Peter Schaerer March 1993

The Avalanche Hazard Index

Definition

Tha avalanche hazard index is a numerical expression of damage as a result of an interaction between snow avalanches and vehicles on a road. The index is determined by calculating the probability of moving and waiting vehicles being hit by various types of avalanches and multiplying the probability with a weight according to the severity of the damage. The hazard index is a function of:

a) the width and depth of the avalanches at the road;

b) the frequency of avalanche occurrences;

c) the number of avalanche paths at the road;

d) the distance between the avalanche paths;

e) the volume of traffic during the avalanche season (usually December - April);

d) the speed of the traffic.

The calculation of the avalanche hazard index is described in detail in Schaerer (1989).[1]

Application

Avalanche hazard indices were calculated for roads in British Columbia, Alberta, the U.S.A., and New Zealand with the following applications:

1) The index allows comparison of the avalanche hazard between roads and the level of control that is applied and is acceptable.

2) The index identifies the avalanche paths that contribute most strongly to the hazard of a road, and consequently the paths that should be given priority for control measures.

3) The index allows the evaluation of the effect of alternative control measures. Indices as a result of a variety of avalanche control options can be introduced in a cost-effective analysis.

4) Calculation of the hazard index for future heavier traffic volumes allow the orderly planning of control measures.

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[1] Schaerer Peter; 1989. The Avalanche Hazard Index. Annals of Glaciology 13; p.241-247. International Glaciological Society.

The Simplified Avalanche Hazard Index

The calculation of the avalanche hazard index requires data about the average width and frequency of occurrence of two types of avalanches at each individual avalanche path. Because this information often is difficult to obtain, a simplified hazard index was developed for the comparison of the hazard among roads (Application 1) and the evaluation of control measures (Application 3).

The simplified avalanche hazard, I_s, is:

$$I_s = A \times p \times N/100$$

where:

A = average annual number of avalanches that cover the full width of the road (sum of all paths);

p = average number of avalanche paths per road kilometre; the road length per avalanche path is limited to a maximum of 1 km.

N = average daily winter traffic volume (vehicles per day).

Categories of Hazard

Practice in Canada and the U.S.A. allows to categorize highways with respect to the avalanche hazard index as follows:

HAZARD	DETAILED INDEX	SIMPLIFIED INDEX
Very low	< 1	< 5
Low	1 to 10	5 to 50
Moderate	10 to 40	50 to 200
High	40 to 150	200 to 750
Very high	> 150	> 750

Correlation Simplified to Detailed Index

In general there is a good correlation between the two indices, but some avalanche areas, including Kootenay Pass and Icefields North, do not follow the rules.

Following are the results of a linear regression analysis with,

I_s = simple avalanche hazard index
I_d = detailed avalanche hazard index

Hazard Level	Number of areas		Correlation coefficient
Very high and high; excluding Kootenay Pass	10	$I_s = 6.9\ I_d$	0.96
Moderate; excluding Icefields North	8	$I_s = 2\ I_d$	0.9
Low and very low	5	$I_s = 10.7\ I_d$	0.95

The sample sizes are too small for making conclusions why the ratios between the two indices are much different for the moderate hazard areas.

Kootenay Pass has a ratio $I_s/I_d = 2$ (equal to moderate areas). The ratio for the Icefields Parkway North equals 1; there is no clear explanation for the discrepancy.

Summary of Calculated Hazard Indices

All indices were calculated for hazards without a control of traffic (highways were considered open to traffic).

Road	Function of Road	Traffic WADT	Simple Index	Detailed Index	Index Moffat
Very High Hazard					
TCH Glacier Park					
- W/O any control	Arterial	2300	5486	852	
- W/O artillery.		2300	1483	216	
- With artillery		2300	322	34	
Kootenay Pass	Arterial	700	806	406	194
Red Mtn. Pass CO	Arterial	675	810	103 (Armstrong)	
		1000	1200		
Little Cottonwood	Recreation	8000	2845	801 (Bowles)	
Seward Highway	Art. Recn.	4500	11138		
Snoqualmie Pass	Arterial	20000	6300		
High Hazard					
TCH Revelst.West	Arterial	2660	687	103	91
TCH Revelst.East	Arterial	2300	416	54	64
TCH Golden East	Arterial	2500	292	67	43
Icefields North	Art./Recn.				
- W/O control		280	56	56	
- residual with explosive		280	36	15	
Bear Pass	Arterial	400	313	48	95
Berthoud Pass CO	Art./Recn.	5140	407		
Loveland Pass CO	Art./Recn.	1190	506		
Carson Pass CA		2500	3125		
Echo Summit CA		10500			
Moderate Hazard					
Kootenay Park	Arterial	1045	32	16	
- residual with closures		1045	16	15	
Maligne Lake	Recreation	300	90	38	
Sunshine	Recreation	2000	80	21	
- residual with control		2000	6	0.4	
TCH Yoho Park	Arterial	2500	48	10.3	
- residual with control		2500	40	10.1	
Blueberry-Paulson	Arterial	1000	46		19
Duffey Lake	Collector	120	37		16

Blueberry-Paulson	Arterial	1333	302	32 (Stethem)	
Revel.-Mica South	Collector	300	33	14	61
North	Collector	120	2	0.5	
Hill	Local	30	9	2	
Klondike USA		150	110	50	
Klondike Canada		150	35	17	
Teton Pass, Wyoming		1000	95	39 (Consultant)	

Low Hazard

Allison Pass	Arterial	1250	24	2.3	22
Red Pass	Arterial	1240	15	1.7	6
Smith-Dorrien	Recreation	50	5		
Smith-Dorrien	Recreation	300	27	17	
Whitewater Skiarea	Recreation	250	16		8
TCH Mt.Revelstoke Pk.	Art.	2300	33	1.2	
Fernie (Hwy 3)	Arterial	1540	8		1.3

Very Low Hazard

Icefields South	Art / Recn.	265	1.1	0.3
- residual with control				0.3
Field Backroad	Local	50	2.9	0.4
Emerald Lake	Recreation	195	0.3	0.01
Minnewanka Road	Local	550		0.1

Caution

One should be cautious in comparing closely the hazard indices, because the standard of reporting avalanche occurrence frequencies may not be equal. For example, powder avalanches and small deposits that do not cover the full width of a highway, were excluded from the calculations for Canadian National Parks, but I suspect, that they were included for other highways. The calculated indices, however, allow well to categorize the highways with respect to levels of hazard.

P. Schaerer 7 March 1993

Monetary Value of Hazard Index Points

Problem

Following is an examination of the question: What is the value of the difference of traffic safety when the avalanche hazard is reduced by a value of one unit?

Probability of a Vehicle/Avalanche Encounter

For an avalanche hazard index of a value "1", the theoretical probability of a vehicle being hit by a deep avalanche is 1/10 = 0.1, or a light snow avalanche 1/3 = 0.33. 10 and 3 respectively are the weights which calculated probabilities are multiplied with in order to determine the hazard index.

In reality, the probability of a vehicle being hit is less than the theoretical, because for hazard index calculations, encounter probabilities are determined on the assumption that the traffic would move freely. In reality, however, the traffic is restricted during periods of avalanche occurrences. An avalanche on the road cuts the traffic flow to all other avalanche paths beyond and even after the avalanche snow has been removed, often the road remains closed until avalanche technicians or maintenance personnel consider conditions are safe.

It was difficult to obtain the number of actual avalanche encounters on roads. For my study in 1988 I found only the following data:

	Average number of encounters per year		
	Theoretical	Observed	Ratio
Rogers Pass	0.3	0.04	7.5
Kootenay Pass	6	1.9	3.2
Red Mtn Pass (Armstrong 1981)	24	1.6	15
Three Valley - Revelstoke	3.4	0.3	10.1

These numbers suggest, that in practice there are on the average about 8 times fewer encounters than calculated. Most encounters were with light avalanches, which is likely the result of the control by artillery which tends to produce smaller avalanches (though a greater number).
In addition, numerous avalanche encounters were reported when vehicles ran into deposited snow without any damage.

For the practical encounter probability, let the theoretical probability be divided by 8, which yields for,

Deep snow 0.1/8 = 0.0125,
Light snow o.33/8 = 0.04.

Cost of Damage

An encounter with a deep snow avalanche results in heavy damage to the vehicle and probably injury and death. A loss of life might occur in half of the encounters. Presently, the value of loss of life is about $ 500 000 according to life insurance companies. To this sum one should add the cost of property damage, possible law suits, and adverse publicity. This means, an encounter with a deep snow avalanche, probably would cost on the average $ 400 000.

Similarily, an encounter with a light snow avalanche would result in vehicle damage and perhaps injury. The cost of damage, injury, and publicity of an encounter might be valued at $ 50 000.

Benefit of Reducing the Hazard

Multiplying the practical encounter probability with the estimated value of damage yields the savings in accident cost when the hazard index is reduced by one point. It is:

For deep snow avalanches 0.0125 * 400 000 = $ 5 000 per year;
For light snow avalanches 0.04 * 50 000 = $ 2 000 per year.

Assuming that half of the encounters are with deep avalanches, and half with light avalanches, the average benefit of reducing the hazard index by a value of 1 would be on the average $ 3 500 per year.

The analysis above takes into account only the cost of accidents. In addition, a reduction of avalanches on the road by control measures reduces closure times. This benefit cannot be estimated in general terms, as it depends on the combination of avalanches over the whole road.

Example Beaver Valley in Glacier National Park

The cost of road re-location (Option B) was estimated at $ 1.3 Million. The annual capital cost on this money with an interest of 8 % is $ 104 000.

The improved road alignment reduces the avalanche hazard index (with traffic control and avalanche control as applied in 1965-1992) by 10.2 (from 13.4 to 3.2). With the benefits determined above, the benefit in accident reduction in Beaver Valley would be, 10.2 * 3 500 = 35 700 per year.

As a conclusion, the road re-location in the Beaver Valley would not be worth the money unless it has benefits other than reducing avalanche encounters. The additional benefits, which justify the work are: a) a reduction of highway closures when avalanches do not occurr at other paths; b) solving a problem at a remote area.

Conclusion

The monetary value of a reduction of encounter probabilities and avalanche hazard seems to be low and in many cases would not justify an avalanche control by structures and earthworks. The benefit remains low even if the cost of accidents would be assumed to be greater.

One has to consider benefits other than accident prevention - for example the influence on availability of the road (closures) - in order to evaluate and justify avalanche control measures.

Snow Avalanche Hazard Lines Stewart
Study for Min. of Trsp. & Hwy, B.C.

STEWART, HZ4

November 1994

APPENDIX I

PARAMETERS FOR AVALANCHE RUNOUT DISTANCES
BRITISH COLUMBIA NORTH COAST

by Peter Schaerer

TYPES OF AVALANCHES

Three types of avalanches must be considered when runout distances are determined for avalanches at the North Coast of British Columbia: Flow Avalanches, Plunging Snow, and Powder Avalanches.

Flow Avalanches

Flow avalanches contain dense snow which moves along the ground surface similar to a fluid. The snow may be dry or wet. Owing to a high friction with the ground and a high friction between snow particles, the avalanches decelerate rapidly in the runout zone. Large avalanche typically deposit 2 to 10 m deep snow in the runout zone.

Plunging Snow

Plunging snow develops when a flowing avalanche falls over a high and steep slope allowing air be mixed into the avalanche snow. The avalanches reach a high speed and have a long runout distance. Owing to the high speed, a density that is considerably higher than the density of powder avalanches, and a strong turbulence, plunging snow avalanches can be highly destructive.

Powder Avalanches

Fine particles of dry flow avalanches and plunging snow become suspended above the avalanche surface to form an aerosol of fine, diffused snow. In the avalanche track the powder usually accompanies the flowing component, but in the runout zone the powder often separates and moves a longer distance. The effect of powder avalanches on objects in their path is similar to wind forces.

CHARACTER OF PLUNGING SNOW

Plunging snow is associated with steep and long avalanche paths, which are often found at the deep U-shaped valleys of Coastal Northern British Columbia, including the valley of Bear Creek at Stewart. The starting zones have low inclines (25° to 40°), allowing deep snow to accumulate prior to an avalanche release event. The avalanches then fall over steep and long slopes (typically 1000 m) to an almost horizontal runout zone in the valley floor. The avalanche snow, becoming strongly fluidized on the long, steep track, develops a high speed, a low density (a guess is 20 to 50 kg m^{-3}), and a very low friction with the ground. The high speed and low friction produces long runout distances and has resulted in surprisingly extensive damage to forest. The avalanche speed probably is close to the speed of powder avalanches falling through the free air, but because of a greater density, plunging snow is more destructive.

Observations of destroyed forest at Bear Pass (Highway 37, Stewart - Meziadin), and structures of the electric transmission line Kemano -Kitimat, and at Highway 16 (Terrace - Price Rupert) suggest that very large avalanches have been more violent and have longer runout distances than could be explained from experience in the Rocky, Purcell, and Selkirk Mountains. A conclusion is that the avalanches probably were plunging snow.

A further problem is that very large avalanches at the North Coast seem to have longer return intervals than maximum avalanches of other mountain ranges. The infrequent occurrences and unexpected violent nature of the plunging snow often lead to an underestimate of the hazard.

Avalanche paths on open steep, long slopes and the associated violent avalanches are common also in the Southern Alps of New Zealand, mainly at the Milford Road. There, the climate is similar to the coast of British Columbia, but due to a greater amount of snowfall, avalanches are more frequent. Blair Fitzharris and Ian Owens (1980) have named them plunging snow for the avalanche atlas of the Milford Road. For lack of a better term, we have used this label also for the similar avalanches at Stewart.

Avalanche researchers in France have mentioned and seem to be impressed by the "terrible, destructive powder avalanche". It is suspected that also in the French Alps, where the valleys are deep and the sides steep, plunging snow, rather than pure powder is responsible for the observed destruction.

ANALYSIS OF PLUNGING SNOW AVALANCHES

An analysis was made with the objective of developing guidelines that could be used for the prediction of the runout distance of plunging snow.

Parameters were fitted to observed and probably maximum runout distances of 7 avalanche paths at Bear Pass, 1 path at Highway 16, and 3 paths at Kemano. The slope profiles of the avalanche paths at Bear Pass were plotted from air photos by Pacific International Mapping Ltd. in 1994, the profiles at Kemano were obtained from contour maps of scale 1:5000, and at Highway 16 from ground observations in 1976.

The sample of 11 avalanche paths is too small for making definite conclusions, but no additional evidence was readily available of destructive avalanches with a return interval of 100 years and greater. The results, however, allow cautious conclusions about the avalanche runout distances at Stewart. It would be useful to analyze additional avalanche paths (not necessarily at a highway) where the runout distance of very large avalanches is evident. The results could be valuable when developments are planned at the North Coast in the future.

Following are given the parameters which could be fitted to the observed long avalanche runout distances.

Model McClung (Norwegian Method)

The Model McClung, which was originally developed in Norway and there is used extensively for the prediction of avalanche runout distances, defines the runout distance by the angle $\alpha = c\,\beta$.

α is the sight angle along the avalanche path from the avalanche starting line to the end of the runout zone.

β is the sight angle from the avalanche starting line to the point P where the terrain incline decreases to 10°.

Avalanche paths may be divided into two types: a) hockey-stick types which have a sharp transition between the steep track and the runout zone on the level valley bottom, and b) normal type paths with a gradual transition, typically on an colluvial fan, between the track and the runout zone. Hockey-stick avalanche paths perhaps produce a stronger mixing and fluidization of the snow and longer runout distances, but it was not clear from the small sample that was investigated (6 hockey-stick, 5 normal) whether or not the slope profile has an influence on the runout distance for plunging snow.

In the analysis, the parameter "c" had a mean value of c = 0.77 (standard deviation 0.07), but the observations with the highest reliability, for example Little Bear No.1 and 2 (hockey-stick paths), had c = 0.72 and 0.70.

It would be reasonable and safe at this time to assume c = 0.70 for hockey-stick paths. For normal paths, a value c = 0.74 might be assumed with some caution.

Following are values for c which were determined statistically for other mountain areas, which may or may not include plunging snow avalanches (McClung, Mears and Schaerer, 1989).

Canadian Rocky Mountains	0.93
South-West Alaska	0.82
East side Sierra Nevada	0.72
Colorado	0.82
Western Norway	0.90

The differences between mountain ranges have not been explained satisfactorily. Perhaps for some ranges, the avalanche paths contained effects of plunging snow which might have pulled down the mean value for "c".

Average Friction Coefficient in the Runout zone

With a given avalanche speed at the begin of the runout zone, calculated either with the Swiss model or the model Perla, the runout distance may be determined by using an average friction coefficient over the length of the runout zone. For the sample that was investigated, the average runout friction coefficient was 0.21 and 0.22 for the avalanches which ran out on level terrain on a mix of open ground and forest (for example Little Bear 1 and 2, and Dahlie). For no obvious reasons, the coefficient was much greater for avalanche runout zones that had an adverse slope (for example Little Bear 4 and Chocolate Bar).

FLOW AVALANCHES

Following are listed the parameters which were applied for the calculation of the runout distances of flow avalanches at Stewart. The values, which have been developed for other mountain areas, support the observed or probable location of deep avalanche deposits at the sites under investigation.

Model McClung

$c = 0.82$

Swiss Model

$d_0 = 1.8$ m on a 37° incline of slope.

$\xi = 900$ to $1200\ \text{m s}^{-2}$ on open terrain. The value depends on the roughness of the terrain; high values apply to the flats of the Bear River.
$\xi = 400$ to $600\ \text{m s}^{-2}$ in forests.

$\mu = 0.15$ in the track.
$\mu = 0.2$ in the runout zone.

Model Perla

$M/D = 700$ m
$\mu = 0.15$

Average Friction coefficient

$\mu = 0.35$

POWDER AVALANCHES

The runout distance for powder avalanches refers to the point where the speed of the avalanche has dropped to 20 m s^{-1}. With this speed the avalanche would produce an impact force of about 3 kPa which corresponds to the effect of a gale force wind. The powder would move across the hazard line and cover the area beyond with snow dust, but no serious structural damage is expected.

The runout distance for damaging powder avalanche is approximately equal to the runout distance of plunging snow, therefore the models and values for plunging snow were applied.

On terrain where plunging snow would not develop, the runout distance of powder avalanches was estimated by assuming that their speed in the track would be equal to the speed of flow avalanches (determined with the Swiss and Perla models), and the Swiss model was applied for calculating the runout distance with:

$\xi = 250$ m s^{-2}
$\mu = 0$
$d_p = 40$ m

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INTERNATIONAL SNOW SCIENCE WORKSHOP 1996

AVALANCHES AT ROGERS PASS

Notes for Field Trip on 11 October 1996

TERRAIN

Rogers Pass at the elevation of 1347 m (4354 feet) is in the Selkirk Mountains, which belong to the Columbia Mountains, one of the interior mountain ranges of the Province of British Columbia. The peaks surrounding the pass are 2850 m (9350 ft) to 3300 m (10820 ft) high and consist mainly of quartzite rock. Rogers Pass is in Glacier National Park, which extends 20 km to both sides of the pass.

The pass is approached from the east through the Beaver Valley - which divides the Selkirk Mountains from the Purcell Mountains - then over a distance of 11 km (7 miles) and 444 m (1434 ft) difference of elevation to the summit. Going West, the highway follows the Illecillewaet River for 64 km (40 miles) to Revelstoke at the elevation 455 m (1490 ft).

CLIMATE

The Selkirk Mountain range is in the interior wet belt of British Columbia, which is characterized by high amounts of precipitation as a result of a prevailing westerly flow of moist pacific air. Although the westerly flow dominates, several times during the winter, dry and cold arctic air invades from across the Rocky Mountains. During the cold periods, the temperature may drop to -20°C and -30°C. Following are observed amounts of precipitation in 1966-1986:

Observatory	Rogers Pass	Fidelity Mountain
Elevation	1315 m	1905 m
Mean annual snowfall	997 cm	1503 cm
Maximum annual snowfall	1553 cm	2151 cm
Maximum snow depth	319 cm	493 cm
Mean annual rainfall	605 mm	603 mm

The Rogers Pass observatory is located at the maintenance compound near the summit, and Fidelity Mountain at the west side and 14 km from Rogers Pass summit.

AVALANCHE PATHS

The combination of heavy snowfall and steep mountain slopes produces numerous avalanches which run out on narrow and at some places V-shaped valley bottoms. The snow avalanche atlas for Rogers Pass lists 134 avalanche paths which affect either the highway, the railway, or both inside the national park. An additional 30 avalanche paths are at the highway and the railway west of the national park boundary.

The vertical drops between the avalanche starting zones and runout zones range between 300 m and 1700 m. Numerous avalanche paths have multiple starting zones and often the runout zones of individual paths overlap. The frequency of avalanche occurrences varies strongly with the incline of the slope. At he steep areas, for example at Mount Tupper at the east side of the pass, avalanches reach the highway location (protected by snow sheds) five to ten times per year, at other sites avalanches have reached the valley once in ten or twenty years.

DISCOVERY OF ROGERS PASS

Native people did not live in the centre of the Selkirk Mountains, because the deep snow restricted travel for man and animals. In 1858 to 1865, gold miners invaded the Columbia river and its tributaries above Revelstoke, but soon left for richer fields. In 1865, the government of British Columbia (at that time a British crown colony) ordered Walter Moberly to explore the region. Moberly discovered Eagle Pass west of Revelstoke, then moved up the north fork (now called Tangier Creek) of the Illecillewaet River to discover Moberly Pass, which he found unsuitable for a road or railway.

In 1871, British Columbia joined the Federation of Canada with the condition that a transcontinental railway be built. The Canadian Pacific Railway undertook this task and hired Major A.B. Rogers, a railway engineer and surveyor from Massachusetts to find a route through the Selkirks. Part of the incentive for finding a crossing of the mountain range was that the pass would be named after him. Following the south fork of the Illecillewaet River from the West, Rogers discovered the pass at the end of May 1881. In the following year, by approaching the Pass from the east side, Rogers confirmed the feasibility of a railway route across the Selkirk mountains.

The railway line on Rogers Pass was built in the summer of 1885, and the last spike of the transcontinental Canadian Pacific Railway line was driven on November 7, 1885 at Craigellachie, 48 km west of Revelstoke.

AVALANCHES AT THE RAILWAY

In the winter of 1884-1885, avalanches had already buried and killed construction workers east of the pass. No sooner had the railway line been completed late in 1885, it had to be closed at Rogers Pass when deep snow and avalanches buried the track. The construction of snow sheds was initiated at serious avalanche paths in 1886 and later extended to other sites. Finally, there were 31 sheds with a total length of 6.5 km. All of them were built of heavy timber.

The railway company had built a hotel where the railway line looped towards the Illecillewaet glacier. The hotel became a centre for tourists and mountain climbers.

On January 30, 1899 an avalanche buried the first Rogers Pass railway station, 3 km east of the summit, and killed seven persons. The most serious avalanche disaster struck on March 4, 1910 when 62 railway workers died in a single avalanche. On that day, an avalanche from Mount Cheops had buried the railway track. While workers were removing the snow with shovels and a rotary plow, a second avalanche struck from the opposite side of the valley and buried them. Another avalanche cycle caused by heavy snowfall and high temperatures closed the railway line for five days in January 1935.

It was estimated that between 1884 and 1948 a total of about 260 men had died in avalanches at the railway line at Rogers Pass.

The disaster of 1910, other avalanches at unprotected sites, the extensive snow removal work, and the need to renew the timber structures of snow sheds persuaded the Canadian Pacific Railway to build the 8 km long Connaught tunnel 162 m (540 feet) below the summit and to abandon the track over the summit. The tunnel by-passed the Glacier House hotel which was then closed and demolished.

A few of the snow sheds west of the tunnel were eliminated in later years when they had deteriorated and the railway considered that the avalanche snow now could be removed efficiently with bulldozers. After the highway was opened in 1962, the railway company cooperated with the National Parks in controlling avalanches by artillery.

TRANS CANADA HIGHWAY

The highway at Rogers Pass is part of the Trans Canada Highway which stretches from Newfoundland to Vancouver Island. It was built by the Canadian provinces with the financial support of the Government of Canada. The construction of the Trans Canada Highway over Rogers Pass began in 1957, and the highway was formally opened on September 3, 1962.

Because the highway engineers knew from the experiences of the railway that avalanches would be a major problem, avalanche protection was planned simultaneously with the location and construction work. In 1953, after the first location reconnaissance, park warden Noel Gardner was assigned the duty of observing avalanche occurrences during the coming three winters. Twice a month he travelled on ski through the pass and recorded avalanches. The information was used to locate the highway away from avalanche paths, where this was feasible, and for the design of protective works. In 1956 Noel Gardner became a full-time avalanche co-ordinator with work base at Glacier at the west portal of the railway tunnel. He established snow and weather study plots in the valley, built an observatory at Mount Abbott, developed the experience of predicting avalanche occurrences at Rogers Pass, and on frequent patrols by Tucker Snocat recorded the avalanches along the future highway. In 1957 Peter Schaerer joined the avalanche survey group for the location and design of engineering avalanche control works. The avalanche survey crew of six men was maintained during the winters when the highway was under construction, although, owing to the deep snow, the road work itself was suspended from November till May.

After the highway was built, Noel Gardner was responsible for the avalanche safety on the completed highway by directing artillery fire and recommending closures to traffic. In 1965, Fred Schleiss and Walter Schleiss, who had worked with Noel Gardner since 1959, assumed this task. They retired in 1991 to leave Dave Skjonsberg in charge.

AVALANCHE CONTROL AT THE HIGHWAY

The winter average traffic volume through Rogers Pass has increased from 400 vehicles per day in 1962 to 2600 vehicles per day in 1995. The combination of numerous and closely spaced avalanche paths, frequent avalanche occurrences, and a high traffic volume produces a very high avalanche hazard which demands extensive protective measures.

The avalanche safety at the Rogers Pass highway relies on a combination of engineering works, control by artillery, and road closures. Engineering works include the following:

* As much as possible, the location of the highway avoided avalanche paths, principally by moving the road grade as far down avalanche runout zones as possible.

* Snow sheds were built at locations where avalanches were expected to cover the highway more frequently then once per year. There are 8 snow sheds with a total length of 2160 m, covering 15 avalanche paths.

* Deflector dikes, arrester dikes, and benches with snow dikes were built at 9 avalanche paths.

* Earth retarder mounds cover 9 avalanche paths; their cost was very low in association with the grading work of the highway.

* Supporting structures cover 2 low elevation starting zones east of the Pass.

The control by explosives relies on 105 mm howitzers and 106 recoilless rifles in the national park and on avalauncher and bombing from helicopter west of the park. Manual road blocks and light signals control the traffic when the highway is closed due to explosive control or excessive avalanche danger.

The Snow Research and Avalanche Warning Section of the Canadian Parks Service is responsible for the control by artillery and road closures inside the national park, and avalanche technicians of the Ministry of Transportation and Highways of British Columbia with headquarters in Revelstoke for the highway west of the national park. The technicians of the Ministry of Transportation and Highways under Bruce Allen are in charge also of the avalanche safety at the highways west, north, and south of Revelstoke. The national parks crew in addition issues avalanche warnings for back country users .

The Snow Research and Avalanche Warning Section has it headquarters at the maintenance compound near the summit of Rogers Pass and occupies an observatory at Fidelity Mountain (elevation 1905 m). A total of five remote weather stations at high elevations serve both avalanche warning services. Papers that are presented at the workshop at Banff contain information in greater detail.

AVALANCHE RESEARCH

The National Research Council of Canada (NRCC) assisted the avalanche control at Rogers Pass from its beginning by supplying the first weather and snow observation equipment and by making available its staff member Peter Schaerer for the design of the engineering work and the development of avalanche hazard forecasting. The continuous winter observations at Rogers Pas in 1957-1961 offered opportunities to develop knowledge about loads on snow sheds, snow loads on buildings, and avalanche hazard forecasting. The results of these observations were published later.

When in 1966 the interest in avalanche safety in Canada grew, the National Research Council of Canada again established research officer Peter Schaerer and a technician for the winters at Rogers Pass. In later years two additional technicians assisted during the winters and Dave McClung joined the staff as a research officer.

The NRCC avalanche research group operated beside the Snow Research and Avalanche Warning Section of Glacier National Park, but had a close cooperation. The research work that was carried out included:

* Observations of the mass of avalanches with the objective of predicting the size characteristics and frequency of avalanches for given terrain and snowfall.

* Observations of the speed of avalanches.

* Observations of the impact pressures of avalanches with instruments at the avalanche path Tupper No.1.

* Correlations of the snow water equivalent with elevation.

* Shear tests on weak layers and slow shears on samples in the cold room.

The avalanche research group of the National Research Council of Canada was disbanded in 1991 and David McClung transferred with the research equipment and the cold room laboratory to the University of British Columbia. He continued the avalanche research work by using the equipment at Rogers Pass.

Peter Schaerer

[illegible] Ditch Design

31 March 2000

GUIDELINES FOR DITCH DESIGN AT CUT SLOPES WITH AVALANCHES

By Peter Schaerer

1. OBJECTIVES

Cut slopes at highways usually have inclines between 34° and 39° in loose soil and are steeper in bedrock. These inclines favour the formation of avalanches when enough snow is available. A highway ditch is capable of catching the avalanches at short slopes, but the problem arises how wide and deep the ditch must be in order to be effective. A curb, wall, or piled-up snow may reinforce the effect of the ditch.

These guidelines outline the procedure for estimating whether a ditch with given depth and width would be capable of retaining avalanches. The guidelines are applicable to open slopes with a uniform incline. The length of slope, where a ditch may be useful for avalanche control, depends on the depth of snow. At locations with a snow depth less than 1 m, the slope may be 100 m long. In deep snow areas, a 30 m long slope may be a maximum.

Information is meager on the dynamics of avalanches at short slopes, and how avalanches act when they hit a ditch. In 1984-1985, I have made observations on avalanche deposits at cut slopes of highways. The number of observations was too small for making an analysis of the numerous variables, but the data allowed general conclusions. In developing these guidelines, I have taken into account my observations and theories of the motion of avalanches.

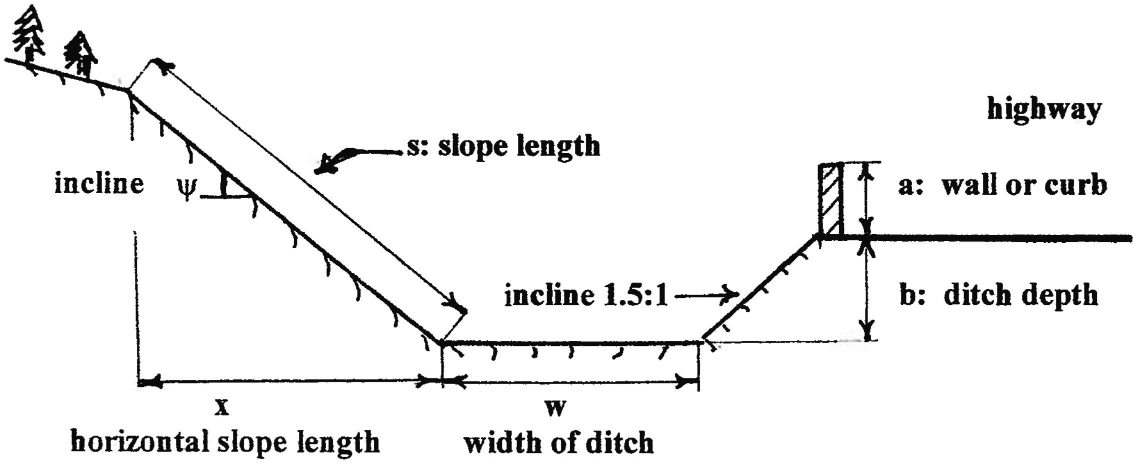

Figure 1

TYPICAL DITCH

2. DESIGN CRITERIA

The function of a ditch is twofold:
a) To catch and store the expected avalanche snow
b) To stop moving avalanches

The effectiveness of a ditch must be investigated separately for the two functions. The common approach is to assume a depth and width of ditch, and height if desired, then to check for snow storage and ability to stop avalanches. The given factors that determine the amount of avalanche snow and the motion of avalanches are:

- The depth of snow that slides
- The incline of the slope
- The length of the slope

A snow depth and avalanches with a 10-year return interval usually are considered for avalanche control on highways, but this standard calls for wide and deep ditches at cut slopes. A shorter return interval may be adequate for minor roads.

Another reasonable criteria is to design the ditch for an avalanche with a 2 to 5 year return interval and to allow a 10-year maximum avalanche to cover the highway shoulder.

3. SNOW DEPTH

3.1 Determine the design snow depth HS on the slope.

The design snow depth on the slope is inferred from the nearest study plot. The study plot observations must be modified by taking into account the exposure to wind of the cut slope under consideration and, when necessary, a difference in elevation. Study plots usually are at sheltered locations, where the snowfall may be greater than on average slopes. In contrast, cut slopes often are exposed to crosswind, therefore receive less snow than the study plot. Conversely, some cut slopes may be on the lee side of forests or wind from behind, therefore receive more snow.

For slopes that are exposed to crosswind, assume a snow depth 80% of the study plot. On lee slopes, take 120% of study plot depth.

For the design of the ditch capacity, assume that 90% to 95 % of the snow on the slope would slide either in several small avalanches, or as a single avalanche near the end of the winter. This means, almost all the snow on the slope is removed in a maximum winter.

4. DESIGN AVALANCHE

4.1 Estimate the depth of a design avalanche.

Consider two types of avalanches.

a) Surface avalanche. The avalanche usually results from a heavy snowfall, and slides on an old snow layer.

For a 10-year maximum avalanche, assume a depth (measured vertically) H = 0.8 m.
An average annual avalanche has a depth H = 0.4.

b) Full depth avalanche. The avalanche contains the full depth of the snow cover and slides on the ground. Full depth avalanches usually are triggered by high temperatures. They are frequent in a cold climate, for example in the Rocky Mountains, where a layer of depth hoar may exist close to the gound.

The depth of a full depth avalanche is equal to the maximum snow depth HS on the slope.

4.2 Choose a density ρ_s for the avalanching snow on the slope.

$\rho_s = 200$ kg m^{-3} for surface avalanches
$\rho_s = 300$ kg m^{-3} for full depth avalanches with HS < 1 m
$\rho_s = 360$ kg m^{-3} for full depth avalanches with HS = 1.5 m
Interpolate ρ_s for depths between 1 m and 1.5 m and extrapolate for HS > 1.5 m.

5. DESIGN FOR CATCHING CAPACITY

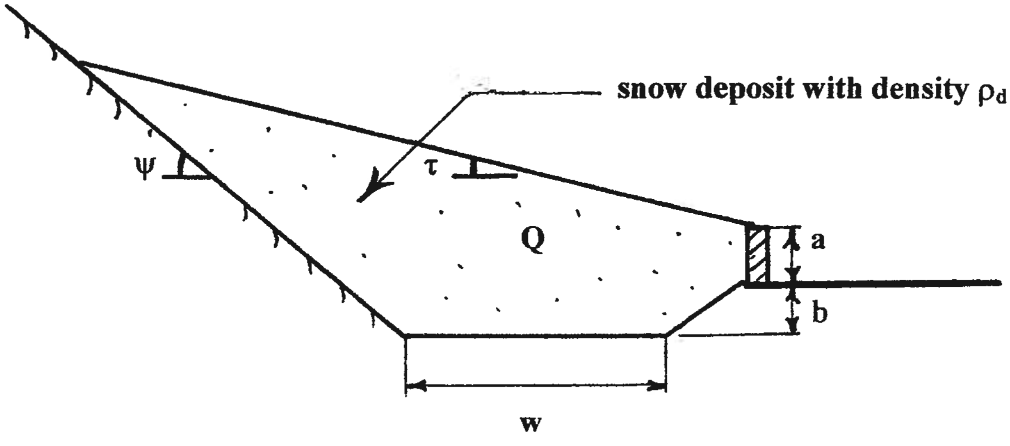

Figure 2

CROSS SECTION OF DEPOSIT IN DITCH

5.1 Choose the angle τ for the surface of the deposited avalanche snow.

The incline τ of the surface depends on the speed and the size of the avalanches.
$\tau = 10°$ for dry snow avalanches with a speed greater than 8 m $s^{-1.}$
$\tau = 15°$ to 20° for a wet snow or a dry snow avalanche of speed less than 8 m s^{-1}.
$\tau = 25°$ at slopes where numerous small and slow avalanches occur in the winter.

*5.2 Determine the cross section area **Q** of the deposit, either graphically by drawing the cross section(Figure 2) or analytically.*

5.3 Choose the density ρ_d of the deposited avalanche snow.

The deposited avalanche snow has a greater density than the avalanching snow on the slope above.
$\rho_d = 350$ kg m^{-3} for dry snow of surface avalanches
$\rho_d = 450$ kg m^{-3} for moist avalanches
$\rho_d = 520$ kg m^{-3} for wet snow

$\rho_d = 520$ kg m^{-3} should be chosen for the end of winter conditions, when a maximum of avalanche snow was deposited.

5.4 Determine the volume of deposited avalanche snow "V" per metre width of the slope.

$$V = H \; X \; \rho_s / \rho_d \qquad \textit{(Equation 1)}$$

$X = s \cos \psi$: horizontal slope length;.

5.5 Estimate the volume V_s of snow in the ditch from snowfall and compacted plowed snow (per metre slope width).

5.6 The catching capacity is adequate, when $Q > V + V_s$. *(Equation 2)*

5.7 Consider whether the cut slope is uniform in width or has depressions where avalanche snow could be concentrated.

If the avalanche snow is concentrated and the deposit in the ditch might have a cone shape, then, $Q > 1.3\, V + V_s$.

6. DESIGN FOR AVALANCHE SPEED

6.1 Calculate the terminal speed v_{max} of an avalanche on the cut slope.

The standard equation for the terminal avalanche speed is:.

$$v_{max} = [\, d\ \xi\ (\sin\psi - \mu\ \cos\psi)\,]^{0.5} \qquad \text{(Equation 3)}$$

$d = H \cos\psi$, or $d = HS \cos\psi$: thickness of the snow that slides, measured perpendicular to the slope.

ξ: turbulent friction coefficient;

$\xi = 700\ \text{m s}^{-2}$ for avalanches with $d > 0.3$ m on open, moderately rough slopes
$\xi = 500\ \text{m s}^{-2}$ for very small avalanches

μ: gliding friction coefficient between the avalanche and a lower snow layer, or between the avalanche and the ground

$\mu = 0.3$ for surface avalanches
$\mu = 0.4$ for wet snow sliding on the ground

Note:

μ depends on the speed and the liquid water content of the snow. The values above are for small and slow avalanches on cut slopes. Values for μ are lower for large avalanches on long slopes; for example, $\mu = 0.15$ for fully developed avalanches with a high speed.

6.2 Calculate the avalanche speed v_a in the acceleration phase

Avalanches require a minimum slope length in order to reach the terminal speed v_{max}. If the length "s" of the cut slope is shorter, an avalanche reaches the speed v_a, only, which is less than v_{max}.

Calculate: $k = \xi\ d / g$, with ξ and d from equation 3 and $g = 10\ \text{m s}^{-2}$ = acceleration due to gravity.

If the slope length "s" is greater than "k", take v_{max} for calculations of the effect of the ditch, because in this case the avalanche speed is close enough to the terminal speed v_{max}.

If the slope length "s" is shorter than "k", determine the avalanche speed at the toe of the slope either with equations 4a and 4b (a calculator with hyperbolic functions is required). or use the coefficients of the table on the following page.

Estimate the time t for the avalanche to reach the bottom of the slope; then,

$$s = k\ \ln\ \text{hyp}\cos(v_{max}\ t / k) \qquad \text{(Equation 4a)}$$
$$v_a = v_{max}\ \text{hyp}\tan(v_{max}\ t / k) \qquad \text{(Equation 4a)}$$

Table of Avalanche Speeds in Acceleration Phase

s: length of slope; $k = \xi\ d / g$; v_a = speed at bottom of slope

s = k	v_a = 0.93 v_{max}
= 0.9 k	= 0.914 v_{max}
= 0.83	= 0.9
= 0.75	= 0.88
= 0.7	= 0.87
= 0.65	= 0.85
= 0.6	= 0.835
= 0.55	= 0.815
= 0. 5	= 0.8
= 0.45	= 0.77
= 0.4	= 0.75

6.3 Calculate the runout distance on level terrain for an avalanche with the applicable speed v_{max} or v_a .

The runout distance Δx on level terrain for the small and slow avalanches is:

$$\Delta x = v_a^2 / 2g\, \mu_b \qquad \text{(Equation 5)}$$

μ_b: friction coefficient that takes into account both turbulent friction and gliding friction in the runout zone

μ_b = 0.38 for dry snow
μ_b = 0.45 for wet snow

6.4 If information about maximum runout distances from a terrain model is available, check the calculated Δx with the runout distance that was determined with the ratio α/β or $\Delta x/x_\beta$. Adjust the speed "v" in equation 5 if the runout distance is different from that of equation 4..

6.5 Determine the runout distance of the avalanche across the ditch and wall.

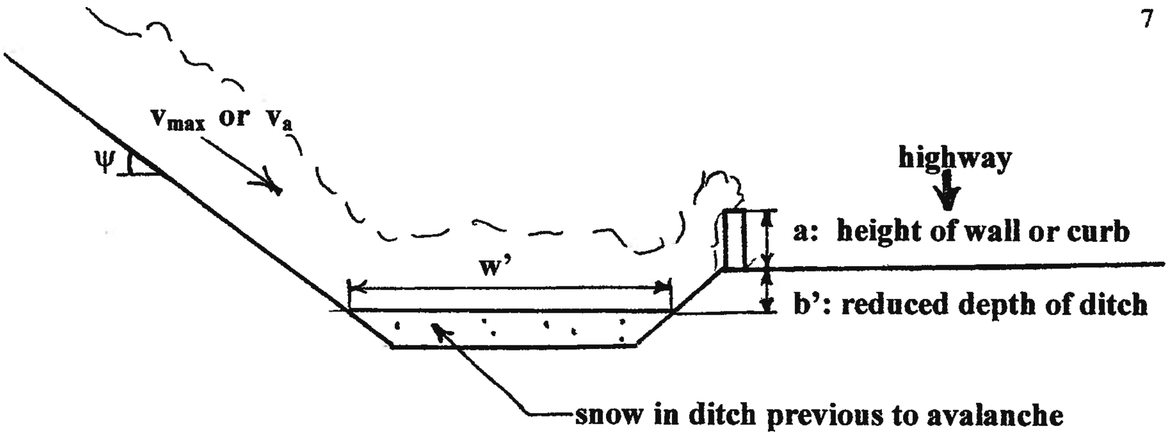

Figure 3

RUNOUT OF AVALANCHE ACROSS DITCH

Apply energy equations for the motion of an avalanche in order to determine the runout distance, as follows

$v_a^2 / 2g$: Energy height of the avalanche at the bottom of the slope (begin runout)

μ_b w': Energy loss when the avalanche moves across the ditch filled with snow

b': Energy loss when the avalanche climbs the side of the ditch above snow

1.5 a: Energy loss when the avalanche climbs the wall and snow is compacted at the wall

The condition for the avalanche to stop at the wall is:

$$v_a^2 / 2g - \mu w' - b' - 1.5 a = 0 \qquad \text{(Equation } \cancel{5}\ 6\text{)}$$

If equation ~~5~~ 6 is positive, the avalanche has climbed and crossed the wall. Determine the runout distance after crossing the wall.

Runout distance = remaining energy height in equation ~~5~~ 6, divided by μ_b.

6.6 Decide whether the remaining runout distance on the highway would be acceptable, and whether the wall should be higher.

As a rule of thumb, each metre height of wall reduces the avalanche runout distance on a level highway by 3 m.

2004-03-13

Models for Runout of Powder

As considered for Pascua-Lama project in Rio Turbio, April 2000.

) Assume that the speed of powder is equal to the speed of flowing snow at the begin of the runout zone (usually at $\psi = 10°$). Then powder has a friction coeff. of 0.2 to 0.25, therefore moves a longer distance.

) Assume that the friction coefficients of Frutiger, used over the full avalanche path apply to powder:
Frutiger determined $\xi = 1360\ m/s^2$, $\mu = 0.16$.
Question is the value for d! Probally the depth of dense snow + saltation layer = d.

c) Apply PCM model over the full path with $M/D = 0{,}25\,S$, $\mu = 0.1$. S is the total length of the path according to McClung.

d) Terrain model with $\alpha = 0.85\,\beta$ for avalanche paths with a smooth profile (no sharp changes of slope. $\alpha = 0.75\,\beta$ for plunging avalanches, according to Schaerer.

e) As a rough personal experience value;
In a wide, flat valley, the runout distance of powder is approximately 1.3 times the runout distance of flowing, dense snow

over ./.

f) A guideline in Japan is $\alpha = 18°$ for powder. This yields very long distances, but would indicate an extreme. (Kobayashi, personal communication 1988)

g) In the extreme avalanche winter 1998-1999 in Switzerland powder destroyed forest and buildings at a distance farther than was predicted. This would indicate that the rundistance or effect of powder often was underestimated.

For the mapping of runout distances at Rio Turbio in March 2004, the boundary of powder was identified where the impact pressure was 1 kPa

With $p = 0.6\,\rho\, v^2 \leq 1\ \text{kPa}$

$\rho = 10\ \text{kg}/\text{m}^3$