (between 0 and 5) that represent the balance between the applied shear load and the local shear resistance. These different states may be understood as a distribution of snow shear resistance along slab depth. As above, the state of a box can be changed depending on the states of its neighbours. A tensile threshold may also be introduced: if the difference of state numbers of two neighbour boxes located along the maximum slope exceeds a given threshold, then the lower box is unloaded, and the corresponding load is redistributed on the neighbour boxes, except for the upper one. In this first version of the automaton, the tensile threshold is not randomly distributed, but has a fixed value. The automaton can be run for different imposed state distributions, the geographical repartition of weak or strong boxes being chosen randomly. Typical results are shown fig. 3.

We also used the automaton to model artificial triggerings: in this case, as a skier travels on the slab, boxes are gradually "broken" (i.e. brought to the 0 state) along the skier's path. An avalanche is usually triggered after the skier has travelled some distance, as shown in fig. 4.
It is worth noticing that, for constant loading conditions and average slab strength, both avalanche triggering and starting zone location may considerably vary from one run to the next one, depending on the random choice of weak boxes, and of spatial distribution and position of the skier's path. A skier may cross the whole slab without any triggering, whereas an avalanche may be triggered under identical average conditions, but a different random arrangement of boxes. General trends can nevertheless be drawn from these simulations: the starting zone sizes, and therefore the avalanche sizes, increase with the slab tensile rupture strength, as expected intuitively: a larger damaged shear zone is necessary to lead to slab tensile failure as the slab failure stress threshold increases. Owing to the computation time necessary to run such simulations, reliable statistical results have not been obtained so far.

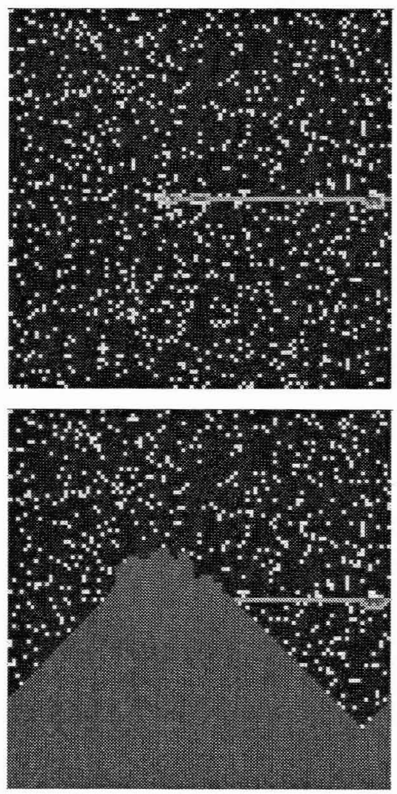

Figure 4: Artificial avalanches simulated by a gradual cellular automaton. The skier comes from the right and travels horizontally.

4. Conclusions

Field data distributions of avalanche sizes confirm the scale invariant (i.e. power law) distributions of slab avalanche sizes, as evidenced by log-log plots of crown crack lengths and surfaces. This is also the case for many other geophysical phenomena such as earthquakes, landslides, rock falls, *etc.* This behaviour may be characteristic of complex systems interacting in a non linear manner, but in a direct or in an indirect way. The roll-off observed at large sizes in plots involving the slab depth suggest that this behaviour may indirectly reflect a scale invariant distribution of snow shear resistance rather than the behaviour of a set of non linearly interacting objects. Simulations, and more particularly binary cellular automata, in which the scatter in snow shear resistance is taken into account in a very crude manner, reproduce qualitatively such a scale invariance. Cellular automata in which the box shear resistance can be found in 6 different levels give interesting qualitative visualisations of avalanche triggering events, from which some qualitative trends can be drawn about the influence of external forcing (e.g. skier) on the triggering event, or the influence of the slab tensile strength on the avalanche size. Statistical analysis of data from the gradual cellular automaton is in progress.

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