Kronholm, K., and K. W. Birkeland (2005), Integrating spatial patterns into a snow avalanche cellular automata model, Geophysical. Research Letters, 32, L19504, doi:10.1029/2005GL024373.

To view the published open abstract, go to http://dx.doi.org and enter the DOI.

Integrating spatial patterns into a snow avalanche cellular automata model

Kalle Kronholm[1,2] and Karl W. Birkeland[1,3]

[1]Department of Earth Sciences, Montana State University, Bozeman, MT 59717, USA

[2]Present address: Norwegian Geotechnical Institute, P.O. Box 3930 Ullevål Stadion, N-0806 Oslo, Norway

[3]USDA Forest Service National Avalanche Center, P.O. Box 130, Bozeman, MT 59771, USA

Abstract

Snow avalanches are a major mountain hazard that kills hundreds of people and causes millions of dollars in damage worldwide annually. Yet, the relationship between the well-documented spatial variability of the snowpack and the avalanche release process is not well understood. We utilize a cellular automata model to show that the spatial structure of shear strength may be critically important for avalanche fracture propagation. Fractures through weak layers with large-scale spatial structure are much more likely to propagate over large areas than fractures through weak layers with smaller-scale spatial structure. Our technique of integrating spatial structure into the model can improve many cellular automata models that aim to explain and predict other natural hazards, such as forest fires, landslides and earthquakes. *INDEX TERMS:* 0742 Avalanches; 0736 Snow; 0515 Cellular automata; 4430 Complex systems

1. Introduction

For more than two decades, cellular automata (CA) models have been widely used to demonstrate everything from the dynamics of sandpiles [*Bak, et al.*, 1987; *Bak, et al.*, 1988] to the spatial patterns of shellfish beds [*Wootton*, 2001]. Researchers have used CA models to investigate natural hazards such as earthquakes [*Olami, et al.*, 1992], landslides [*Hergarten and Neugebauer*, 1998] and forest fires [*Bak, et al.*, 1990; *Drossel and Schwabl*, 1992]. These models are remarkably good at broadly explaining overall system behaviour, such as frequency-magnitude power laws [*Turcotte and Malamud*, 2004]. However, we believe more accurate models are possible by rigorously integrating observed spatial patterns. To demonstrate, we use results from field measurements to simulate spatial patterns in a CA model for a better understanding of the fracture initiation and propagation processes that lead to snow avalanches, a hazard that kills hundreds of people worldwide annually [*Atkins*, 2004]. Here we show that including spatial structure in the model inputs, independent of the overall statistical characteristics of those inputs, is critically important for the propagation of fractures and the resultant release of snow avalanches. A similar approach might help to better quantify the risk of other hazards investigated with CA models.

Spatial structure can be quantified using standard geostatistical techniques [*Cressie*, 1993]. In essence, these techniques utilize the semivariogram to measure the spatial autocorrelation, or how correlated measurements are to adjacent measurements in a given spatial dataset. The semivariogram provides a measure of the overall variance (sill), the average length of the spatial autocorrelation (range), and the amount of variation in the data that occurs at distances shorter than the smallest distance between measurements and due to measurement error (nugget). The relative nugget is the ratio of the nugget to the sill. Thus, a dataset with the same site-wide statistical characteristics (e.g., a normal distribution with a known mean and standard deviation) can have quite a different spatial structure, and this difference can be quantified with the associated semivariogram (Figures 1 and 2).

Slab avalanches are the most dangerous type of snow avalanches, affecting lives and property in mountain communities worldwide. They occur when a slab layer of relatively more cohesive snow fractures along a less cohesive weak layer or interface underneath the slab [*Schweizer*, 1999]. After the slab fractures along its base, fractures initiate along the upper edge, sides and lower edge of the slab, releasing a large, plate-like block that slides downhill, entraining additional snow and becoming an avalanche. Since fractures initiate along the interface or weak layer under the slab, and since this surface is typically orders of magnitude larger than the combined area of the other fracture surfaces, this is where most research has been focussed.

In principle, snow avalanches should be easy to predict. One needs only to measure the stresses applied to the weak layer or interface and the strength of that layer to determine whether avalanches are likely. However, snow avalanches, like other geophysical phenomena, defy such easy explanations and avalanche forecasting remains complex [*McClung*, 2002a; *McClung*, 2002b]. Firstly, snow is a highly complicated and dynamic material that exists near its melting point; its material properties change with even small changes in snow grain type and snow temperature [*McClung and Schweizer*, 1999]. Secondly, and most importantly for our work, snow cover properties are highly variable [*Birkeland, et al.*, 1995; *Conway and Abrahamson*, 1984; *Föhn*, 1989; *Kronholm and Schweizer*, 2003]. This variability, widely explored in a number of field studies, is important for the avalanche release process since fractures initiate in zones of localized weakness within the weak layer and then grow to a critical size (thought to be on the order of 0.1 to 10 m) before rapidly propagating under a snow slope and triggering an avalanche [*Schweizer*, 1999].

Over the past four years, our field research in Switzerland and the western United States has quantified the spatial structure of various snow cover properties on potential avalanche slopes [*Birkeland, et al.*, 2004; *Kronholm, et al.*, 2004]. This work, as well as work by others [*Conway and Abrahamson*, 1984], demonstrates that spatial patterns of weak layer shear strength, snow layer characteristics, and layer interface characteristics exist on some slopes (Figure 3). Such spatial structure may prove to be critically important for assessing the avalanche danger. Therefore, we test the effect of spatial structure on slope stability using our field data to initialize a physically-based CA model developed by *Fyffe and Zaiser* [2004].

2. Methods

We use a slightly modified version of an existing model [*Fyffe and Zaiser*, 2004]. In the model, values of individual cells represent the shear strength of that area of the weak layer. The shear stress on the cells is increased until the weakest cell fractures. That fracture results in cell displacement and stress transfer to neighbor cells. This may cause some of the neighbor cells to fracture, resulting in fracture propagation through the model domain, but alternatively only one cell may fracture.

Our model differs from *Fyffe and Zaiser* [2004] in four ways. First, we use peak shear strength values taken from field measurements rather than assuming a ratio between the shear modulus and the mean peak shear strength. Second, the statistical distribution of initial shear strength follows a normal distribution rather than a Weibull distribution since extensive field measurements show shear strength to be primarily normally distributed [*Jamieson and Johnston*, 2001]. Third, we investigate only the size of the fracture (number of cells and related area) caused by the initial cell fracture rather than increasing the stress on all cells until the last cell has fractured. This gives us a measure of the potential for fracture propagation under the specific model settings. Finally, and most importantly for this paper, the spatial distribution of shear strength in our model is not completely random. Instead, we use the turning bands method to generate grids of initial shear strength values with known statistical distributions and spatial structures [*Chilès and Delfiner*, 1999]. The grids used in the simulations (some examples are shown in Figure 1) represent spatial structures observed in field measurements (Figure 3) [*Birkeland, et al.*, 2004; *Kronholm*, 2004; *Kronholm, et al.*, 2004].

We assume the fracture size to give a measure of slope stability since larger initial fractures are more likely to reach the critical crack size necessary to rapidly propagate under the slope and cause an avalanche. The process is analogous to a snowfall uniformly blanketing a slope until the weakest part of that slope fractures.

Our grid consists of 100 by 100 cells, each scaled at 0.15 m by 0.15 m, giving a total area representative of a small avalanche starting zone that is similar in size to our field studies. We keep the snowpack parameters for the model runs constant, varying only the spatial structure (Table 1). By running the model 1000 times for each defined spatial structure, each time with a different grid that has the same statistical distribution and semivariogram, we investigate the effect of spatial structure on snow avalanche release.

3. Results and Discussion

Our results show that the model is likely to either produce a small fracture (only a few cells) or else nearly the whole grid catastrophically fractures, and the percentage of large fractures is strongly dependent on spatial structure (Figure 4). Given identical marginal statistical distributions of shear strength, slopes with strong spatial structure (highly autocorrelated with a low nugget to sill ratio, such as Figure 1c) are much more prone to propagating the large fractures necessary for avalanche initiation than slopes with weaker spatial structure (a high relative nugget, such as Figure 1a). A strong spatial structure means that weaker cells are more likely to be near other weak cells. Therefore, when fractures initiate in the weakest cell they will tend to spread throughout a weaker area, increasing the size of the initial fracture and possibly leading to an avalanche. On slopes with weak spatial structure (high level of spatial randomness), fractures are more likely to be arrested by stronger adjacent areas, and therefore those slopes tend to be more stable. Our results are consistent with recent work on systems without spatial autocorrelation; randomness in those systems also inhibits crack propagation [*Zaiser, et al.,* 2004].

Our work has important practical implications. For example, weather events forming spatially continuous weak layers with strong spatial structure should result in more hazardous conditions once the weak layer is buried in comparison to more variable weak layers. Surface hoar is an example of a notably dangerous weak layer that forms remarkably uniform layers under specific weather that include cold, clear, calm and relatively humid night time conditions [*Hachikubo and Akitaya*, 1998]. This work also suggests methods for preventing snow avalanches, and increasing public safety in avalanche terrain. Disrupting the spatial structure of the snowpack should inhibit avalanche formation in places like ski areas where public safety is a primary concern. Indeed, some ski resorts reduce avalanching on specific slopes using early season boot-packing, whereby people walk down the slope without skis and break up the snowpack layers [*Heineken*, In press]. We contend that the success of such programs is due, at least in part, to the decreased spatial structure of the treated slopes.

Investigations of other natural hazards using CA models may benefit from these same techniques. For example, the classic forest fire model looks at whether or not a tree occupies a specific grid cell and what the chances are of lighting that cell on fire [*Bak, et al.*, 1990; *Drossel and Schwabl*, 1992]. An alternative model might employ a continuous variable like fuel load in each cell and then give those cells a spatial structure that represents the landscape to be investigated. Like the snow avalanche example above, disrupting the spatial structure of the forest (through small fires, for example) decreases the probability of large fires [*Malamud, et al.*, 1998]. Our approach, accompanied by site-specific field data, might provide additional information as to whether an area is vulnerable to catastrophic wildfires.

4. Conclusions

Our model results show that fractures through snowpack weak layers with large-scale spatial structure are much more likely to propagate over large areas than fractures through weak layers with smaller-scale spatial structure. Though spatial structure appears to be important for snow avalanche release, practical field assessments remain elusive. Such assessments must take only minutes to be useful to avalanche workers, but quantifying the spatial structure of a given slope has proven to be challenging even when using data from our extensive day-long field campaigns [*Birkeland, et al.*, 2004; *Kronholm*, 2004]. Given the difficulties involved, avalanche forecasting for individual slopes will continue to be a risk-based endeavour that emphasizes careful targeting sampling [*McClung*, 2002a].

Acknowledgements. Two anonymous reviews improved the paper. The U.S. National Science Foundation (Grant #BCS-024310, K. Hansen, P.I.) provided partial support for this work.

References

Atkins, D. (2004), Though relatively mild, 2002-03 winter took a toll, *Ski Patrol Magazine*, *21*, 50-58.

Bak, P., K. Chen, and C. Tang (1990), A forest-fire model and some thoughts on turbulence, *Phys. Lett. A*, *147*, 297-300.

Bak, P., C. Tang, and K. Wiesenfeld (1987), Self-organized criticality: an explanation of 1/f noise, *Phys. Rev. Lett.*, *147*, 297-300.

Bak, P., C. Tang, and K. Wiesenfeld (1988), Self-organized criticality, *Phys. Rev. A*, *38*.

Birkeland, K. W., H. J. Hansen, and R. L. Brown (1995), The spatial variability of snow resistance on potential avalanche slopes, *J. Glaciol.*, *41*, 183-189.

Birkeland, K. W., K. Kronholm, and S. Logan (2004), A comparison of the spatial structure of the penetration resistance of snow layers in two different snow climates, *Proceedings of the International Symposium on Snow Monitoring and Avalanches*, Snow and Avalanche Study Establishment (SASE), Manali, India, 3-11.

Chilès, J.-P., and P. Delfiner (1999), *Geostatistics: Modeling spatial uncertainty*, 695 pp., John Wiley and Sons, New York.

Conway, H., and J. Abrahamson (1984), Snow stability index, *J. Glaciol.*, *30*, 321-327.

Cressie, N. A. C. (1993), *Statistics for spatial data*, Revised ed., 900 pp., John Wiley & Sons, New York.

Drossel, B., and F. Schwabl (1992), Self-organized critical forest-fire model., *Phys. Rev. Lett.*, *69*, 1629-1632.

Föhn, P. M. B. (1989), Snow cover stability tests and the areal variability of snow strength, *Proceedings of the International Snow Science Workshop*, Whistler, British Columbia, Canada, 262-273.

Fyffe, B., and M. Zaiser (2004), The effects of snow variability on slab avalanche release, *Cold Reg. Sci. Technol.*, *40*, 229-242.

Hachikubo, A., and E. Akitaya (1998), Daytime preservation of surface-hoar crystals, *Ann. Glaciol.*, *26*, 22–26.

Heineken, K. (In press), Highland bowl, *Proceedings of the International Snow Science Workshop, Jackson Hole, Wyoming*.

Hergarten, S., and H. J. Neugebauer (1998), Self-organized criticality in a landslide model, *Geophys. Res. Lett.*, *25*, 801-804.

Jamieson, J. B., and C. D. Johnston (2001), Evaluation of the shear frame test for weak snowpack layers, *Ann. Glaciol.*, *32*, 59-68.

Kronholm, K. (2004), Spatial Variability of Snow Mechanical Properties with regard to Avalanche Formation, Ph.D. thesis, 187 pp, University of Zurich, Zurich, Switzerland.

Kronholm, K., M. Schneebeli, and J. Schweizer (2004), Spatial variability of micropenetration resistance in snow layers on a small slope, *Ann. Glaciol.*, *38*, 202-208.

Kronholm, K., and J. Schweizer (2003), Snow stability variation on small slopes, *Cold Reg. Sci. Technol.*, *37*, 453-465.

Malamud, B. D., G. Morein, and D. L. Turcotte (1998), Forest fires: An example of self-organized critical behavior, *Science*, *281*, 1840-1842.

McClung, D. M. (2002a), The elements of applied forecasting - Part I: The human issues, *Nat. Hazards*, *26*, 111-129.

McClung, D. M. (2002b), The elements of applied forecasting - Part II: The physical issues and the rules of applied avalanche forecasting, *Nat. Hazards*, *26*, 131-146.

McClung, D. M., and J. Schweizer (1999), Skier triggering, snow temperatures and the stability index for dry slab avalanche initiation, *J. Glaciol.*, *45*, 190-200.

Olami, Z., H. J. S. Feder, and K. Christensen (1992), Self-organized criticality in a continuous, nonconservative cellular automaton modeling earthquakes., *Phys. Rev. Lett.*, *68*, 1244-1247.

Schweizer, J. (1999), Review of dry snow slab avalanche release, *Cold Reg. Sci. Technol.*, *30*, 43-57.

Turcotte, D. L., and B. D. Malamud (2004), Landslides, forest fires, and earthquakes: examples of self-organized critical behavior, *Physica A*, *340*, 580-589.

Wootton, J. T. (2001), Local interactions predict large-scale pattern in empirically derived cellular automata, *Nature*, *413*, 841-844.

Zaiser, M., B. Fyffe, P. Moretti, A. Konstantinidis and E.C. Aifantis (2004), Pinning and propagation of interface cracks in slope failure, in *Modelling of Cohesive-Frictional Materials,* edited by P.A. Vermeer, et al., pp. 435-446, Taylor and Francis, London.

Figure captions

Figure 1: Each grid above represents shear strength data with a mean of 1500 Pa and a standard deviation of 150 Pa. However, the spatial structure of the three grids varies from essentially spatially random (a relative nugget of 100% (a)) to partially structured (a relative nugget of 50% (b)) to a strong spatial structure (a relative nugget of 0% (c)). These grids are representative of the data used for our model runs.

Figure 2: A conceptual representation of the semivariogram for each of the three grids in Figure 1, where the range and sill are constant while the relative nugget varies. The letters correspond to the letters in Figure 1.

Figure 3: A semivariogram for 68 shear strength measurements on a slope in southwest Montana, U.S.A. shows spatial autocorrelation with a relative nugget of about 44%.

Figure 4: Model avalanches tend to involve only a few cells, or to fracture the entire grid. The percentage of avalanches where the initial fracture is large (more than 99% of the grid fractures) is highly dependent on the spatial structure of shear strength. Strong autocorrelation (i.e., a low relative nugget) leads to relatively more large initial fractures. Since larger initial fractures are more likely to reach the critical size necessary to initiate an avalanche, the spatial structure of a slope strongly affects its avalanche potential.

Table 1. Snowpack Parameters Used in the Model Runs.

Parameter	Value
Peak shear strength, mean	1500 Pa
Peak shear strength, standard deviation	150 Pa
Ratio peak shear strength/residual strength	1.5
Slab density	200 kg m^{-3}
Slab thickness	0.5 m
Displacement to failure	4 mm
Autocorrelation length (range), peak shear strength	4 m
Relative nugget, peak shear strength	0% - 100%

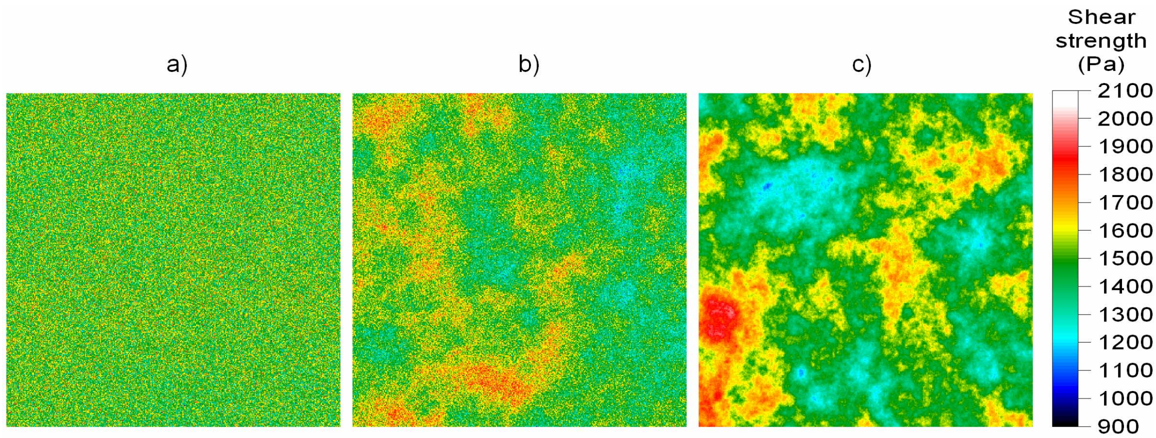

Figure 1: Each grid above represents shear strength data with a mean of 1500 Pa and a standard deviation of 150 Pa. However, the spatial structure of the three grids varies from essentially spatially random (a relative nugget of 100% (a)) to partially structured (a relative nugget of 50% (b)) to a strong spatial structure (a relative nugget of 0% (c)). These grids are representative of the data used for our model runs.

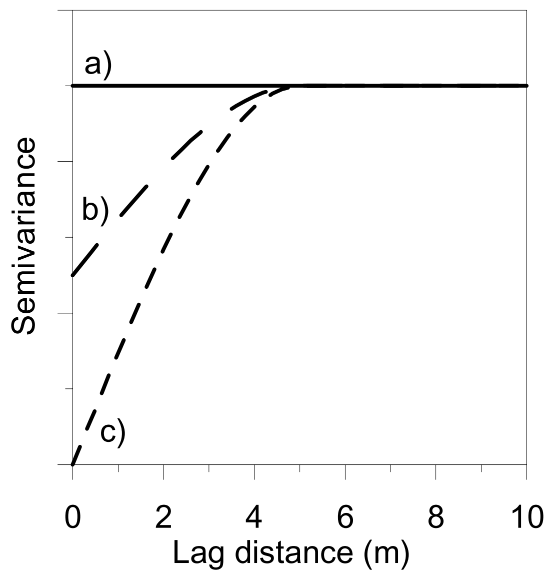

Figure 2: A conceptual representation of the semivariogram for each of the three grids in Figure 1, where the range and sill are constant while the relative nugget varies. The letters correspond to the letters in Figure 1.

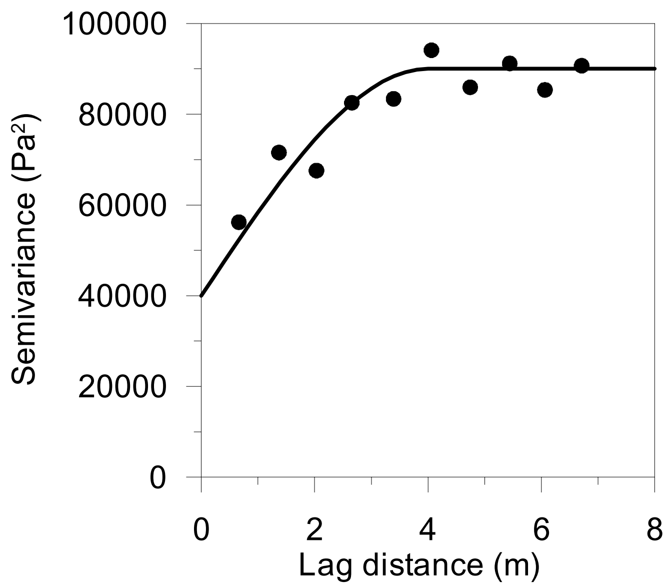

Figure 3: A semivariogram for 68 shear strength measurements on a slope in southwest Montana, U.S.A. shows spatial autocorrelation with a relative nugget of about 44%.

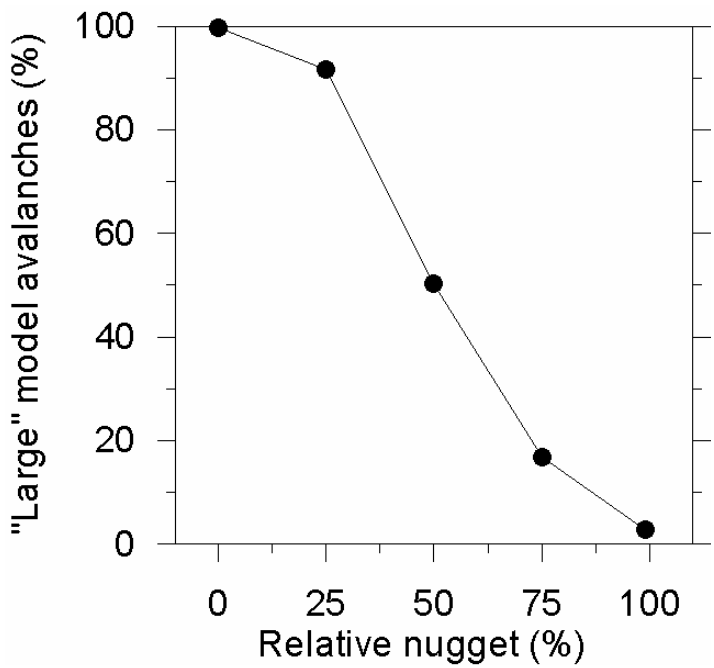

Figure 4: Model avalanches tend to involve only a few cells, or to fracture the entire grid. The percentage of avalanches where the initial fracture is large (more than 99% of the grid fractures) is highly dependent on the spatial structure of shear strength. Strong autocorrelation (i.e., a low relative nugget) leads to relatively more large initial fractures. Since larger initial fractures are more likely to reach the critical size necessary to initiate an avalanche, the spatial structure of a slope strongly affects its avalanche potential.