PREDICTION OF THE DESTRUCTIVE SIZE OF DRY SLAB AVALANCHES FROM FIELD MEASUREMENTS

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ABSTRACT: In this paper we present estimates of the Destructive Size of dry snow slab avalanches based on field measurements of initial dimensions. The dimensions are combined with fracture line data from dry slab avalanches to predict, statistically, the initial mass released. The results should be of use as guidelines for backcountry travelers, avalanche forecasters and as input to avalanche dynamics applications.

KEYWORDS: Dry slab avalanche, Destructive Size, Statistical prediction

1. INTRODUCTION

The initial Destructive Size of dry slab avalanches released is highly related to the probability of death for backcountry travelers. It is also important since some modern avalanche dynamics models call for the initial mass released in order to start the calculations. In this paper, length data on downslope length, width and depth from field data on dry slab avalanches are used to estimate the initial mass released as input the mass categories of the Destructive Size. The estimates are compared to data on skier triggered avalanches from 20 years of data from Canada. The comparison shows generally good agreement and rough guidelines are given for Destructive Size versus slab depth D. However, the data from fallen avalanches imply wide variations.

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2. STATISTICAL CONSIDERATIONS

From McClung (2009), the median value of fracture length from initiation to terminal tensile fracture at the crown scaled with the depth is taken as: $l / D = 50$ from 63 field measured avalanches. The data base of 191 avalanche fracture line profiles used here has slab depths from 0.1 m to 4 m. The mean slab density with depth is:

$$\rho = 226 D^{0.236} \ (\mathrm{kg/m^3});\ R^2 = 0.19;\ S.E = 0.31$$

where the standard error refers to the regression equation written in terms of $\ln \rho$. Helicopter skiing company Canadian Mountain Holidays presented data on fallen slabs with depths over the same range: 0.1 m to 4 m. for more than 3000 events.

McClung (2009) showed from 63 dry slab avalanches measured in the field that $2l / D$ ranges from about 15 to 750 with a median 100.

The 63 avalanches from McClung (2009) were shown to adequately fit a lognormal distribution with $2l / D = \exp(4.605 + 0.91q)$ where q is the lognormal quantile. The lognormal quantile is written: $q = \sqrt{2} erf(2p - 1)$ where *erf* is the error function and p is non-exceedance (cumulative probability) for a normal distribution and $q = 0$ represents the median value. For $q = 0$, the

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median is determined: 100, for $q = -0.91$, the most probable value is given: 44.

3. SIMPLE MODEL TO PREDICT AVALANCHE DIMENSIONS

There are a number of applications for which avalanche dimensions are needed. One is to predict the mass so that size on the Destructive Scale (McClung and Schaerer, 2022) can be estimated. Another is as input of initial mass to avalanche dynamics applications. Here, a simple model is constructed based on measured dimensions from released slabs and the mean density of slabs from 191 dry slab avalanche profiles. In this section, the total length from crown to stauchwall is considered. McClung (2009) presented data on initial slab width and depth to enable volume inputs along with the model estimates here as input to mass calculations which is given in the next section. Figure 1 shows the geometry for a fallen dry slab avalanche.

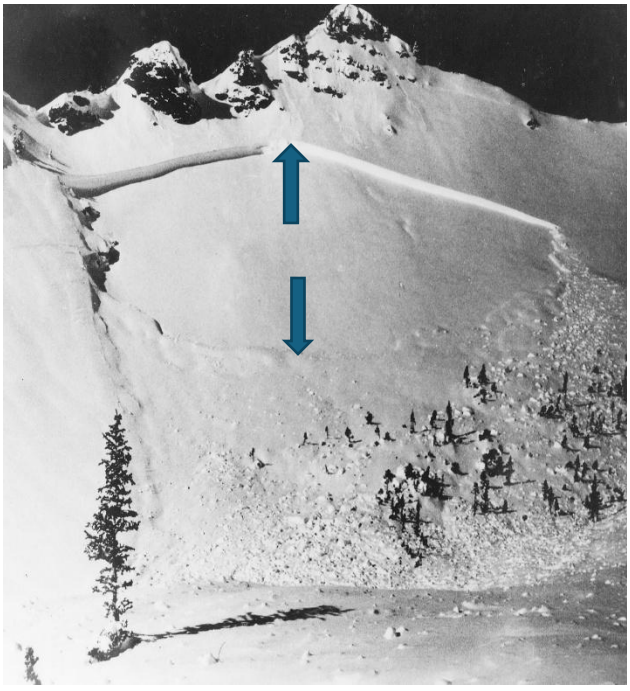


Figure 1: Fallen dry slab avalanche with tensile fracture line at the crown and lower boundary of the slab called the stauchwall with debris below the stauchwall.

In this section, the analysis is intended to predict the distance $2l$ (m) from the crown to the stauchwall in the center of the slab between the two arrows. Photo by R. Perla.

To use the probabilistic version of the model, one must specify the lognormal quantile (or cumulative probability) which gives the ratio of the total downslope avalanche dimension (2l) divided by the slab depth (D). The formula is: $2l / D = \exp(4.605 + 0.91q)$ for the lognormal plot below. For dry slab avalanche profiles, the parameter: $c_0 = \rho_B / \rho$ is expected from: 1 (homogeneous slab) to about 2. For $c_0 = 1,\ q = 0$, it gives the median value of $2l / D$ for the data in Figure 2.

For any value of c_0, the location parameter $\mu_L = 4.605 + \ln(c_0^{2.4})$ and the scale parameter is: $\sigma = 0.593$ (unchanged). Figure 2 shows the data from the 63 values in the 2009 paper.

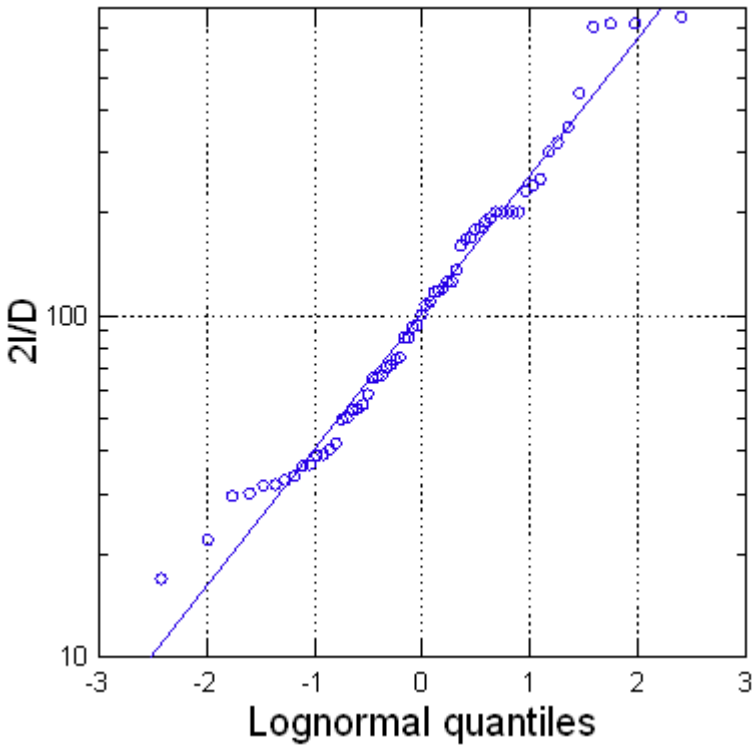


Figure 2: The 63 values of $2l / D$ from McClung (2009). The range is: 17 – 750 with median 100. The equation based on the data is: $2l / D = \exp(4.605 + 0.91q)$.

An analytical expression for the model (Figure 2) is:

$$\frac{2l}{D} = \left[1534 \left(\frac{\rho}{917} \right)^{1.942} D^{-0.458} \right] c_0^{2.4} \exp(0.91q) \quad (1)$$

which accounts for density increase with depth. Equation (1) is based on fracture mechanics by calculating the length from fracture initiation until tensile fracture initiation occurs at the crown due to the stress drop with residual friction behind the crack tip using the in-situ tensile strength measurements of Jamieson and Johnston (1992) for large sample sizes. Since snow is a strain softening material it is assumed there is a stress drop behind the advancing crack which generates tensile stress at the base of the slab as predicted by McClung and Schweizer (2006) and McClung (2021, 2025). Equation (1) is derived in a forthcoming paper (McClung and Pugno), to be submitted). Using the default density: $\rho = 226 D^{0.236}$ $(\mathrm{kg/m^3})$, the expression inside the square brackets yields the median value of $2l / D = 100$ for any slab depth (D).

Examples calculated from the model (equation 1) with $c_0 = 1$; $\mathrm{q} = 0$, for values of $2l$ compatible with Figure 2 are given below.

1. Kvitberget, Norway: Model calculated value: $2l = 80$ m; measured 94 m, measured depth = 0.8 m, $\psi = 40^0$, model density $214\ \mathrm{kg/m^3}$. No densities were measured. The measured value (94 m) implies $c_0 = 1.07$ using the model density $(\rho = 226 D^{0.236})$. For the Kvitberget avalanche, calculations (Figure 6) gave the results: 32 m, 80 m, and 200 m for quantiles: -1, 0 (median), 1 with $c_0 = 1$, with most probable value 35 m.

2. VDLS: Measured value: $2l$ = 300 m; Measured density: $\rho = 290\ \mathrm{kg/m^3}$; Measured: $\rho_B = 340\ \mathrm{kg/m^3}$: Average depth estimated = 1.5 m. varying from 0.5 – 2m. The result using measured densities $(\rho = 290\ \mathrm{kg/m^3};\ \rho_B = 340\ \mathrm{kg/m^3})$ and $D = 1.5$ m : 298 m. Model density: $249\ \mathrm{kg/m^3}$; Model prediction; $2l = 152$ m using the model density and depth 1.5 m; The measured value (300 m) implies $c_0 = 1.57$ using the model density. Using $D = 2.0$ m gave $2l = 350$ m using the measured densities.

McClung (2025) reported on 10 profiles with surface hoar in the weak layer. The median value of c_0 was 1.23. Using the median of $c_0 = 1.23$ for surface hoar at VDLS gives: 350 m versus 300 m measured. For Kvitberget, using the median (1.23) gives: 131 m vs. 94 m measured when using the model densities for both avalanches.

The calculations, along with measurements, show wide variations with emphasis on density measurements being very important.

4.ESTIMATES OF DESTRUCTIVE AVALANCHE SIZE

In this section, the expected mass of dry slab avalanches is estimated and related to the Canadian Destructive Size scale. The size scale is represented by the mass in tonnes given by:

$$M = 10^{size}\ \mathrm{(t)} \quad (2)$$

For example, if size = 2, then the mass is estimated as 100 tonnes.

From McClung (2009), the median of the ratio of total width (B) to length $(2l)$ was 2.1 with a range 1 -5 for unconfined avalanches (N= 26) and the median of the ratio $B / 2l$ (both confined and unconfined avalanches) ratio was : 1.2 (N = 63). The median ratio B / D was 113 (N = 130) for confined and unconfined avalanches. . From the data base of 191 dry slab avalanche profiles the mean slab density was: $\rho = 226 D^{0.236}$. Mass calculations for median size released are determined from:

Unconfined: $M = 4745 D^{3.236}$; Mix: confined, unconfined: $2710 D^{3.236}$ (3)

Table 1: Calculations of median Destructive Size versus slab depth: D (m)

D (m)	Size (Unconfined)	Size (Mix)
0.2	1.4	1.2
0.4	2.4	2.2
0.6	3.0	2.7
0.8	3.4	3.2
1.0	3.7	3.4
1.5	4.3	4.0
1.75	4.5	4.2

The calculations suggest that even for very modest slab depths beyond 0.3 m, the median Destructive Size is about 2 which according to the descriptors of the size system can bury, injure or kill a skier. For slab depths beyond 0.5 m, the size approaches 3. From a risk perspective, depths between about 0.6 m to 1 m were shown to exhibit the highest chance of death if triggered from Canadian statistics (McClung, 2014). The statistical relation (Figure 2) shows that much larger sizes can be expected than in Table 1. Table 2 shows comparison from the risk analysis of McClung (2014) for fatal accidents in Canada from 1984- 2013.

Table 2: Data on fatal accidents from Canada.

Destr. Aval. size	Fraction of fatal accidents	Range of $D(m)$ from analysis	Median $D(m)$ estimated by guides in skier triggering
1	0.02	0.15 – 0.20	0.30
2	0.275	0.30 – 0.40	0.40
3	0.54	0.60 – 0.80	0.65
4	0.165	1.30 – 1.70	1.4

Column 3 is based on the analysis in Table 1 for median size avalanches. Column 4 is based on median values from a data base of 1200 skier triggering avalanches including Destructive Size Scale estimates by guides at Canadian Mountain Holidays. The data suggest the highest chance of death is for slab depths about 0.6 m to 1 m or size 3 on the Destructive Scale.

5. SUMMARY

1. Calculations (Table 1) have been provided for the Destructive Size of avalanches represented as the initial mass released based on field data (McClung, 2009) and a data base of 191dry slab avalanche profiles. Table 1 contains the estimates for median values of the length parameters and densities required. Both data bases used imply wide variations in the parameters.
2. Comparison of the values (Table 1) for D versus size suggest reasonable agreement with guides estimates for 1200 skier triggered dry slab avalanches in relation to size (Table 2).
3. The values in Table 2 suggest rough guidelines with highest risk of death for slab depths between about 0.6 m to 1m or size 3 on the Destructive Scale. However, we believe a very important element of this study is to highlight the wide variations the data imply in relation to expected initial Destructive Size of avalanches. In mountain guiding and backcountry travel, in general, terrain management is of primary importance for safety.

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