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Analysis of snow avalanche terrain[1]

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A multiple regression analysis has been performed of the average annual number of avalanches and terrain factors. Observations were made at 36 paths at Rogers Pass over a period of 9 years. The average slope inclination measured from the starting point to the beginning of the run-out zone and exposure to wind proved to be the most significant variables. Slope angle at the starting point, variations over the track, and roughness of the ground surface were of secondary significance and their influence varied strongly from site to site. The analysis confirmed that avalanches need either a steep slope or a snow drift to start and a mimimum inclination of track to maintain their motion.

On a effectué une analyse par régression multiple du nombre annuel moyen d'avalanches et des facteurs du terrain. Pendant une période de 9 ans on a également fait des observations sur 36 parcours suivis par des avalanches. Il s'est avéré que les variables les plus significatives étaient l'inclinaison moyenne du talus mesurée de son point de départ jusqu'au commencement de la zone de réception de l'avalanche et l'exposition au vent. L'angle du talus au point de départ, les variations sur la longueur du couloir et la rugosité de la surface du sol étaient d'importance secondaire et leur influence variait beaucoup d'un site à l'autre. L'analyse a confirmé que les avalanches ont besoin d'une pente abrupte ou d'un amoncellement de neige pour partir et d'une inclinaison minimum du couloir pour maintenir le mouvement.

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Introduction

When the hazard of avalanches is assessed for a specific site, estimates must be made about frequency of occurrence and size. Reliable information can usually be obtained only by observations made over many years, but the time to do this is often not available. One must draw conclusions from an analysis of terrain, weather, tree growth, and debris in the run-out zone. Terrain and weather are factors that influence the formation of avalanches; trees, or lack of them, and debris are indications of actual occurrences.

The Division of Building Research of the National Research Council of Canada has been studying avalanches for the past 10 years at Rogers Pass, British Columbia, a favourable area for observation because it has numerous, closely spaced avalanche paths with run-out zones easily accessible from a major highway. The topography is typical of that of most avalanche areas west of the Rocky Mountains. Avalanche paths are rugged and steep, with differences in elevation of 500–1000 m between starting zones and the valley floor. The same type of avalanche terrain is encountered

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in many areas where roads, railways, buildings, or utility lines are built and maintained.

One of the continuing research projects at Rogers Pass has been the observation of the number of avalanche occurrences and the amount of snow contained in each along an 18-mile stretch of the Trans-Canada Highway. A multiple regression analysis has been carried out of the dependence of the number of observed avalanches on various terrain factors. The results are now reported. The relation between avalanche mass and terrain has been reported in an earlier paper (Schaerer 1975).

Start of Avalanches

Avalanches occur when the stress imposed on snow on a slope exceeds the strength of the snow. High stresses develop either at steep local slopes or at sites where there are accumulations of deep snow. Steep local slopes can be found in rolling terrain, at outcrops of bedrock, and as high cliffs (Fig. 1). Accumulations of deep snow with high stresses form on the lee side of ridges exposed to the wind (Fig. 2). A steep slope or a snowdrift area, or both, can be identified as the fracture location for all avalanche paths. Some paths are V-shaped, *i.e.* deep gullies, with several branches from which other avalanches start independently. In any analysis of terrain, each gully branch must be considered as a separate avalanche path.

When snow fails in shear, it must overcome the static and kinetic friction at the bed surface and then accelerate in order to develop into an avalanche. Little is known about the friction of snow sliding on snow, but some experiments have shown that the angle of friction is between 17° and 35° (Roch 1965).

The equation of motion after an avalanche has overcome initial friction can be written as (Fig. 1)

$$[1] \qquad M\, du/dt = M\, g \sin \psi - \Sigma R$$

where M = mass of snow, u = speed of the avalanche, g = acceleration due to gravity, ψ = slope angle, and ΣR = sum of the resistance forces. The resistance forces having the strongest influence are dependent on the speed u. Because resistance is rather small in the initial stage, the snow accelerates rapidly until it reaches a terminal velocity at which the resistance forces are in balance with the driving force $M\, g \sin \psi$. The terminal velocity is usually reached after a distance of 30–100 m, and motion is maintained as long as the track has a minimum incline.

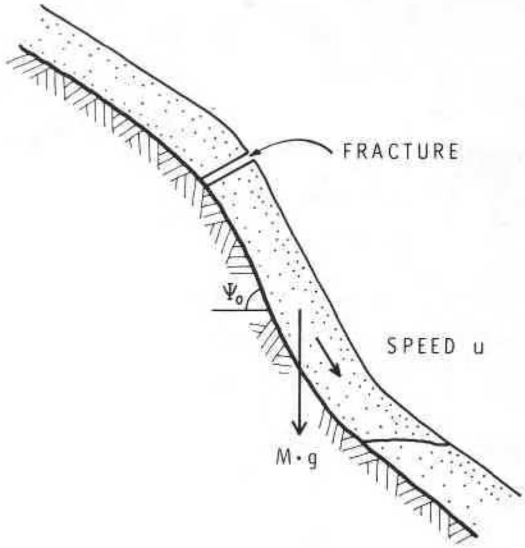

FIG. 1. Start on a steep slope.

In summary, avalanches depend on two important characteristics of terrain:

1. a fracture point that is either a steep slope or a snow drift area;
2. a slope below the fracture point that has sufficient incline and is smooth enough for snow to accelerate and maintain speed.

Observations of Avalanches

The average number of avalanche occurrences per year, F_a, observed in a 9-year period, 1966–1975, has been introduced as the dependent variable in a regression analysis. Normally, the avalanches were recorded during frequent patrols of the highway, but at times of high avalanche activity such as during a snowstorm observations were made every 2 h. The paths under observation produced between 0.25 and 20 avalanches per average year.

Classification of the size of avalanches is a controversial topic. For Division of Building Research studies they are classed as slough, small, medium, large, or major according to the mass of snow in relation to the surface of the accumulation area (Schaerer 1975). The present analysis included all classes greater

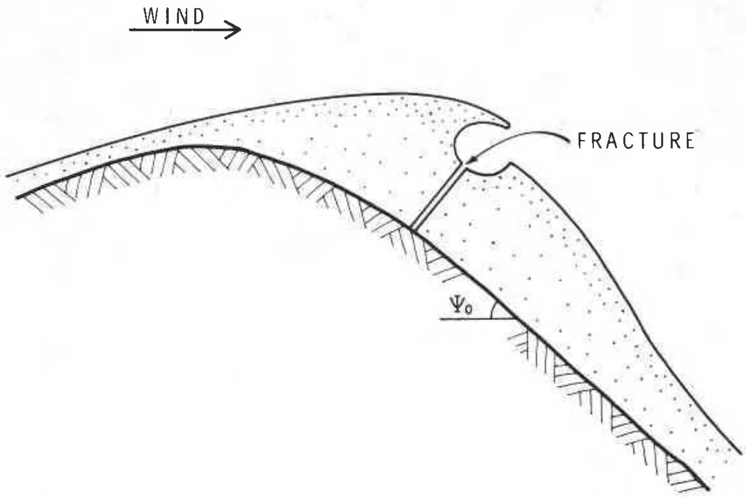

FIG. 2. Fracture at snow drift.

than slough. Such avalanches would be large enough to bury a person and move more than 100 m. A comparative analysis was made for medium, large, and major avalanches only — all could be hazardous to traffic on a road — but the result was not significantly different.

Observations of Terrain

Terminology

An avalanche path is the specific area in which a snow mass moves, and is generally divided into the *starting zone* at the top, the *run-out zone* at the bottom where the moving snow stops, and the *track* that connects the starting zone with the run-out zone. Avalanches remove snow from the starting zone and pick up additional snow in the track; the starting zone and the track together are the *accumulation area.* The term *fracture point*, as used in this paper, refers to the specific point in the starting zone at which an avalanche starts by failure of the snow.

Paths Selected for Analysis

A total of 36 avalanche paths with well-defined, unbroken starting zones and run-out zones that could be observed from the highway under any weather conditions were selected. The principal analysis contained only paths that were not regularly controlled by artillery, which is one of the methods applied to protect the highway at Rogers Pass. The influence of artillery on frequency of avalanches is a separate study.

There is some variation in the climate of the two sides of the pass. Snowfall on the east side is about 80% of that at an equal elevation on the west side. The avalanche starting zones on the east are higher, however, and because of an increase in snowfall with elevation they receive the same average amount of snow as the zones on the west side. With respect to the formation of avalanches, all avalanche paths can be considered to be exposed to the same climate and any variation in the number of avalanches would be mainly a function of terrain.

Method of Observation

The terrain variables suspected of influencing the formation of avalanches are listed in Table 1. Their values were determined from topographical maps, air photos, and observations in the field, the latter with respect to the exact location of the avalanche starting zones and their exposure to wind. Special topographical maps, scales 1:5000 and 1:2500, with contour intervals of 7.6 m (25 ft) and 5 m, respectively, were made of the avalanche paths. The standard maps of scale 1:50 000 proved to have insufficient accuracy.

Terrain Variables

Some of the independent variables of Table 1 should be explained.

Incline at the Fracture Point (ψ_0) — The incline refers to the steep slope where avalanches are initiated and was measured over

TABLE 1. Terrain variables

Variable	Observed values Mean	Minimum	Maximum
Incline fracture point ψ_0 (degree)	50	35	75
Exposure to wind W	2.7	1	5
Mean incline of track ψ_T (degree)	40.9	33.4	47
Variation of track incline S_ψ (degree)	7.8	4.4	12.4
Convexity–concavity V	2.1	0	8
Cross section mean β (degree)	19.6	1	40
Cross section standard deviation S_β (degree)	6.4	0	20
Accumulation area A (10^3 m^2)	97	14	222
Drainage density D (10^{-3} m^{-1})	13	5	26
Ruggedness number R_G	7.5	1.2	17
Aspect A_Z (degree)		(Compass bearing)	
Mean incline of area α (degree)	41.3	33.4	50.2
Standard deviation of incline of area S_α (degree)	8.1	4.8	11.6
Maximum incline of area α_{MAX} (degree)	62	46	80
Area steeper than 42° A_{42} (%)	42	8	80
Rougness R (mm)	250	150	300

a difference of elevation of 20 m, corresponding to the accuracy of the topographical maps. Determining this important slope angle from maps proved to be unreliable, and in future studies the incline of terrain should be observed at the site.

Exposure to Wind (W) — This variable is an index of the magnitude of snow drifting that can be expected in the avalanche starting zone. Because no method could be found to express the action of wind quantitatively, nominal values were assigned according to the following definitions.

- $W = 1$: starting zone completely sheltered from wind by surrounding dense forest
- $W = 2$: starting zone sheltered by an open forest or facing the direction of the prevailing wind
- $W = 3$: starting zone an open slope with rolls or other irregularities where local drifts can form
- $W = 4$: starting zone on the lee side of a sharp ridge
- $W = 5$: starting zone on the lee side of a wide, rounded ridge or open area where large amounts of snow can be moved by wind.

The analysis yielded better correlation when the wind exposure number was squared.

Mean Incline of the Track (ψ_T) — This refers to the average incline of the avalanche flow path from the fracture point to the top of the run-out zone. There was no significant variation in the frequency of avalanches for mean inclines steeper than 42° and ψ_T was assumed to be 42° for all steeper slopes.

Variation of the Track Incline (S_ψ) — Variation was expressed as the standard deviation of the incline of the avalanche flow path from the fracture point to the top of the run-out zone.

Convexity–concavity (V) — This variable is the number of 'breaks' where the slope angle in the flow path of the avalanches changed by at least 5°.

Cross Section Mean and Standard Deviation (β, S_β) — These variables indicate whether an avalanche flows in a channel or on an open slope and refers to the slope angles in cross sections perpendicular to the direction of the avalanches.

Drainage Density (D) — $D = L/A$, where L is the sum of the lengths of individual avalanche tracks and A is the accumulation area (Doornkamp and King 1971).

Ruggedness (R_G) — $R_G = DH$, where H is the difference in elevation between the top and bottom of the accumulation area (Doornkamp and King 1971).

Mean, Standard Deviation, and Maximum Incline of Area (α, S_α, α_{MAX}) — These variables refer to all slopes in the accumulation area, not to the profile between the fracture point and the run-out zone only. The slope angles were measured at 30 to 120 locations selected at random in the accumulation area.

Area Steeper than 42° (A_{42}) — This is the ratio between the surface area with slope incline greater than 42° and the total accumulation area. The angle of 42° was chosen because it is the maximum angle of repose of loose soil in the starting zones; furthermore, avalanches appeared to run at a maximum frequency on this and greater inclines.

Roughness (R) — Roughness of the ground is expressed by the water equivalent of the snow required to cover rocks, shrubs, and ledges before avalanches will run (Schaerer 1975).

The density of the forest would be an additional factor, but it was not considered because the avalanche starting zones were not tree covered.

Results

Univariate Analysis

A univariate analysis was conducted to determine which terrain factors were most highly correlated with frequency of avalanche occurrence. In addition to the simple independent variables described, certain combinations in the form of cross products, justified on physical grounds, were included in the study. The following variables were found to correlate significantly with avalanche frequency at the 99% level:

Variable	*Correlation coefficient*
Product of fracture point incline and wind exposure ($\psi_0 W$)	0.73
Roughness (R)	−0.68
Wind exposure, squared (W^2)	0.67
Fracture point incline (ψ_0)	0.67
Wind exposure (W)	0.67
Mean incline of track ψ_T	0.66

Multivariate Analysis

After identifying the most significant terrain factors in terms of simple regressions, a multilinear regression analysis with backward elimination was performed on the entire set of variables to determine whether a particular combination of terrain factors would result in a higher correlation of avalanche frequency. The following best regression resulted from the successive removal of insignificant terms.

$$F_a = 1.17\,\psi_T + 0.45\,W^2 - 41.8 \qquad [2]$$

with a multiple correlation coefficient of 0.82. F_a is the expected average number of avalanche occurrences per year.

Partial F-values for the ψ_T and W^2 factors were 22.0 and 24.8, respectively, indicating a highly significant contribution from each term. Residual errors appeared to be random and unbiased, indicating that this simple two-term model can be used to describe frequency of avalanches as a function of terrain for the particular set of avalanche paths used in the study.

Discussion

The regression analysis confirmed that avalanches are influenced by conditions at the fracture point represented by variables W, ψ_0, and R, and conditons in the track below, variables ψ_T and R. At the fracture point drifting of snow proved to be more significant than slope incline and roughness.

Incline of Track

The minimum mean incline necessary for avalanches to maintain momentum can be determined from [2] by setting $F_a = 0$ (Table 2). Calculated minimum values agree with general experience; avalanches appear to occur on average slopes steeper than 25°, but occasionally slide on slopes with less incline (Mellor 1968). When the track is steeper than 42° any increase in incline has little influence on frequency of avalanches. They would probably run whenever the weather was favourable for their release.

Incline at Fracture Point

It was not possible to draw conclusions about the minimum incline of the starting slope because no observations were made in the low range of inclines and other variables proved to be dominant. The slope angles of Table 2, however, are in the range of the angles of friction observed to be necessary for the initiation of avalanches. They could also be applied to the incline at the starting point.

Other studies have been made of the fre-

TABLE 2. Minimum mean incline of track

	Average	With confidence limit 95%
Sheltered starting zone ($W = 1$)	35.3°	30.7°
With strong influence of wind ($W = 5$)	26.1°	20.7°

quency distribution of the incline of slope at the fracture point of slab avalanches in the U.S.A., Japan, and Switzerland (Perla 1975; Perla and Martinelli 1976) and in Bulgaria and the U.S.S.R. (Peev 1959). The majority of avalanches were observed to start on slopes between 30° and 40° with a peak at 36°, and a few avalanches on slopes steeper than 50°. There is no logical reason for a decrease in frequency on steep slopes, except that avalanche frequency increases with slope incline until the average size of each avalanche is too small to be observed. Perla (1975) noticed a shift of the peak of frequency distribution to between 40° and 50° when small slab avalanches were included. Terrain steeper than 60° is usually avalanche-free. This angle is greater than the angle of repose of new snow. It sloughs off as soon as it is deposited.

The significance of avalanches that start on inclines in the range of 40–60° should not be underrated. Even small avalanches can grow into large ones by setting into motion unstable snow in the track below. The chance of this happening would be determined by the incline of the track, which again points to the high significance of the variable ψ_T.

Roughness

Ground surface, often considered to be an important factor in the formation of avalanches (Peev 1959), was found to have little significance in the multivariate analysis. The reason is that the snow at Rogers Pass is between 2 and 5 m deep, covers irregularities of the ground surface, and provides a smooth bed except at the beginning of the winter. Roughness would probably be more significant in areas with little snowfall.

Channel Effect

In an earlier study with less data the significance of the track cross section was found to be second only to the mean incline of the track (Schaerer 1972). In the present study, however, it was of no consequence. The explanation lies in a correlation between channel variables and exposure to wind, suggesting a stronger influence of wind for channelled paths than open slopes.

Aspect

Aspect had no influence on the average frequency of avalanches. Fourteen paths under investigation faced northwest to northeast, seven paths faced east, and eighteen paths faced south. No difference in the variation of the number of avalanches was noted.

Influence of Artillery Control

It is the objective of artillery fire to bring down avalanches frequently, under controlled conditions. To determine the influence of artillery fire on number of avalanches, a prediction was made, using [2], for frequency of avalanches at 15 paths at Rogers Pass regularly controlled by artillery. The average number of avalanches predicted was 9.2, whereas the average number of avalanches observed was 17.6. This leads to the conclusion that artillery produced, on the average, 1.9 times more avalanches than could be expected to run naturally. No comparison was made of the size of the avalanches.

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