Approximate estimates of fracture speeds for dry slab avalanches

D. M. McClung

Department of Geography, University of British Columbia, Vancouver, British Columbia, Canada

Received 9 January 2005; revised 16 March 2005; accepted 4 April 2005; published 29 April 2005.

[1] Dry slab avalanches release by propagating shear fractures. It has been suggested that slab wave or fracture speed on horizontal terrain is consistent with the propagation of a flexural wave in the slab. In this note, an alternate proposal is made. Namely, it is proposed that the fracture speed is consistent with dynamic crack propagation speeds from other materials. The theory is compared with an in situ measurement of speed associated with shear fracture propagation in a weak snow pack layer sensed by geophones placed on the surface of a horizontal snow pack. The theory is shown to be consistent with the mechanical properties of alpine snow and known characteristics of slab avalanche release. **Citation:** McClung, D. M. (2005), Approximate estimates of fracture speeds for dry slab avalanches, *Geophys. Res. Lett.*, *32*, L08406, doi:10.1029/2005GL022391.

1. Introduction

[2] In spite of many observations of propagating waves or fractures in snow packs, the theoretical basis for estimating the speeds has remained elusive. Slab avalanches release by propagating shear fractures in both mode II and mode III [*McClung*, 1979, 1981] within thin weak planar layers under stronger, more cohesive slabs. The up-slope propagation is often sensed when avalanches are triggered by skiers. Shear fracture propagation can continue up-slope sometimes for hundreds of meters before dynamic mode I tensile fracture takes place at the crown. Similar propagating fractures are also observed on horizontal or flat terrain triggered dynamically by people moving over the top of the snow pack.

[3] *Johnson et al.* [2000, 2004] reported the measurement of propagation speed of a wave triggered on horizontal terrain and they suggested that their measured propagation speed should be explained as the speed of a flexural wave. Here, I consider an alternate view, namely, that the measured propagation speed is due to crack propagation speed of mode II and mode III fracture. The proposal here is analysed from the known mechanical properties of alpine snow, terminal crack propagation speeds known from other materials, observations of slab avalanche release and the measurement of *Johnson et al.* [2000, 2004].

2. Supporting Evidence

[4] Since there is only one measurement of propagation speed, it is very important to consider evidence from a variety of sources including field observations about avalanches, mechanical properties and failure characteristics of alpine snow as well as expected fracture propagation speeds of alpine snow and the measurement of *Johnson et al.* [2000, 2004].

0094-8276/05/2005GL022391$05.00

2.1. Field Evidence of Propagating Fractures and Avalanche Release

[5] In simplest form, the stratigraphy associated with slab avalanches consists of a cohesive, strong slab over a thin planar weak layer and this stratigraphy matches that at the site of the measurement of *Johnson et al.* [2000, 2004]. They found a 10 mm surface hoar layer underneath a slab of more cohesive snow of thickness about 400 mm.

[6] The primary release mechanism for dry slab avalanches consists of rapid up-slope and cross-slope mode II and mode III fracture within the weak layer [*McClung*, 1979, 1981] followed by mode I fracture at the crown and avalanche release. On slopes, the mode I fracture at the crown occurs at an angle 90 ± 10° [*Perla*, 1970] or essentially perpendicular to the planar weak layer shear fracture. The propagating shear fractures may travel underneath the slab for more than 100 m before avalanche initiation takes place.

[7] Propagating shear fractures are frequently triggered by skiers and other winter travellers when the stratigraphy is as described above. The crowns of dry slab avalanches are observed on slopes of angle generally exceeding 25° [*Perla*, 1976; *McClung and Schaerer*, 1993]. However, propagating shear fractures are commonly triggered on slope angles below 25° [*Logan and Atkins*, 1996] including on horizontal snow packs similar to the situation described by *Johnson et al.* [2000, 2004].

2.2. Vertical Collapse During Fracture and Link to Mechanical Properties and Snow Failure

[8] There are persistent observations of a vertical or "collapse" deformation component of snow packs associated with fracture or wave propagation in snow packs. Field observations and measurements in alpine snow packs show that vertical deformation or rapid settlement of the snow pack is associated with relatively thick weak layers of three crystal forms in the weak layer: surface hoar, depth hoar and faceted crystals. When weak layers of these crystal forms, called persistent forms by *Jamieson* [1995], are such that thickness exceeds about 10 mm, a collapse or settlement is noticed by people on the snow pack surface [*Bohren and Beschta*, 1974; *Johnson et al.*, 2000, 2004; *DenHartog*, 1982].

[9] For most snow forms, alpine snow [*McClung*, 1977] is a pressure sensitive, dilatant, strain-softening material. However, for the persistent forms [*Jamieson*, 1995] it is suggested [*McClung*, 2003] that they are anisotropic in their mechanical properties. That is they are relatively weak in shear and resistant to vertical deformation. *Jamieson* [1995, pp. 83–86] performed shear frame tests on surface hoar and facetted snow to investigate pressure sensitivity. He concluded that these forms are essentially pressure insensitive. That is, there is negligible increase in shear strength with

normal load. The range of his normal load testing was narrow. However, his observations suggest that peak friction angle as on a Coulomb-Mohr plot is very close to zero for facets and surface hoar. No such measurements are available for depth hoar. However, field observations suggest that depth hoar resists vertical deformation or settlement in the snow pack and it is known that it densifies very slowly under load.

[10] Field observations also show that the persistent forms are extremely prone to shear fracture propagation and they are primary sources of avalanche fatalities. They persist for long periods and gain strength slowly and they are responsible for large avalanches.

[11] Based on information from mechanical properties, what I suggest is that relatively thick layers (10 mm or greater) of persistent forms will fracture easily in shear once disturbed with rapid vertical settlement or collapse taking place behind the propagating shear fracture process zone as it propagates through the weak layer. Once disturbed by dynamic stresses, the friction angle near zero should allow the fracture to propagate even on horizontal terrain coincident with loss of gravitational potential energy as the collapse of a thick weak layer takes place at and behind the crack tip to allow the slab to drop. What I suggest, consistent with *Johnson et al.* [2000, 2004], is that the loss of gravitational potential energy drives the crack forward. The anisotropic structure of the forms is very important so that vertical collapse deformation energy is mostly transformed into shear deformation to drive the crack forward.

[12] When a person travels on a snow pack on skis, foot or snowshoes a complicated stress pattern will result including shear stresses and shear deformation even on a horizontal snow pack. The stresses will be delivered dynamically and , if a relatively thick layer of persistent forms is disturbed such that shear fracture toughness is overcome, a dynamically propagating shear fracture can result.

3. Empirical Terminal Fracture Speeds From Other Materials

[13] It is unknown whether the speed measurement of *Johnson et al.* [2000, 2004] is close to terminal speed of the propagating disturbance. The disturbance arrested before it reached two of their geophones. It propagated to a position somewhere between 12.7 and 17.4 m from the trigger point but it was sensed by three of their six geophones prior to this.

[14] There are two important sources of mode II rupture speeds and there are also theoretical predictions of maximum, limiting speeds for mode II and mode III. The results are summarized here as a fraction of the shear wave speed: $C_s = \sqrt{\mu/\rho}$ where μ is elastic shear modulus and ρ is material density. *Heaton* [1990] presents an analysis of seven large crustal earthquakes by inversion techniques to yield mode II speeds in the range: 0.7–0.9 C_s. These results are consistent with theoretical predictions [*Fossum and Freund*, 1975; *Freund*, 1990] based on singular (infinitesimal fracture process zone) theory. They predict that the limiting speeds are the Rayleigh wave speed in mode II (0.87–0.92 C_s for Poisson ratios, ν, from 0–0.25) and the shear wave speed in mode III [*Kostrov*, 1966; *Eshelby*, 1969; *Freund*, 1990].

[15] Laboratory data from shear fracture propagation speeds [*Rosakis et al.*, 1999: *Rousseau and Rosakis*, 2003; *Xia et al.*, 2004] in which the rupture runs as a shear crack along a weakly bonded interface between brittle polymeric plates show rupture speeds close to C_s with speeds induced to exceed C_s in some cases.

[16] Thus, from what is known from seismic evidence and laboratory polymeric specimens in mode II, one may expect shear rupture speeds in the range 0.7–0.9 C_s with even higher estimates possible for high values of initial stress.

[17] Most snow avalanches are triggered by loading from storm snow or blowing snow so I expect that values of initial stress are low. Even triggering from by skiing or walking on top of the snow pack may involve low values of initial stress so I suggest that one may expect shear rupture speeds in the range 0.7–0.9 C_s as typical. Higher values cannot be ruled out particularly if explosives are used as the triggering mechanism to deliver high initial stresses. Thus, typical terminal speeds shear might be expected in the range:

$$V_t = (0.7 - 0.9)C_s = (0.7 - 0.9)\sqrt{\mu/\rho} \qquad (1)$$

4. Estimate of Propagation Speed

[18] *Johnson et al.* [2000, 2004] measured propagation speed of a disturbance associated with fracture and collapse of a 10 mm surface hoar layer underneath a planar slab of mean density: ρ = 190 kg/m^3. The reader is referred to *Johnson et al.* [2000, 2004] for details. The propagating disturbance was triggered by a person on snow shoes walking on the snow surface. The speed was measured by a series of geophones placed at 5 m intervals on top of the snow pack. Their speed estimate is: 20 ± 2 m/s. No snow pack temperatures were reported but the snow pack was dry. The elastic modulus of dry alpine snow is essentially temperature independent [*McClung*, 2003] so that the lack of temperature measurement is not crucial.

[19] *Mellor* [1975] provides estimates of the elastic Young's modulus of snow for well settled snow. There is a wide range quoted by Mellor as a function of density. For density, 190 kg/m^3 the values are in the range, $E = 2\mu(1 + \nu) = .8 - 2$ MPa Mellor states that the values are for well bonded dry snow and values for snow with low cohesion are expected to be lower. I suggest that the lower value is most appropriate for the snow pack where the measurements took place : the weak continental snow pack of the Canadian Rockies. Support for such a value comes from *Campanovo and Schweizer* [2001]. They performed dynamic measurements of μ with a rheometer at a strain rate of 1/s for 20 samples from a single snow layer with snow densities in the range 215–255 kg/m^3 giving values for μ in the range .38–.8 MPa. The snow they used came from an alpine snow pack with weak snow of hand-hardness index of 2 as might be expected for the continental snow pack of the Canadian Rockies. For Poisson ratios typical of low density alpine snow (0 to 0.25) , their data suggest values of E in the range 0.76 MPa (ρ = 215 kg/m^3; ν = 0) to 2MPa (ρ = 255 kg/m^3; ν = 0.25). Since the mean density at the site of the speed measurement was 190 kg/m^3, the data of

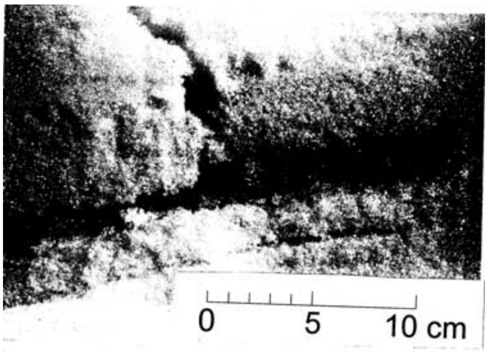

Figure 1. Photograph of shear/collapse within a weak layer of surface hoar. The propagation was from left to right. The propagating disturbance was stopped by a tensile fracture which ran through the entire slab and formed roughly perpendicular to the failure layer. Ahead of the tension crack, the weak layer did not collapse. Photo: University of Calgary, Department of Civil Engineering.

Campanovo and Schweizer [2001] support the choice of Mellor's lower value.

[20] For E = 0.8 MPa, using equation (1) for expected Poisson ratios (0–0.25), gives terminal speed estimates in the range: 29–41 (m/s). Extrapolation of the regression line through the data of *Campanovo and Schweizer* [2001] to ρ = 190 kg/m^3 gives a value μ = 0.3 Mpa to yield speed estimates from equation (1) in the range 28–36 (m/s). The estimates from Mellor's lower value suggest that the measured speed is in the range, 0.43–0.49 C_s which is the range typical for mode I terminal crack speed propagation 0.4–0.6 C_s [*Kanninen and Popelar*, 1985] and somewhat below the estimates provided by equation (1). For amorphous materials in mode I, *Sharon and Fineberg* [1999] suggest that multiple micro-branching events can appear to limit speeds below the range of mode I terminal speeds stated here.

5. Interruption of Acceleration by Tensile Fracture

[21] It is not known whether the disturbance described above was still accelerating at the position of the measurement. If so, the limit in equation (1) may not have been attained. Field observations show that tensile fracture at the crown results in avalanche formation after the shear fracture has propagated up-slope at high speed.

[22] Figure 1 is a photo of a shear/collapse propagation (not the one for which the speed measurement was made) which ran on a slope of 13°. The fracture propagated for about 8 m [*Johnson et al.*, 2000, 2004] and the slab depth was about 0.40 m when tensile fracture initiated. The propagation was terminated by tensile fracture perpendicular to the shear failure surface which is exactly the way avalanches are predicted to evolve [*McClung*, 1979, 1981; *Bažant et al.*, 2003].

[23] I suggest tensile fracture takes place through the body of the slab after propagating some characteristic distance L (8 m in Figure 1, and about 15 m in for the measurement of *Johnson et al.* [2000, 2004]) to stop the shear fracture. For these two cases, the ratio of L (propagation distance) to H (slab thickness) is estimated to be: $L/H \gg 1$ (about 20 and 40 respectively) which agrees with slab avalanche dimensions: the ratio $L/H \gg 1$ is always observed. The slip weakening model in historic paper of *Palmer and Rice* [1973] , as applied by *McClung* [1979, 1981], suggests qualitatively that tensile stress should build at the tip of the propagating disturbance as L/H increases. It may be that tensile fracture takes place as tensile stresses build to approach the mode I fracture toughness of the slab. A dynamic treatment is beyond the scope of this note. However, if the dynamic weak layer mode II stress intensity factor increases faster with propagation distance L than resistance to weak layer fracture increases, then it is possible that the disturbance can continue to propagate only until tensile fracture occurs through the slab to limit shear fracture speed.

6. Discussion

[24] Based on observations of avalanche release and the mechanism and based on mechanical properties of persistent forms, I suggest that collapse of thick (>10 mm) weak layers is coincident with propagation of shear fractures in the weak layer with rapid settlement or collapse of the layer at and behind the propagating shear fracture process zone.

[25] The estimates of terminal crack speed from equation (1) are higher than the measurement of *Johnson et al.* [2000, 2004]. Since they provided no measurement of the shear modulus along with their speed measurement, the uncertainty in estimating the speed is high from a theoretical point of view. Several possibilities exist for the differences between the speed measurement of *Johnson et al.* [2000, 2004] and equation (1). These include:

[26] 1. It is easily possible that the shear modulus used in my calculations is higher than the actual value where the measurement was made.

[27] 2. There is a physical difference between the shear/collapse mode of propagation in relation to the data (mode II) on which equation (1) is based. It is possible that speeds less than the Rayleigh speed imply an energy absorbing process with the speed governed by the rate at which energy can be supplied to the fracture process zone. Alpine snow has typically only 20% of volume fraction filled by solid material (ice) for avalanches (and the present case) with grain sizes typically mm or even cm for collapsing surface hoar layers. This is fundamentally different than rock or most engineering materials for which the data on equation (1) are based.

[28] 3. It is not known whether or not the disturbance was accelerating at the time. If it was accelerating, then the speed measurement will not have been the maximum achieved.

[29] The possibility that slab tensile fracture cuts off the disturbance, as suggested in Figure 1, is of primary importance for slab avalanche formation and the speeds attained. Persistent field observations of tensile slab fractures suggest that they evolve when the weak layer shear fracture is propagating at high speed underneath the slab. I suggest that the interplay between slab tensile fracture toughness and tensile stresses built in the slab after the disturbance propagates for some characteristic distance ($L/H \gg 1$) can determine what speed is attained.

[30] The speed measurement of *Johnson et al.* [2000, 2004] seems comparable to typical maximum speeds in mode I for other materials. Since mode I speeds can be limited by branching, it may be possible in the avalanche case that shear rupture terminal speeds are limited to about 0.5 C_s, as suggested by comparison of the measurement and the calculations. A tensile fracture branching condition coincident with a high tensile stress intensity factor could play a role. From a practical perspective, to a person on skis in avalanche terrain, it will not matter much whether this estimate or that of equation (1) is adopted. Once an avalanche is triggered, very little time will be available for alternatives in human action for either estimate.

[31] The theory proposed here is consistent with observations and the mechanism of slab avalanche release, the mechanical properties of persistent forms and terminal crack speeds from other materials. In geophysical problems with high uncertainty, such as for the present problem, with only one speed measurement, evidence from numerous sources has to be considered to determine the most likely explanation. Based on the evidence presently available, I suggest that the phenomenon is essentially the same as for the avalanche case. In most cases when avalanches release on steep slopes, the failure layers are thin and the collapse mode in the weak layer is not available. For surface hoar, a common failure layer consists of crystals with a layer thickness of only 1 mm. However, the avalanche field observations are the same as suggested for the horizontal snow pack: rapid (up-slope) shear fracture in the weak layer causing tensile fracture at the crown at high speeds for $L/H \gg 1$.

[32] Shear fracture propagation of thick surface hoar or faceted layers, accompanied by audible collapse, are commonly observed on low angle terrain (without avalanche release) and on steeper slopes with avalanche release on the same day for the same snow pack. There are reports of accidents [*McClung and Schaerer*, 1993, p. 76; *Logan and Atkins*, 1996, pp. 143–144, 160–163] occurring for these forms when a shear fracture was triggered on flat terrain with propagation up the adjacent slope to trigger an avalanche. This important observation links shear fracture and collapse on flat or low angled terrain to avalanche release and suggests that the mechanism is the same regardless of the initial slope angle.

[33] I do not exclude other explanations of the phenomenon such as the flexural wave theory proposed by *Johnson et al.* [2000]. A flexural wave theory [e.g., *Fung*, 1965] would need several assumptions and it should include an explanation for why the wave stopped at about 15 m from initiation.

[34] The theory here might apply to firn quakes which are also associated with rapid snow pack settlement and propagating disturbances as discussed by *DenHartog* [1982]. However, without any supporting snow pack measurements, it would be very speculative to apply it.

[35] **Acknowledgment.** I am grateful for the research support of Canadian Mountain Holidays, the Natural Sciences and Engineering Research Council of Canada, and the University of British Columbia.

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D. M. McClung, Department of Geography, University of British Columbia, Vancouver, BC, Canada V6T 1Z4. (mcclung@geog.ubc.ca)