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REVIEW PAPER

Structural Measures for Controlling Avalanches in Formation Zone

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ABSTRACT

Jammu-Srinagar national highway (NH-1A), a lifeline of the Kashmir valley, gains considerable importance as being the only link between the Kashmir valley and the rest of the country. A stretch of 15 km is marred by 15 major avalanche sites, out of that D-10 avalanche site takes a heavy toll of life and property, besides bringing the busiest highway to a standstill for days together, year after year. Therefore, this avalanche site was selected for installation of avalanche-control structures in formation zone and demonstration of technology thereof. A combination of wind-control structures, supporting structures, and controlled release of avalanches using explosive, has been adopted to mitigate avalanche hazard. As a result, the D-10 site can boast of having become a school for live demonstration of the avalanche-control methods on the mighty Pir Panjal range at more than 3200 m above the sea level. This paper deals with the methods used for control of avalanches in formation zone of D-10 avalanche site and brings out their effectiveness and site-specific applications.

Keywords: Formation zone control structures, snow fence, snow nets, avalanche-contol avalanche sites, avalanche-control structures

NOMENCLATURE

A_f	Formation zone area
θ	Formation zone slope
d	Fracture depth
L	Length of gulley in formation zone
v	Velocity at the end of formation zone
t	Time required by fracture mass to cross the end of formation zone
K	Volume of snow released from formation zone (m^3)
Q	Discharge released from formation zone
M	Length of cornice-free area along ridge
N	Length of snow-free area in avalanche prone slope
O	Length of densification zone in avalanche-prone slope
S	Storage capacity of drifting snow in cubic meter per meter length of fence.

1. INTRODUCTION

The great Himalayas always pose challenges to the scientific community besides adventure-yearning community. Jammu and Kashmir (J&K), the coldest state of India, having number of mountain ranges,

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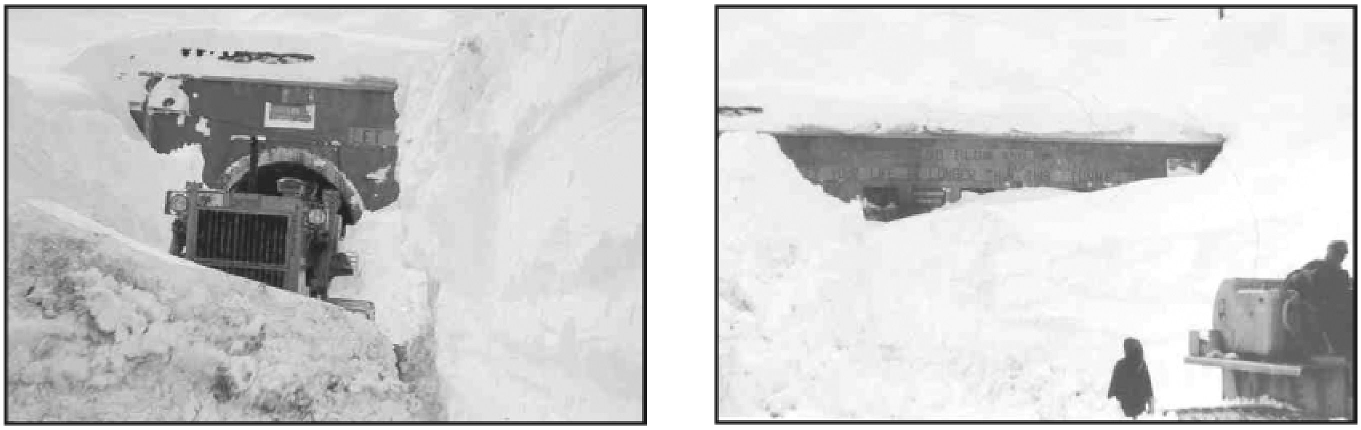

(a) (b)

Figure 1. D-10 avalanche sites: (a) blockade of Jawahar tunnel and (b) BRO personnel clearing the tunnel mouth.

extends an open invitation to the researchers too. Jammu-Srinagar national highway, known as NH-1A, is a vital link to the Kashmir valley. Being the only conduit for the Kashmir valley, the road is extensively used by local population and defence forces. A stretch of 15 km between Naugaum (200 km from Jammu) and Lower Munda (215 km) is marred by 15 major avalanche sites, which disrupt traffic and normal life during winters, besides heavy loss of property and life. The D-10 avalanche site on this axis is one of the most active avalanche site which attains catastrophic dimensions, blocking mouth of the Jawahar tunnel [Fig. 1(a) and (b)] and extracting a heavy toll of lives, property, cultivated land, etc almost every year.

In the first attempt, supporting structures were made of wooden, prestressed concrete, aluminium, and steel. European countries had tested supporting structures of the said materials during 1951-57 (Frutiger[1] and Bruno Haller[2]). Failures during the trial stage and observations made by skiers proved fruitful for establishing the guidelines for alpine snow conditions and helped to standardise their designs. In 1962, a set of guidelines for permanent supporting structures were released which include primarily structural requirements needed to withstand natural forces. a manual was published to cope with complexities of design, layout and arrangement of the new structures. Presently, Swiss Guidelines[3,4], have been adopted as the basis for applications of supporting structures which are widely applied in Alps conditions. Similarly, these guidelines have been adopted and applied for the lower Himalayan belt for supporting structures. However, a few parameters are required to be modified to Indian conditions which are yet in the research phase. In India, a few numbers of snow rakes and snow nets were designed and erected on trial basis at the D-10 avalanche site during 1983-89. The snow rakes of an effective height of 3.75 m were designed as isolated structures[5]. After few winters, having observed damages to some structures of the first rows, the design was modified by increasing height of the structures to 4.2 m and strengthening of rafters[6]. High strength low alloy steel was used to overcome problem of transportation of structures to the erection-site. The advantages gained over mild steel[7] have been highlighted. In the later years about 2000 m of the supporting structures in the form of snow rakes, snow bridges, and snow nets were erected in some frequent avalanche-triggering gullies of the D-10 avalanche[8] site for achieving better safety from avalanche occurrence. The snow nets were designed with articulated ball & socket joint arrangement at the base of swivel post as a solution to the failure of base hinge joint of previous snow nets erected[9] during 1987-89. Behaviour of different formation zone control structures and their geometries have been highlighted[10].

With a view to demonstrate technology for control of avalanches in the formation zone by various means, Snow & Avalanche study Estt (SASE), Chandigarh, has carried out some pioneering work in the design and development of various types of control structures on this site. This paper highlights the methods used for control of avalanches in formation zone of D-10 avalanche sites and brings out their effectiveness and their site-specific applications.

2. SITE DESCRIPTION

The D-10 avalanche site along the Jammu-Srinagar national highway is considered to be the most suitable site for carrying out experiments using various avalanche-control structures for field trials for judging their efficacy. Selection of this site was made due to the advantages, which otherwise would not have been available at one site. This site located on the mighty Pir Panjal range receives 7-9 m annual snowfall (cumulative snow). The snow precipitation is generally concentrated between December and March with the periods before and after experiencing wet snow precipitation or rains. Prevalent warmer temperatures influence the snowcover to change the snowcover very soon into isothermal snowpack at 0ºC. The avalanche activity is quite high with most of the avalanches triggering during snowfall as direct-action avalanches due to excessive overburden, or within 24 h after a heavy snowfall on a clear sunny day. The peak-winter avalanches are generally slab avalanches and late-winter avalanches are melt avalanches (thaw avalanches) containing snow, mud, and stones.

The site offers vast formation zone (area 22 hectare) having multiple sub gullies and unstable geological features (predominantly loose soil on top strata) and high wind velocity causing varied snow accumulation pattern (1.5 m to 3.0 m) due to heavy drifting snow. Avalanche-triggering frequency varies from rare to very high, north and north-east aspect and ridge-width varies from 2 m to 45 m where different control structures/measures could be applied. The other important criterion being the location of strategically important Jawahar tunnel located down below. This avalanche site has immediate utility for the users.

3. STRUCTURAL TECHNOLOGIES FOR CONTROL OF AVALANCHE IN FORMATION ZONE OF LOWER HIMALAYAS

A number of avalanche-control structures have been designed and installed in various gullies of D-10 avalanche site dedicated to specific structures. A series of trials and design improvements were carried out to finally arrive at the optimal design of these structures, which are based on scientific studies, field trials, and observations over a span of 15 years. Categorisation of the structures used for field trials is given in Table 1.

Aforesaid structures have been developed and tested for their efficacy in one of the typical avalanche site known as D-10 avalanche site.

3.1 Supporting Structures

An avalanche can be controlled by supporting structures/retaining barriers which are installed in the formation zone area to prevent avalanche initiation. The basic concept lies in converting shear stresses and tensile stresses in the snowpack into compressive

Table 1. Categorisation of the structural technologies for control of avalanche in formation zone

Type of structures	Categorisation of structures	Nomenclature of structures
Supporting structures	Flexible-retaining barrier	Snow nets
	Rigid-retaining barrier	Snow rakes; snow bridges
Wind-control structures	Snow collector	Snow fence
	Cornice-control structures/snow deflector	Jet roof; baffle wall
Controlled release of avalanches	Mechanically-operated system	*Avdhav Visphotak Vahan*
	Hand placing of explosives Delivery by weapons	Avalancher, 81 mm mortar

stresses, which can be conveniently sustained by the snowcover. Type of the retaining plane is significant in categorisation of the supporting structure as rigid or flexible structures. snow rakes and snow bridges can be categorised as rigid structure, whereas wire rope nets (snow nets) as flexible structure.

3.1.1 Snow Rake

Its members are supported vertically on cross members and lower portions are embedded in the foundations. Its supporting plane retains snow on uphill side of the structures. Rakes are used where saplings are planted. The gaps between the vertical members allow young trees to grow (Fig. 2).

Figure 2. Snow rakes.

3.1.2 Snow Bridge

Its supporting plane made of rigid steel sections undergoes only slight elastic deformation due to static forces. In plan, it looks like a bridge. It retains snow mass on uphill side of the structures and acts as a dam against creep and glide motions. Snow bridges can be used, both above and below the tree line. They are comparatively more effective than the snow rakes (Fig. 3).

3.1.3 Snow Net

The Snow nets serve as retaining barriers by adjusting their supporting plane with the increasing amount of snow. The snow nets as flexible retaining barriers have additional advantages due to their flexibility, adaptability to terrain configuration and also adjustment with the amount of the snowcover on the slope, from time to time (Fig. 3).

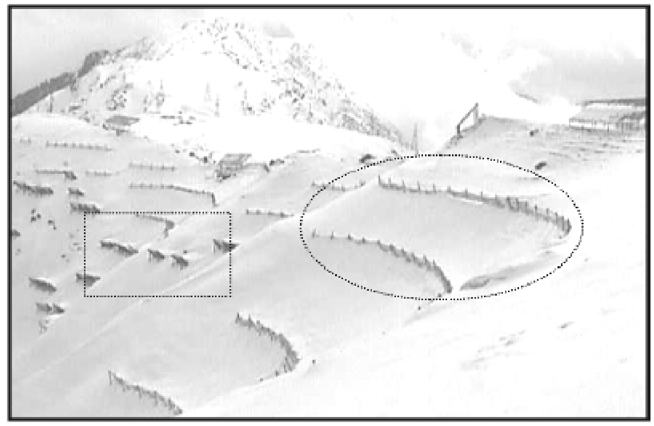

Figure 3. Arrangements of snow nets represented by circular dotted line & snow bridges by rectangular dotted line.

3.2 Wind Drift-control Structures

Wind drift-control structures are used in and adjacent to avalanche starting zones to control drifting snow that would contribute to avalanche formation. These are generally used in combination with supporting structures for control of avalanches as well as cornices. Such type of structures play significant role only in wind-dominant areas. Snow fences and wind baffles are basically designed to withstand wind forces.

3.2.1 Jet Roof

It influences the snowcover qualitatively, viz., jet/nozzle effect resulting in densification of the snowcover. Jet roof is a cornice-control structure and works on the principle of continuity equation. It is erected on the ridge crest to accelerate and deflect strong wind under the jet roof, thereby ensuring the deposition away from the ridge line (Fig.4).

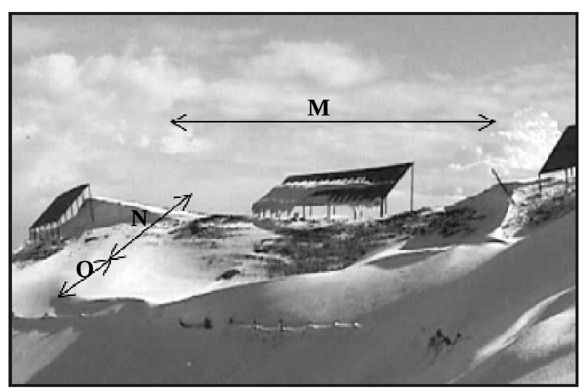

Figure 4. Effectiveness of jet roof.

3.2.2 Snow Fence

Snow fence is erected on a flat ridge-facing windward side to trap drifting snow on the ridge. Front panel of the fence is designed in such a way that 40 per cent to 60 per cent porosity is achieved, which creates turbulence, resulting in retarding and unstable flow-line of wind-favouring formation of eddies near the structures. Drifting snow in well defined pattern gets deposited on front and rear sides of the snow fence (Fig.5).

Figure 5. Snow deposition profile on back side of snow fence.

3.2.3 Wind Baffle

Trapezoidal shaped barrier having no gap in its panel is called wind baffle. These are used to interrupt the wind flow and thus cause wind scouring and wind toughening of the snowcover. It is placed on the edge of the ridgeline to prevent formation of a continuous cornice (Fig.6).

Figure 6. Formation of moat / snow scoop by wind baffle.

3.3 Controlled Release of Avalanches

The aim of controlled release of avalanches is to release small volumes of snow mass from the formation zone to prevent avalanches of catastrophic dimensions. Unstable snow mass is released by imparting shock waves over the snow surface with the help of detonating small charges. The delivery of the explosives could be placed by hand at the desired spot or by projectile, or by mechanical means.

3.3.1 Avdhav Visphotak Vahan

Avdhav Visphotak Vahan is a mechanical system developed to transport explosive to the desired location in the formation zone. It consists of a cable and pulleys supported on two towers/columns. This cable rope carries explosive to the area of interest for maximising the effects. The explosive charge is detonated above the targeted snow mass for controlled release of avalanche (Fig.7).

Figure 7. *Avdhav Visphotak Vahan* for carrying the explosive.

4. RESULTS AND DISCUSSION

To demonstrate the technology for control of avalanches in formation zone as well as to test the efficacy of the various types of structures, the following control measures were taken up on D-10 avalanche site (Table 2). The effectiveness of each type of structure and the observations made are discussed below:

4.1 Supporting Structures

Earlier, number of snow rakes per hectare was 95-100 m in gulley No. 4 which were placed

Table 2. Structural control measures at D-10 avalanche site

Type of structure	Area under control	Extent/ quantity
Supporting structures	10 Hectare	2400 m (running)
Wind drift-control structures	Whole ridge line	400 m (running)
Avdhav Visphotak Vahan	4 Gullies	325 m (span)

as staggered arrangement[5]. This was probably insufficient to retain the snow mass. To achieve adequate safety, required supporting structures in the form of snow nets and snow bridges are 350 m to 450 m per hectare. These are erected in continuous arrangement (Fig.3). This arrangement provides the highest degree of safety to road users and important installations down below, and requires lesser maintenance. Optimum effectiveness with minimum cost is often achieved with a combination of the continuous and staggered arrangements, which are followed in gulley Nos. 1-3.

The D-10 avalanche site comprises 12 gullies of which, gulley Nos 1-4 contribute major share of avalanche debris. The volume of the snow debris (snow mass) before these gullies were taken up for control, as arrived at using swiss guidelines[4]. It is seen from the table that a snow mass of 66,100 m^3 volume would get released when gulley Nos. 1-3 triggered simultaneously and about 62,700 m^3 of snow mass when gulley Nos. 3-4 triggered simultaneously (Table 3). Such a huge volume of avalanche debris would require days together to clear the snow from the mouth of the Jawahar tunnel for keeping it operational, besides causing other damages to man and material in the lower reaches [Figs 1(a) and (b)]. However, placement of the structures in these gullies, sluff of small magnitudes only could get released on a few occasions. Thus, the placement of structures in four rows with proper layout and arrangement (Fig. 3) has helped in preventing fracture as well as retaining 100000 m^3 volume of snow in formation zone which has not only prevented avalanche activity, but also resulted in availability of water at lower reaches.

4.2 WIND DRIFT-CONTROL STRUCTURES

Cornice, an overhang structure of weak snow, gets formed because of boundary separation theory and successive deposition of drifting snow on sharp terrain bends (ie, knife-edge of ridge). Jet roof ensures a cornice-free area of about 20-25 m ridge length (M in Fig. 4) as well as snow-free area from 0 to 20 m (N in Fig. 4) and densification of snowcover from 20 m to 30 m from ridge towards avalanche-prone slope (O in Fig. 4). Before erection of jet roof, formation of huge cornice up to the 3-4 m with overhang of 2-3 m was observed on the ridge-line, breakage of which triggered a large number of avalanches. However, after erection of jet roof, triggering of avalanches due to breakage of cornice was arrested.

Snow fences are used to trap the drifting snow on flatter ridge, thereby preventing drifting snow accumulation on avalanche-prone slope(s), ie, slope above 30° in formation zone. Therefore the area of ridge on leeward side is required to be large enough to accommodate the redistribution of snow. A 4 m high snow fence creates huge storage (S) up to

Table 3. Volume of snow mass released from gulley Nos 1-4 before erection of the control structures

Gulley No.	A_f (m^2)	θ (deg)	*d* (m)	*L* (m)	*v* (m/s)	*t* (s)	*K* (m^3)	*Q* (m^3/s)
G-1	1.2	33	1.2	300	22.30	13.45	14400	1070
G-2	2.1	34	1.1	345	21.76	15.85	23100	1457
G-3	2.6	34	1.1	400	21.76	18.38	28600	1555
G-4	3.1	34	1.1	400	21.76	18.38	34100	1855

Table 4 . Site-specific application and effectiveness of the structures

Control structures	*Recommended terrain*	*Placement of structures*	*Effectiveness*	*Remarks*
Snow fence	Flat ridge of 40-50 m on mountain top with gentle slope (10°) towards leeward side	Towards windward side down the ridgeline, at a distance of 15 times height of snow fence	Prevents drifting snow and cornice formation	• Suitable for the areas having high velocity wind • Suitable for improving the visibility
Jet roof	Knife-edge of ridgeline and roof preferably parallel to lee slope	Exactly on top of ridgeline having knife-edge	Prevents cornice formation	Suitable for areas having high velocity wind
Wind baffle	Small flat ridge or gentle slope below ridgeline in formation zone	Edge of mountain towards leeward side	Prevents continuous cornice formation	Suitable for areas having high velocity wind
Snow nets	Upper reaches of formation zone having slope 35° to 40°	• Irregular terrain • Area affected by rockfall / shooting stone • Irregular snowfall pattern	Prevents avalanche initiation	• Approachable site for erection work • Heavy traffic/ important installation in a avalanche path • Standing snow not more than 4 m
Snow bridges/ snow rakes	Lower reaches of formation zone having slope 30° to 35°	• Regular terrain • Area above / below the tree-line	Prevents avalanche initiation	• Approachable site for erection work • Heavy traffic/ important installations in an avalanche path • Standing snow up to 4 m
Avdhav Visphotak Vahan	Frequent avalanche occurring gullies	Span covering maximum deposition zone / probable fracture zone in a gulley	Prevents catastrophic avalanche by releasing premature snow mass in the form of small sluffs	• Approachable site during winter months • Operating team staying at the top

220 m^3 of drifting snow on its rear side[12]. It was observed that in the case of D-10 site, a voluminous snow mass of such a great magnitude got deposited on safer place (ie, flatter ridge) which otherwise would have got accumulated in the formation zone as an unstable cornice on the ridge, causing damage to the supporting structures. These snow fences also become a source for accumulating snow for use as water in spring season.

Wind baffle produces an angular or horse shoe-shaped consolidation of snowcover around the structure which is called moat or snow scoop of 6 m to 8 m diameter with a ground clearance of 0.3 m. In this zone, velocity increases and snow particles are thrown away evenly[13,14]. This scoop produces discontinuity in the snowcover and breakup of the stress field which reduces the probability for occurrence of a slabsnow avalanche. Wind baffles with the bottom gap prevent the cornice formation on a lee slope (Fig. 5).

4.3 Controlled Release of Avalanches

In most of the cases, small charges of 1 kg are used for explosion at 1.0-1.5 m above the snowcover in air. It gives best results by releasing dry slab avalanche when the fire is coupled with good avalanche warning system and snowpack stability evaluation. Effective range for shooting varies from 17-70 m depending on the slope stability and propagation of primary fracture in potential starting zone. Sometimes, it extends up to 120 m for 01 kg charge[15]. If snowpack is slightly stable, most of the energy of explosion is consumed in the formation of crater and compaction of snow, which also indicates stability of the slope. One number of charge for 1 kg to 2 kg weight is preferred for air explosion, 1-2 No of charges for 3 kg weight for air explosion below cornice, and 2-3 No of charges for 4 kg weight are used for surface blast on the top of a cornice. Use of explosive charge below a certain depth of burial (Bore hole method) does not produce desired results as the energy of the explosion is expended or absorbed by the snowcover, hence no release of snowcover is observed.

Controlled release of avalanches prevents avalanche occurrence of large dimensions. The released unstable snow mass gets accumulated in the middle zone of the avalanche path and subsequently retards the flow of avalanches triggered thereafter. The best results are obtained from this technique when applied in the morning hours after building-up of 70-80 cm snowcover is observed. Application of controlled release not only ensures safety to the traffic on the highway but also mitigates the chances of any casualties besides reducing long closure periods of the highway. This method is very simple, cheap, effective, and relatively easy to apply in snowbound areas.

Summary of the technology developed for control of avalanches in formation zone is tabulated in Table 4.

5. CONCLUSIONS

The structures described were installed at the D-10 avalanche site to demonstrate the technology of control of avalanches in formation zone as well as to assess efficacy of various types of structures which have withstood the test of time. The work was done on various principles summarised in Table 4 to facilitate users to adopt similar type of methods in other avalanche affected areas. The structures installed have not only proved helpful in mitigating avalanche hazard at north portal of the Jawahar tunnel, gateway of Kashmir, but also reduced substantially the efforts and time of BRO to clear-off the avalanche debris.

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