The Cryosphere Discuss.,
https://doi.org/10.5194/tc-2019-86-AC2, 2019

The Cryosphere
Discussions

# *Interactive comment on* "Modeling snow slab avalanches caused by weak layer failure – Part I: Slabs on compliant and collapsible weak layers" *by* Philipp L. Rosendahl and Philipp Weißgraeber

**Philipp L. Rosendahl and Philipp Weißgraeber**

mail@2phi.de

Received and published: 12 July 2019

The anonymous referee has detailed his or her view on the modeling framework itself and addressed other material and structural modeling concepts such as plasticity as well as a three-dimensional modeling approach to better capture the behavior of the snowpack.

In our detailed point-by-point response below we explain that we have chosen a linear elastic framework due to the nature of brittle onset of anticracks and that we are aware of the simplifications. We will further improve their discussion within the manuscript. The two-dimensional modeling framework was chosen because it provides direct insight into the effects of many important parameters. Both assumptions are common for studies of dry-slab avalanche release.

We thank the anonymous referee for the detailed comments on our manuscript. We have addressed all comments below and have modified the manuscript according to the reviewer's concerns.

### General reviewer comments

This manuscript deals with the failure modeling within a snow mantel including a weak layer. This topic is of importance in snow engineering, as just a little is known today about how failure occurs and which parameters control the failure propagation within a snowpack. The authors have developed an original, analytical approach, based on elasticity equations and crack propagation. The basic idea is that the weak layer is prone to collapse, triggering a cracking mechanism within the subsequent layers. Even though this approach is appealing as it is quite easy-to-use, some remarks should be raised. In particular, the assumption that the computation can be run starting from an elastic state is questionable. What does elasticity mean in snow? Snow is first and foremost a (cohesive) granular material, in which the elasticity domain is very limited. Plastic dissipation develops early. Additional remarks are reported below.

In conclusion, I consider that this manuscript should be revised before being considered for publication in The Cryosphere.

Presuming linear elasticity is the most fundamental assumption of the present work. This assumption is common for models of skier-triggered avalanches. See, for instance [1, 2, 3, 4, 5, 6, 7, 8], to name only a few. The assumption agrees with the observation that dry-snow slab avalanche release occurs within short time scales [9]. We would describe snow rather as visco-elastic than plastic. That is, dissipative effects are of minor importance in the presence of rapid deformations caused by skiers. Further, van Herwijnen et al. [10] have shown a good agreement of displacements measured using particle tracking with linear elastic models. We always prefer to use models that use a minimum level of complexity for capturing and understanding physical mechanisms at play. For instance, closed-form analytical solutions directly elucidate the interplay of different quantities of interest which otherwise may remain hidden behind the colorful curtain of finite element plots.

Please note that while the model presented in this first part of the two-part paper is linear elastic, the failure criterion employed in part II accounts for quasi-brittleness of the material.

**Specific reviewer comments**

Introduction section Line18 "If the conditions allow for crack propagation,. . ." Could the authors be more specific?

In this part of the introduction, it is our intention to point out the importance of distinguishing between crack nucleation and crack propagation. The conditions for crack propagation first and foremost refer to the Griffith criterion, of course. That is, the snowpack must release enough energy to drive the crack. Relevant are in particular weight, stiffness, fracture toughness, slope angle, etc. We have (briefly because it is the abstract) clarified this in the manuscript:

> If the conditions allow for crack propagation*, i.e., if the energy release rate of a growing crack suffices*, a triggered initial defect may extend across slopes and eventually cause the slab to fail and slide.

Mechanical modeling Failure initiation and propagation is a truly 3D problem. How can this approach be extended in 3D conditions?

The approach can be readily extended to a 3D analysis. In the presented work we decided to restrain to a 2D analysis as many physical effects governing the problem

can be studied in 2D. To name only a few, these are for instance, bridging, mode-mixety, slope angle dependence, slab thickness dependence, among others. See, e.g. [11, 12, 13].

An important feature of the present model is considering the weak layer as a so-called weak interface. That is, it is elastic but does not need to be treated as a full continuum but can be modeled using simplified kinematics. This idea can be readily transferred to 3D by replacing the bedded Timoshenko beam with a bedded Reissner-Mindlin plate. In 2D, the weak layer with its simplified kinematics provides a system of differential equations that can be solved in a closed-form analytical manner. The 3D case will yield a system of coupled partial differential equations whose solution is more involved.

Boundary conditions are supposed to play a very important role in failure propagation. How can this aspect be accounted for?

The present work considers displacement differential equations. Boundary conditions for this kind of boundary value problem are given in terms of vertical beam deflections, horizontal beam displacements, rotations of the beam cross section, normal and shear section forces as well as section moments. For the propagation saw test, all sides of the isolated snowpack column are free ends. Hence, the corresponding appropriate boundary conditions are vanishing section forces and moments, which we employed in the present work. For skier loaded slopes, we considered free ends with vanishing section forces and moments, as well. This is convenient because their implementation is straightforward, and the analytical framework allows for considering large enough domains (without increasing the computational effort) so that all boundary effects have decayed. If crack propagation and long cracks are to be considered, we could instead use so-called boundary conditions at infinity representing a domain extending to infinity.

FEM computations make it possible to estimate both strain and stress within the snow pack, even though inhomogeneous conditions are considered. Thus, what is the interest of applying a simplified approach? In addition, more complex mechanical constitutive relations can be used in FEM (visco-plastic models, etc.). Could the authors develop a little bit more along this line?

We make use of the elastic framework to obtain a real-time solution that can be evaluated in milliseconds even on a mobile device, e.g., in the field. The efficiency can be exploited for intensive parameter studies as, e.g., uncertainty quantification analyses or inverse parameter identifications (multi-parameter fits) in which easily 10.000 to 100.000 model evaluations can be required. Of course, FEM is more versatile and allows for arbitrary constitutive laws. These could also be implemented in a closed-form analytical solution but then quite often a numerical solution scheme (as the FEM) is to be preferred.

As mentioned above, major effects that govern the failure process leading to slab-avalanche release are covered by a linear elastic analysis.

Weak layer collapse under the snowpack can be regarded as the triggering event preceding snowpack failure. How this collapse can reasonably be considered in the present approach?

To model the collapsed weak layer below the slab and the the consequential loss of load transfer in normal and shear direction we remove the support of the elastic foundation. This changes the structural response (deformation) and provides the energy release rate of weak layer anticracks. The conditions required for the collapse of weak layer (the nucleation of the anticrack) are addressed in part II of this work.

Equation 29 The Young modulus is expressed as a function of the relative density of snow. Does the temperature play no role and can it be ignored? Is it the expression of the Young modulus, referring to a truly elastic behavior, or does this term refer to the compressibility of a given snow specimen, irrespective of the behavior (elastic or anelastic)?

The considered experiments contain little to no information of the respective tempera-

tures. We have employed the widely used [7, 13, 14, 15, 16, 17, 18, 19, 20] equation for the dependence of the Young's modulus on the slab density that has been proposed by Scapozza [21]. Of course, it would be interesting to study the effect of the Young's modulus on the slab temperature as well.

As discussed by Köchle and Schneebeli [22], Scapozza's density-modulus relation is based on deformation measurements in the laboratory, i.e., on the actual structural response. Other authors, such as Gerling et al. [23], provide equations for the density-dependence of the Young's modulus derived from FE models of CT scans or acoustic wave propagation measurements. Elastic moduli derived this way correspond to the response of an ideal material. The equations derived by the two different approaches differ in their absolute magnitude but provide the same trend $E \sim \rho^4$, approximately.

Finally, more recent numerical tools exist to deal with the mechanical behavior of snowpack, including the detection of failure. DEM (discrete element method) approaches stand probably as a convenient and promising way. Also, micro-mechanically based constitutive approaches should be mentioned. It is regrettable that the authors have completely ignored this part of the state-of-the art. This should be considered in the revised version.

We agree that the literature review on modeling approaches of part I must be extended by DEM and micromechanics approaches. We have discussed DEM models in the second part when reviewing existing approaches to failure modeling of snowpacks. However, they should not be omitted in part I. In the revised manuscript, we now briefly cover DEM analyses and micromechanical approaches:

> *Considering the complex microstructure of snow, micromechanical models derive the macroscopic constitutive behavior from representative volume elements [24, 25]. Similarly, discrete element models assemble the continuum from individual particles to model the effective structural response [13, 17].*

[1] J. Schweizer and C. Camponovo. The skier's zone of influence in triggering slab avalanches. Annals of Glaciology, 32(1):314–320, 2001.

[2] J. Schweizer, B. Jamieson, and M. Schneebeli. Snow avalanche formation. Reviews of Geophysics, 41(4):1016, 2003.

[3] J. Heierli and M. Zaiser. Failure initiation in snow stratifications containing weak layers: Nucleation of whumpfs and slab avalanches. Cold Regions Science and Technology, 52(3):385–400, 2008.

[4] J. Schweizer, A. van Herwijnen, and B. Reuter. Measurements of weak layer fracture energy. Cold Regions Science and Technology, 69(2-3):139–144, 2011.

[5] J. Gaume, J. Schweizer, A. van Herwijnen, G. Chambon, B. Reuter, N. Eckert, and M. Naaim. Evaluation of slope stability with respect to snowpack spatial variability. Journal of Geophysical Research: Earth Surface, 119(9):1783–1799, 2014.

[6] F. Monti, J. Gaume, A. van Herwijnen, and J. Schweizer. Snow instability evaluation: calculating the skier-induced stress in a multi-layered snowpack. Natural Hazards and Earth System Sciences Discussions, 3(8):4833–4869, 2015.

[7] B. Reuter, J. Schweizer, and A. Van Herwijnen. A process-based approach to estimate point snow instability. Cryosphere, 9(3):837–847, 2015.

[8] J. Gaume and B. Reuter. Assessing snow instability in skier-triggered snow slab avalanches by combining failure initiation and crack propagation. Cold Regions Science and Technology, 144(May):6–15, 2017.

[9] H. Narita. Mechanical behaviour and structure of snow under uniaxial tensile stress. Journal of Glaciology, 26(94):275–282, 1980.

[10] A. van Herwijnen, J. Gaume, E. H. Bair, B. Reuter, K. W. Birkeland, and J. Schweizer. Estimating the effective elastic modulus and specific fracture energy of snowpack layers from field experiments. Journal of Glaciology, 62(236):997– 1007, 2016.

[11] S. Thumlert and B. Jamieson. Stress measurements in the snow cover below localized dynamic loads. Cold Regions Science and Technology, 106-107:28–35, 2014.

[12] I. Reiweger, J. Gaume, and J. Schweizer. A new mixed-mode failure criterion for

weak snowpack layers. Geophysical Research Letters, 42(5):1427–1432, 2015.

[13] J. Gaume, A. van Herwijnen, G. Chambon, K. W. Birkeland, and J. Schweizer. Modeling of crack propagation in weak snowpack layers using the discrete ele- ment method. The Cryosphere, 9(5):1915–1932, 2015.

[14] J. Heierli. Anticrack model for slab avalanche release. PhD thesis, Universität Karlsruhe, 2008.

[15] J. Schweizer, B. Reuter, A. van Herwijnen, B. Richter, and J. Gaume. Temporal evolution of crack propagation propensity in snow in relation to slab and weak layer properties. The Cryosphere, 10(6):2637–2653, 2016.

[16] J. Schweizer, B. Reuter, A. van Herwijnen, D. Gauthier, and B. Jamieson. On how the tensile strength of the slab affects crack propagation propensity. In Proceed- ings, International Snow Science Workshop, Banff, pages 164–168, 2014.

[17] J. Gaume, A. van Herwijnen, G. Chambon, N. Wever, and J. Schweizer. Snow fracture in relation to slab avalanche release: critical state for the onset of crack propagation. The Cryosphere, 11(1):217–228, 2017.

[18] L. Benedetti, J. Gaume, and J.-T. Fischer. A mechanically-based model of snow slab and weak layer fracture in the Propagation Saw Test. International Journal of Solids and Structures, 2018.

[19] B. Reuter, N. Calonne, and E. Adams. Shear failure of weak snow layers in the first hours after burial. The Cryosphere Discussions, (January):1–17, 2019.

[20] K. W. Birkeland, A. van Herwijnen, B. Reuter, and B. Bergfeld. Temporal changes in the mechanical properties of snow related to crack propagation after loading. Cold Regions Science and Technology, 159:142–152, 2019.

[21] C. Scapozza. Entwicklung eines dichte- und temperaturabhängigen Stoffgesetzes zur Beschreibung des visko-elastischen Verhaltens von Schnee. PhD thesis, ETH Zürich, 2004.

[22] B. Köchle and M. Schneebeli. Three-dimensional microstructure and numerical calculation of elastic properties of alpine snow with a focus on weak layers. Jour- nal of Glaciology, 60(222):705–713, 2014.

[23] B. Gerling, H. Löwe, and A. van Herwijnen. Measuring the Elastic Modulus of Snow. Geophysical Research Letters, 44:11,088–11,096, 2017.
[24] François Nicot. From constitutive modelling of a snow cover to the design of flexible protective structures Part I—-Mechanical modelling. International Journal of Solids and Structures, 41(11-12):3317–3337, 2004.
[25] F. Nicot. From constitutive modelling of a snow cover to the design of flexible protective structures Part II—-Some numerical aspects. International Journal of Solids and Structures, 41(11-12):3339–3352, 2004.

---

Interactive comment on The Cryosphere Discuss., https://doi.org/10.5194/tc-2019-86, 2019.