Def Sci J, Vol 35, No 2, April 1985, pp 255-266

Avalanche Protection and Control in the Himalayas

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Abstract. The problems of snow avalanches, their prediction and control in the Himalayas have assumed great relevance and importance not only for the Army but also for the progress of the Himalayan States of Jammu & Kashmir, Himachal Pradesh and Uttar Pradesh, whose upper reaches remain snowbound for nearly six months in a year. The paper discusses briefly the gravity of the problem and presents a broad outline of a case-study of avalanche control for Badrinath Temple and Township in Uttar Pradesh undertaken by the Snow & Avalanche Study Establishment (SASE), Manali. This and many other studies undertaken by the SASE illustrate the contribution of Defence Science to the solution of this major problem affecting communications, tourism and hill development, as a spin-off from Defence Research.

1. Introduction

The Pirpanjals and the Great Himalayas, besides other ranges, experience heavy snow during the winter months particularly from January to March. The total snowfall is as much as 1500 cm in some years in the Western Himalayas. Storms lasting for several days bringing down at times more than 200 cm of snow in one spell lasting from 3 to 7 days are not uncommon. The problem is further accentuated when high intensities of 8 to 10 cm/hr prevail. The result is a heavy avalanche activity affecting Army posts and movements, communications, villages and winter tourism.

The avalanche activity is most pronounced during Januray to March. Yearwise avalanche occurrence data for major road axes are presented in Fig 1. Problems on our roads in the mountain ranges due to avalanches are indeed very grave. These arise out of heavy avalanche concentration over long stretches of important road axes and large deposition of avalanche snow on the road over a great width besides the ever present danger to life and property. More than 300 avalanches have so far been mapped by SASE. Fig 2 shows the avalanche paths crossing an important highway in the Himalyas. The concentration and density of avalanches on this road is one of the heaviest in the world. In the worst affected stretch, about 75000 to 1,00,000 cubic metres of avalanche snow is deposited over a short length of 3 Km. Apart from the highways, avalanches are taking a heavy toll of forests. Famous pilgrim centres like Badrinath,

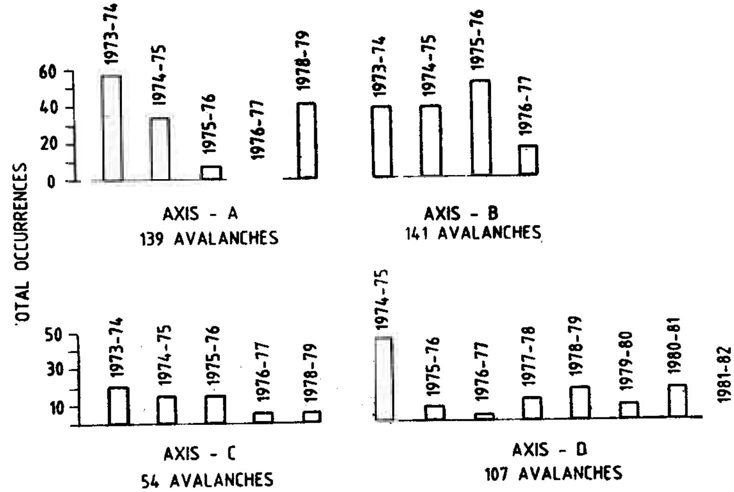

Figure 1. Yearwise avalanche occurrence data for major road axes.

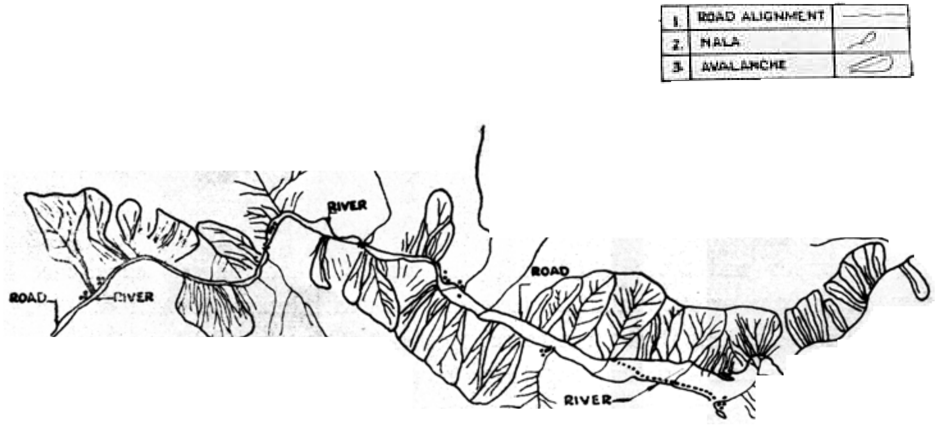

Figure 2. A typical road alignment in the Himalayas showing avalanche paths affecting the road.

Kedarnath, the Valley of Flowers and Trilokinath remain vulnerable to avalanche danger. Avalanche fatalities among the population living in the shadow of these great mountains are quite significant (Fig 3.)

In the Himalayas, the starting zones or formation zones of avalanches are generally above timber line and therefore exposed to heavy snow deposition due to wind action. These are also located at very high altitudes (greater than 4000 metres) and on critical slopes of 30° to 45°.

Studies conducted by the SASE over the last decade indicate that loose snow (both dry and wet) avalanches and soft slab avalanches are most frequent and

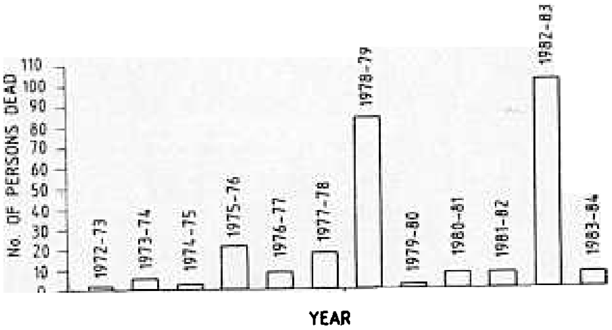

Figure 3. Avalanche fatalities in Jammu & Kashmir.

predominant. Airborne powder avalanches are not uncommon (Fig. 4 & 5). The experiments conducted with pressure cells by the SASE indicate avalanche impact pressures in the range of 20 to 30 tons/sq metre in the track. While a beginning is being made to experimentally determine avalanche velocities, it is empirically estimated that they are in the range of 30 to 40 m/sec.

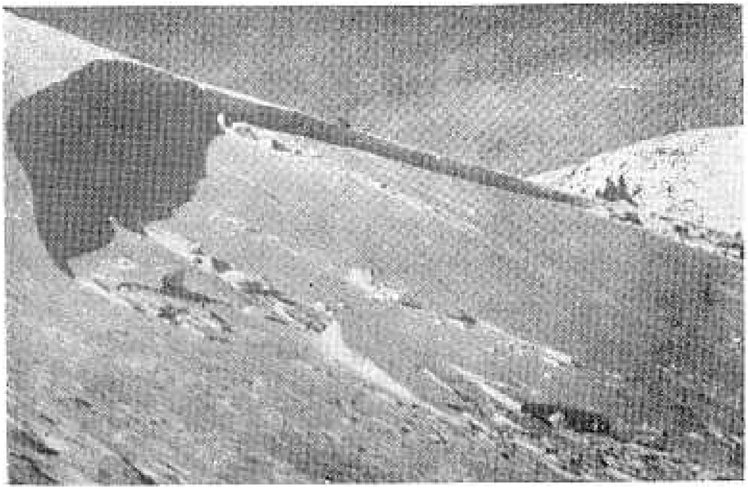

Figure 4. A slab avalanche.

2. Avalanche Protection

The recognised approach to avalanche protection, besides avalanche control, is to provide services by way of avalanche warnings, avalanche rescue etc. The SASE as already made significant contribution to avalanche protection in the States of

Figure 5. Powder avalanche.

Jammu & Kashmir, Himachal Pradesh and Uttar Pradesh by conducting several studies and investigations such as (*i*) Cadestral surveys involving registration and mapping of significant avalanche paths, (*ii*) Preparation of avalanche maps and avalanche atlas, (*iii*) Selection of safe winter routes for selected locations, (*iv*) Issue of avalanche warnings and avalanche forecas tbulletins, (*v*) Instructions on temporary suspension of moves and temporary closure of roads and traffiic, and (*vi*) Investigations and designs for avalanche control including zone planning to identify danger zones from the angle of habitation and investment.

A scientific basis has been evolved for forecasting of avalanches 24 to 48 hours in advance based on studies on the relationship between climate, weather, topography and avalanche formation. As a permanent solution to the problem of avalanches, structural control of avalanches is being advocated. The structures designed by the SASE, depending on the topography, strategic importance of the site and avalanche frequency and type, are the formation zone structures consisting of snow bridges which retain the snow in position and thus prevent avalanche formation and the deflecting and retarding structures in the track and run out zones which go a long way in deflecting the avalanches and retarding the avalanche force and speed. Work is in hand to control all the major avalanches in the trans-Himalayan region.

3. Avalanche Control—Case Study

3 *Terrain Characteristics*

Shri Badrinath Temple complex at a height of over 3000 metres and located on the right bank of the turbulent Alaknanda River is exposed to avalanche hazard from the steep slopes of Narayan Parbat massif at a height of about 6000 metres. The strata of granitic gneiss is observed to dip outwards with the slope of the mountain at 35°. These slopes with SE aspect, being slightly convex, add to avalanche danger. The hill slopes are totally barren. Huge boulders are found in gullies. Short grass and bushes found upto 3800 metres above MSL make the glide problem significant. Three distinct gullies (AA-1, BB-1 and CC-1) have been identified which trigger avalanches from time to time (Fig 6).

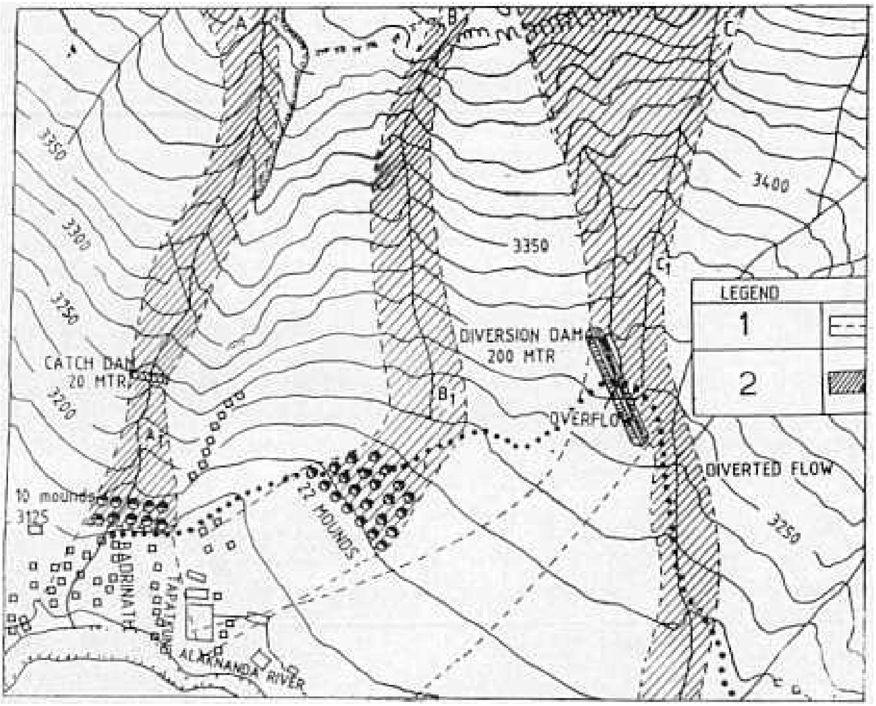

Figure 6. Avalanche gullies and the layout of the control structures construction. (Badrinath avalanche area—control interval 25m). Legend 1—Flow boundaries before control structures constructions Legend 2 Avalanche flow with boundaries after control structures construction.

3.2 *Snowfall and Weather*

Observations from 1978-79 show that this area experiences maximum snowfall of about 400 cm in February and March which is, however, relatively less than in the Western Himalayas. In the years of heavy snowfall, the standing snow is around 250 cm. The weather warms up considerably during the days in the months of February/ March which is generally the time when avalanches occur in this area. The maximum temperatures in March are around 20°C while the minimum temperatures remain sub-zero (around −11°C). The winds are not a major problem. Wind velocities in the valley remain around 10 to 15 Kmph in the north-north-west direction.

3.3 *Avalanche History*

While the general area of Badrinath Puri must have witnessed major avalanches from the time of its inception, no proper record is available even in District Gazetteers. SASE observations are available from 1978. The known avalanches are listed in Table 1.

Table 1. Avalanche occurrences

Sr No.	Date of occurrence	Nature and extent of damage
1.	Winter of 1948	No details available.
2.	16 March 1952	Avalanche triggered from AA_1 gully and bifurcated in two paths. Roof tops carried away. Andhra & Nepal rest houses hit. Three million cft of snow was brought down.
3.	January 1974	Extensive damage to buildings, structures, water tanks to north and south of the temple.
	February 1978	Mana village hit. Pre-fabricated structures completely damaged.
5.	8 March 1979 at 01.30 hours	Heavy avalanche activity. Severe destruction of Bamni Village.
6.	20 March 1983 at 10.30 hours	All three gullies have triggered wet slab avalanches. Avalanche AA_1 deposited 6 metres of snow. No serious damage to temple but buildings on north east of the temple were damaged.

3.4 *Dynamics of Avalanche Flow*

The dynamics of well developed 'flowing' avalanche is approached from the fluid machanics analogy (flow of a turbulent fluid). In the flowing avalanche, snow pouring down the mountain side has many superficial similarities to fluid. It tends to follow the slope like a flow of water, it displays turbulence and it deforms freely under shear, giving the appearance of typical fluid velocity distribution[1]'. The motion of the flowing avalanche is influenced by the frictional forces occuring between the ground or standing snow and the moving avalanche snow.

In the design of structures for control of avalanches, the most important problems are related to the realistic estimation of the destructive effect in terms of impact forces and also to the estimation of the extent in space upto which the destructive effect is felt or the distance over which the initial kinetic energy is completely dissipated. While force is proportional to specific weight and the square of velocity of flow, the runout distance is dependent on the square of velocity and upon the coefficient of kinetic friction. Avalanche velocity, impact pressure and runout distance which can be derived from equations of avalanche flow are affected by avalanche volume, flow depth, snow density, discharge rate, turbulent friction, kinetic friction and the geometry of the flowing avalanche. These paramaters are very much influenced by the nature of snow dislodged, its specific weight, type of avalanche released, ground conditions, roughness of the terrain, hydraulic radius etc.

On the basis of snow and meteorological observations made during the last six years and based on the study of condition of terrain and avalanche release and also theoretical considerations[2], the following assumptions are considered appropriate as inputs : (a) Only wet snow avalanches are most probable from Narayan Parbat slopes, (b) These avalanches can be reasonably assumed to be 'flowing' type, moving close to ground and demonstrating turbulent flow, (c) The flow is channelised in all the three gullies, (d) The wet snow avalanches are assumed to be fully developed avalanches flowing at or near terminal velocities and behaving as fluids. Flow is assumed as turbulent cascade of solid particles and blocks of snow which, because of high water content, do not become dispersed in air to become powder avalanche, (f) Voellmy's equations based on relationships in hydraulics are applicable, (g) Wet flowing avalanches with their higher densities and lower velocities are amenable to control by deflection and retarding structures, (h) The laterally constrained tracks will help in increased velocity and increased runout potential of the avalanche by increasing flow depth, (i) Hydraulic analogies are less accurate during final stages of flow in runout zone as the avalanche snow at this stage may behave like compressible solid, (j) For flowing avalanches the depth of avalanche flow is close to the thickness of the released snow-pack, and (k) The density of flowing avalanche is same as density of snow released from starting zone.

3.5 *Estimation of Velocity of Flow*

Voellmy's equation for calculating velocity of a flowing avalanche on an unconfined slope is

$$V^2 = \xi\, h' (\sin \psi - \mu \cos \psi)$$

where V = Terminal avalanche velocity

ξ = Coefficient of turbulent friction (400 to $1200 \mathrm{m/s^2}$)

h' = Depth of flow

ψ = Angle of slope inclination

μ = Coefficient of kinetic friction at the interface between avalanche and the snow or ground beneath it (0 to 0.3)

This equation is applicable only after terminal velocity is attained, that is, after the driving and resisting forces are equal and acceleration[2] is zero. It is generally assumed that 90 per-cent of terminal velocity is attained in distance of 40h (*Salm*). In this study, this equation is used to determine the velocity of flow in the starting zone after attaining the terminal value.

For confined or channelised avalanches, the velocity in the track is given by Voellmy's equation.

$$V^2 = \xi R (\sin \psi - \mu \cos \psi)$$

Where R is the hydraulic radius; other notations remaining same as in earlier equation. Knowing the starting zone area and thickness of released snow slab and the velocity of flow, the volume of snow released and the time required to discharge the avalanche snow into the confined track are worked out which lead to the estimation of mean discharge rate.

The runout distance is calculated using the formula

$$S = \frac{V^2}{2g \left(\mu \cos \beta - \tan \beta + \frac{V^2}{2\xi h}\right)}$$

where g is gravitational acceleration

β is slope of the runout zone

h is average height of deposition in runout zone

V is velocity of flow at the start of runout zone.

The calculated values for velocity of flow, avalanche discharge and impact pressure are presented in Table 2.

3.6 *Zone Planning*

The zone planning exercise carried out to demarcate danger zones as per standard norms utilising the data in Table 2 revealed the following :

3.6.1 *Gully AA-1.*—The avalanche in Gully AA-1 follows a fully confined track and by the time it reaches the bank of the river the avalanche is still in the 'track' and no well defined runout zone could be demarcated. The shops on the right bank of the Alaknanda are located in the track of this avalanche and are exposed to its flow at a velocity of about 16 to 11m/sec. The maximum impact force to which the shops are likely to be subject to is in the range of 8 tons/m^2 to 4 tons/m^2. At per standard convention, this falls in prohibited zone and no construction should be allowed in this area without suitable avalanche control. However, this avalanche does not trigger frequently.

3.6.2 *Gully BB-1.*—The velocity of the avalanche at the time of entering the runout zone is 9 m/sec. The length of runout zone is 305 metres. The Temple complex falls within the runout zone. The threat to the Temple exists during climax avalanches, the frequency of which is not yet known because of no past data.

Table 2. Terrain data avalanche flow values

Parameter	Unit	Gully AA-1	Gullly BB-1	Gully CC-1
Starting zone				
Altitude	m	3575-3400	3750-3275	3825-3350
Area A	ha	4.06	15.45	24.14
Length L	m	340	845	910
Inclination	degrees	30.3	32.7	35.1
Gradient of channelled track	degrees	26.6	24.2	18.8
Thickness of released snowpack ho	m	1.4	1.3	1.2
Assumptions				
Released slab thickness h'	m	1.4	1.3	1.2
Turbulent friction ξ	m/s^2	500-800	500-800	500-800
Kinetic friction μ		0.15	0.15	0.15
Velocity V	m/s	16.1	16.3	16.6
Δt	sec	21.13	51.8	54.8
Released volume K	m^3	56770	200850	289700
Discharge Q	m^3/s	2686	3879	5270
Density of avalanche snow P	Kg/m^3	300	300	300
Derived quantities for flow in the track				
Flow depth h'	m	7.0	8.0	8.0
Hydraulic Radius R	m	3.64	3.73	5.06
Track cross-section F	m^2	109.9	145	257
Average velocity V_t	m/s	24.13	22.5	21.35
Max impact pressure P	T/m^2	17.5	15.2	13.7
Discharge Qt	m^3/s	2686	3879	5270
Turbulent friction ξ	m/s	500	500	500
Kinetic friction μ		0.15	0.15	0.15
Quantity				
Runout distance S	m	Not applicable	305	270

3.6.3 *Gully CC-1.*—The velocity of this avalanche is 17.7m/sec at the time of entering the runout zone. The length of runout is about 270 metres. Even in this case, the temple falls within the runout zone and is exposed to its threat during climax avalanches.

4. Control Measures

4.1 *Formation Zone Control*

Formation zone control was not considered for the following reasons because (a) The formation zone heights are rather inaccessible for carrying heavy equipment and stores and formation zone control will prove positively costly, (b) The formatione zone is very extensive in Gullies BB-I and CC-1 thus making formatiom zone control uneconomical, (c) The Temple is likely to be threatened only during climax avalanche period which does not appear frequent and hence relatively less costly measures should serve the purpose, and (d) Since wet snow avalanches and that too channelised avalanches are only expected, diversion and retarding structures can be fully exploited to achieve the desired and results.

4.2 *Catch Dams, Diversion Dams and Retarding Structures*

In this study, catch dams, diversion dams and earthen mounds as retarding structures are considered the most ideal choice for controlling the avalanche problem.

4.2.1 *Catch Dams*—Dams built perpendicular to the avalanche direction act as braking barriers designed to reduce the energy of a moving avalanche and halt its advance. These are more effective against avalanches of wet, heavy snow than against those of fast moving dry snow[3]. The structure height is determined knowing the design avalanche velocity V, flow height h[1] and the snow pack depth at the structure ho. The design height H of a vertical structure is determined from the expression[4].

$$H = \text{ho} + h^1 + \frac{V^2}{2g}$$

The forces on the catching dam are determined considering the avalanche impact and uplift forces in terms of vertical shear per unit area (0.5 Pn). Keeping the other limitation that the catching dam control cannot be effective against fast moving avalanches and that they should be preferably located on flater slopes, this is being recommended only for gully AA-1 as shown in Fig. 6.

4.2.2 *Diversion Dams*—Diversion Dams or deflection dams can be profitably located to deflect a flowing avalanche into a desired direction away from the installations to be protected. The angle between the dam and direction of avalanche is kept below 20° and the dam height is kept higher than the depth of the avalanche plus the head of water corresponding to loss of energy when the avalanche hits the dam. The side of the dam facing the avalanche is made as steep as possible in order to produce a good deflecting effect[3]. These structures are found to be most effective on lower track slope (20°). The magnitude of deflection force (i.e. per unit area of impacted surface) is defined in terms of three mutually perpendicular components; normal shear, and uplift. A diversion dam is recommended for Gully CC-1 in continuation of a spur as shown in Fig 6 Slope of the ground at the dam site is about 20°.

4.23 *Retarding Earthen Mounds.*—These structures are laid in the runout zone on relatively flat slopes with the object of reducing avalanche velocities and of shortening avalanche path by increasing ground friction and modifying flow characteristics of avalanches. These mounds are designed to absorb energy from the avalanche and stop it before it reaches the area needing protection by causing lateral spreading and decrease in flow depth. These are laid in rows and alternately spaced. Experience shows that two or more rows of mounds are required for control of avalanches. Austrian and Canadian experience indicates that the mounds should be as close together as possible. The base of one should almost meet the base of the adjoining one. The width of avalanche path should be completely covered by the mounds. Retarding mounds are proposed to control the avalanches at AA-1 and BB-1 gullies (Fig. 6).

4.3 *Afforestation*

It is evident that the hill slopes around Badrinath township have been a scene of heavy erosion and deforestation over several decades. The barren slopes with no soil mantle left are an eloquent testimony to this phenomenon. Afforestation in the whole area on a war footing is a very essential measure that is needed to supplement the other control measures. In the first phase tree plantation with properly designed forest stands in the vicinity of the structures has been recommended.

5. Summary of Recommendations

The summary of recommendations for control of avalanche problems in this area are given in Table 3. These recommendations have been accepted by Uttar Pradesh Government for implementation at a cost of about Rs. 25 lakhs. Already the construction of retarding mounds in Gully BB-1 is complete and the work of diversion dam is in progress as shown in Fig 7.

Figure 7. Earthen mounds under construction for Gully BB-1.

Table 3. Summary of recommendations for avalanche control

Gully	Type of structure	Dimensions			No. of structures	Type of construction
		Top	Base	Height		
AA-1	Catch dam				20 M average	Concrete
BB-1	Mounds				22 Nos	(a) Earthen (b) Pitching on frontside
CC-1	Diversion dam.	2.5 M	21.25 M	7.0 M	200 M length	(a) Earthen (b) Pitching on frontside
	Total Area Afforestation					Type and species and design of forest-stands to be decided by Forest Department

Acknowledgement

Field investigations and the design and layout of control structures for the Badrinath project were carried out by Maj. T. Rajaram (Engr) and Shri D. N. Sethi, Scientist. The snow and meterological data since 1978-79 was collected by the SASE winter teams.

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