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THE MAIN PRINCIPLES OF SLUSHFLOW HAZARD MITIGATION

Erik Hestnes and Frode Sandersen

ABSTRACT

Slushflow hazard detection and control are based on both active and passive mitigative measures performed above and within the starting zones as well as along the path and in the runout zone. The main aims of preventive measures are to regulate the use of hazardous areas, detect acute slushflow hazard, reduce the possibility of slushflow release and to restrict the size and runout as well as the consequences of destructive events. Automatic warning systems are either based on recording of the rise of water table in snowpack or on registration of slushflows in motion. Methods for prevention of slushflow release are principally based on the control of water influx, drainage pattern and snowpack stability in potential starting zones. Similar control measures may also be used to restrict the size of slushflows along tracks. The main principles for reducing the runout and consequences are control of drainage direction, retardation or stopping of the snow-masses and restrictions on land-use. The principle methods and their use are summarised.

INTRODUCTION

Slushflows - flowing mixtures of water and snow - are a major natural hazard in Norway. They interfere with dwellings, structures, communication lines, power- and pipelines etc., and they are of critical concern in land-use planning (Fig. 1). According to historical documentation, slushflows and snow avalanches are almost equally responsible for damages and economic losses in Norway. Districts exposed to high cyclonic activity during autumn and winter are most liable to slushflow hazard. Slushflows released during intense thaw in spring are frequent in the inland and mountainous areas. They primarily affect inhabited areas in North Norway.

Norwegian Geotechnical Institute, P.O.Box 3930 Ullevaal Hageby, N-0806 Oslo, Norway.
Phone: +47 22 02 30 00; Fax: + 47 22 23 04 48; E-mail: eh@ngi.no and fs@ngi.no

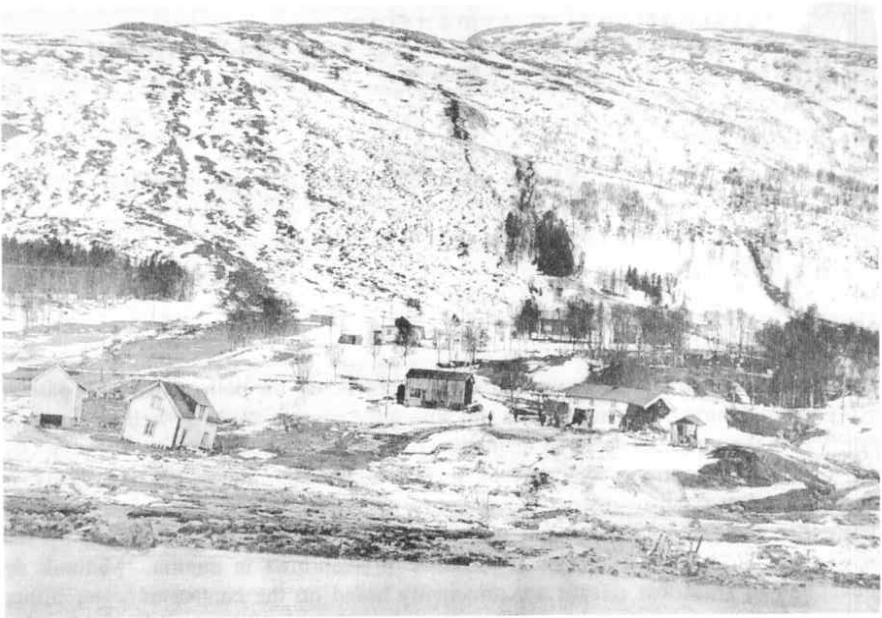

Fig. 1 Destructive slushflows of low density new snow were released when a snowstorm turned into heavy rainfall. 12-15 slushflows were released within a distance of 2.5 km along the mountainside. The newspaper reported 2 fatalities and 6 badly injured, 4 houses and 3 cowsheds destroyed. Handnesøya, North Norway 16.01.1967. (Photo B. Madsen, Rana Blad)

An abundant supply of free water in the snowpack is a principle requirement for slushflow release. Whether a snowpack will reach critical instability during rain and snowmelt depends on the complex interaction between geomorphic factors, snowpack properties and relative rate of formation and discharge of free water. The size, downslope propagation and runout of slushflows are controlled by the corresponding conditions along the slushflow paths (Hestnes et al. 1994).

The results of a world-wide questionnaire on slushflows, literature studies and scientific contacts, indicate that slushflows occur in all countries having a seasonal snow cover (Onesti and Hestnes 1989). Experiences and scientific documentation concerning slushflow occurrence, hazard analysis and hazard prediction are summarised by Hestnes (1998). The present paper reviews methods used in slushflow hazard mitigation, knowledge gathered by the Norwegian Geotechnical Institute during more than 25 years of slushflow consulting and research.

SLUSHFLOW HAZARD CONTROL

Slushflow hazard is basically handled within the following frames:

- Area planning and development
- Acute hazard prediction and warning
- Hazard control by mitigative measures

A wide variety of solutions and mitigative methods are used, and often in combination. Most of the applied principles are adjusted from methods known from snow avalanche, debris flow and stream control, but location, design and dimensions will normally deviate (Sæterbø et al. 1998, Norem 1994, VanDine et al. 1984, Voight et al. 1990). Other methods are exclusively serving slushflow control due to the fact that water is the driving force (Reger 1975, Sandersen and Hestnes 1995). This paper will focus on the principles and methods applied in slushflow hazard control.

Hazard detection and control are based on both active and passive mitigative measures performed above and within the starting zones, as well as along the path and in the runout zone. The main aims of preventive measures are to regulate the use of hazardous areas, detect acute slushflow hazard, reduce the possibility of slushflow release and to restrict the size and runout, and the consequences of destructive events.

Both permanent and temporary mitigative measures are used. Temporary measures are primarily applied pending permanent safety solutions, or when the activity in the hazardous area is limited by time. Alert systems as well as detrimental material like snow and ice barriers and continuous material, are used. The decision to build temporary protection measures has to take into account the necessity of removal after the need has ceased.

MITIGATION BY REGULATION

Despite the importance of regulation as a mitigative method, the following precautions are not dealt with in this context:

- Exclusion of hazardous areas during planning stage
- Qualified use of hazard areas according to regulations
- Temporary evacuation of potential hazard areas during critical weather conditions
- Removing activity/constructions/dwellings from potential hazard areas

The reason is that these precautions are primarily based on hazard evaluation and prediction, lately summarised by Hestnes (1998). However, the basic elements of acute hazard control programmes are cited. Prior to the decision of using such indirect control measures the possibilities of establishing satisfactory in situ safety measures will normally be assessed.

HAZARD PREDICTION AND WARNING

Slushflow prediction

Acute hazard prediction and warning are performed for securing people and communication lines. Predictions are based on meteorological data, observation of field predictors, knowledge of snowpack properties, as well as runoff characteristics when available (Hestnes 1998, Hestnes and Bakkehøi 1995).

Currently updated meteorological records and forecasts, as well as on-line access to quantified prognoses and weather charts, are available from the Norwegian Meteorological Institute.

Typical field predictors are:

- water accumulation in snowpack (ponding water)
- high water table and drainage atop snow in channels
- slumping snow on sloping bedrock in brooks
- minor slushflows in drainage channels
- slushflows observed in neighbouring paths
- abundant water supply (precipitation, snowmelt)
- persistent or increasing rainfall, temperature and wind

The texture and structure of the snowpack before the critical weather situation are decisive to slushflow release (Hestnes et al. 1994, Hestnes and Bakkehøi 1996). In situ snowpit observations as well as in situ stress testing during the critical period should be performed if possible. Models of snowpack development are supplementary tools for the forecasters (Brun et al. 1992).

Automatic weather stations and the monitoring of water level in snowpack by pressure transmitters as well as snowpit observations, are recommended for supervision of weather parameters, runoff characteristics and snowpack conditions in starting zones critical to dwellings and important road segments (Table 1) (Hestnes and Bakkehøi 1995).

Internationally there is an increasing effort in developing analytical tools for slushflow prediction and warning as well as dynamic models (Bozhinskiy and Nazarov 1998, Bakkehøi and Hestnes 1995, Chernouss et al. 1998, Hestnes et al. 1994). Adjusted methods and experiences from comparable scientific fields are also applied (Buser et al. 1987, Bakkehøi 1987). However, the scientific community has a long way to go before the secrets of slushflows are fully understood and slushflows tolerably controlled.

Table 1 Slushflow monitoring, transmission and warning systems

Field systems	Instruments	Objectives
Data monitoring	· Weather station · Precipitation gauge · Water gauge · Pressure transmitters	· Supervision of potential hazard · Basic data in prediction and warning · Input data to prediction models · Register critical water level in snow
Slushflow monitoring	· Electric circuits · Magnetic devices · Load cells · Radar · Pressure transmitters	· Activate public warning systems · Alert road / railroad supervision central · Alert police headquarters
Transmission utilities	· Cables · Telemetry	· Power supply & signal transmission · Transmission of data
Public warning	· Lights, bells & sirens · Gates · Road signs · Information boards	· Alert traffic, workers & dwellers · Stop & keep traffic in safe locations · Speed & parking regulations · Guide travellers & workers

Warning systems

The automatic warning systems of acute slushflow hazard are based on three main principles (Table 1):

- Supervision of hazard potential
- Registration of slushflows in motion
- Registration of slushflows hitting objects or communication lines

The supervision system should consist of an automatic weather station monitoring temperature, humidity, radiation, wind speed and direction, as well as precipitation. The water level and fluctuation in the snowpack should be monitored at critical locations and preferably also the water discharge. Data scanning and transmission to a supervision centre, should be done every 10th minute to document the intensity and variation during critical weather periods. The supervisor should consecutively evaluate the data and take action when necessary during critical weather periods (Hestnes and Bakkehøi 1995). Registration of critical water level in snowpack in the starting zone may also be calibrated for triggering public warning systems.

Public warning systems activated by registration of slushflow release or motion, are used where there is sufficient distance between the location of the monitoring system and the communication line or evacuation object. The actual location of the monitoring system and the public warning unites, are evaluated based on estimated or registered slushflow speed, width of path and expected stopping distance of cars during critical weather periods. Specific calculations have to be done when dealing with railway lines.

Activation of public warning by monitoring slushflows hitting objects or communication lines, is often an important alternative where the travel time of critical slushflows is too short for the above mentioned solution. This is applied where recurrent slushflows may occur in the same path or there are multiple slushflow paths within the same area. In such cases it is important to avoid or prevent access to critical zones after the first slushflow has occurred (Hestnes and Sandersen 1987).

The monitoring systems applied in the two cases might be identical. They are triggered by short-circuit, disconnection of electronic or magnetic devices, radar etc.,

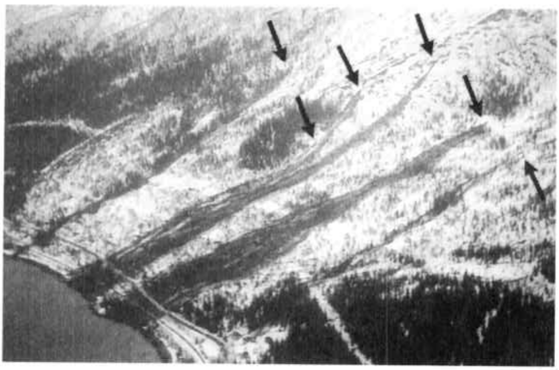

Fig. 2
The six slushflows released on this sparsely forested hillside in Rana, North Norway, 27-28.01.1981, closed the road and the railway between North and South Norway for 2 and 4 days respectively. Cars waiting for the road to be opened after the first blockage were hit by the second slushflow and thrown of the road, causing 3 fatalities and 5 badly injured. The fourth and largest slushflow demolished two houses and two huts and caused two more fatalities. The whole area has been abandoned and 20 houses removed. (Photo H. Norem, NGI)

caused by slushflows applying load to installations in the starting zone or path. Geophones are normally not recommended because of problems with false registrations. The signals are transmitted by cable to the warning unites and by telemetry to the supervision central and possibly the police headquarters.

The main components of the public warning systems are alarms with lights and sound signals, gates for closing the road, traffic regulation by road signs and information boards for guiding travellers and workers. Safe access to the electronic control system and gates are important.

Clearing of blocked roads and railways can only be carried out if the access and working location are safe or satisfactorily supervised (Fig. 2). The annulment of road closures will normally require controlled winding up of the queues by separation of heavy and light traffic and driving at intervals.

PREVENTION OF SLUSHFLOW RELEASE

Slushflow release is closely tied to high influx of water to potential starting zones, causing rise of water level in snowpack (Hestnes 1985, Onesti 1985, Hestnes and Bakkehøi 1996). Thus, the basic ways to control slushflow release are to reduce the water supply to critical areas, reduce the possibilities of water accumulation in the snowpack and to improve the stability of the snowcover. Consequently, the frequency, size and runout of slushflows, are reduced.

It may not always be possible or economically favourable, to accomplish mitigative measures above or within potential starting zones. However, the main methods applied are summarised below (Table 2).

Control of water influx

When possible, permanent diversions of drainage into alternative runoff routes are preferable. Partly cutting off the critical water influx might be an option. Gathering and controlling drainage through or beyond potential starting zones may sometimes be another possibility. The ditches and channels can be of different size and design depending on the local terrain, drainage conditions and expected water supply, during critical weather periods.

Table 2 Mitigative measures above and within starting zone and their objectives

Measures	Objectives
Water supply control: · Ditches & channels · Trenching of snowpack	*Reduce water influx to critical zone:* · Divert drainage · Drain water out of snowpack
Snowpack stability improvement: · Ditches & channels · Trenching of snowpack · Snow fences · Afforestation · Nets, dams etc. · Outlet systems, pipes	*Reduce frequency and size of flow:* · Restrict water acc. in snowpack · Drain water out of snowpack · Avoid snowdrifts blocking runoff · Reduce potential starting zones · Control of potential starting zones · Control of runoff
Eliminate hazard problem: · Remove snow in starting zones · Development of starting zones (buildings, roads etc.)	*Permanent safety solutions:* · Prevent slushflow release · Favourable solution to problem
· Artificial release of slushflows	*Temporary solution to roads & lines*

Drainage control can also be executed by trenching the snowcover. This is an effective method to restrict water accumulation in the snowpack and to route water towards safe courses.

Improvement of snowpack stability

The morphology and ground conditions of starting zones are summarised by Reger (1975), Hestnes (1985) and Hestnes and Sandersen (1987). The drainage of potential starting zones may be improved by establishing permanent ditches and channels to restrict the rise of water level in snowpack in critical areas (Fig. 3). To limit the water accumulation and divert or control the runoff, it may also be wise to remodel the terrain reducing the size of starting zones or eliminating ponding of water.

The size of potential starting zones and slushflows can be reduced by afforestation. Trees can prevent a saturated snowpack to start flowing. A mixture of evergreen and deciduous trees is favourable if diseases should occur. The use of fertiliser and species must be adjusted to the local growing conditions (climate, soil and altitude).

Saturated snowfields on bogs, lakes and low grade terrain may be potential starting zones of slushflows. Building low barriers and adjusted outlet systems can often master them. Strong nets, dams and concrete walls may be used. If a release could occur at

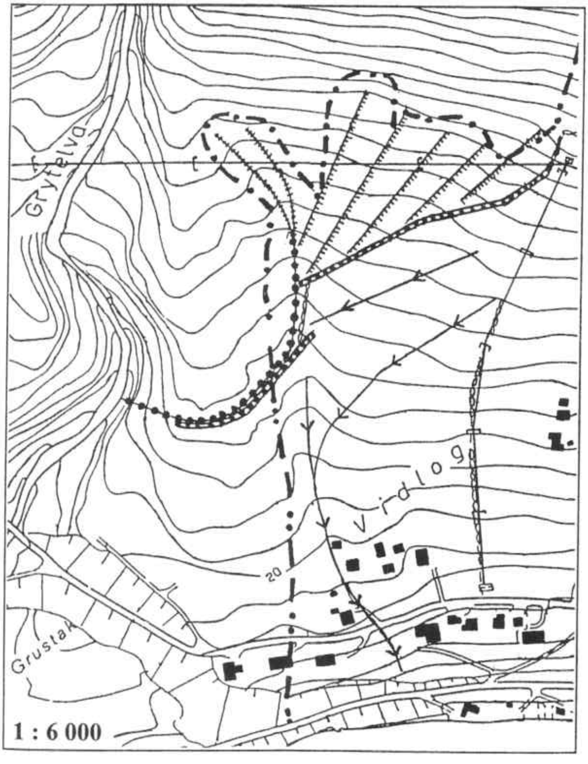

Fig. 3

Plan for elimination of slushflow hazard at Vidlog, Syvde, Vanylven, West Norway.
Improvement of snowpack stability in starting zone by ⟂⟂⟂⟂ *ditches and* ▬▬ *control works and controlling runoff by* ●●●● *plastered channel diverted into safe course.*
In addition:
⟶ *trenching of snowpack in low-grade starting zone and along drainage course, prior to acute hazard situations.*

different elevations within such starting zones, there might be a need for retaining structures at different locations. The height of the preventive measures should correspond to the expected water level in the snowpack. Such measures should not be applied if the impact of avalanches can force the saturated snow across the actual barriers.

Snow embanked water may occur due to snowdrifts and avalanches. Such ponding is critical because erosive drainage across a week barrier may rapidly empty the basin above and cause critical slushflows downstream. Snow fences may prevent the creation of snowdrifts in unfavourable locations and retaining structures with controlled outlets or runoff through pipes, may be alternatives in other cases. However, in most cases the problem is not easily solved on a permanent basis. Blasting or trenching of such barriers prior to critical weather periods is sometimes advisable, but access to the potential starting zones may be a limiting factor.

Acute hazard prevention can normally be executed by trenching the snowpack in low grade starting zones as well as in drainage courses. It is important to control the runoff into safe courses or beyond the exposed buildings or structures (Fig. 3). This method is well known from historical documentation.

Elimination of hazard problem

Removing snow from the starting zone and track may also be chosen as a permanent solution to the problem of slushflows (Fig. 4). A far more favourable solution is achieved when potential starting zones are developed into residential or industrial areas.

Slushflows can be triggered by the impact of detonations as well as avalanches and rockfalls. However, artificial release of slushflows has not been systematically applied in acute hazard control because the timing is difficult, although there are reports on successful operations. Experiments with tumbling and plunging stones into saturated snowpacks in channels have also triggered slushflows.

Fig. 4

Permanent slushflow hazard mitigation. Removal of snow from the potential starting zone and track in Vannledningselva, Longyearbyen, Svalbard, is done every spring to protect the development area on the fan. The rockfill in the right half of the picture is part of a huge direction control work. (Photo E. Hestnes, NGI)

MITIGATION IN TRACKS AND RUNOUT ZONES

Slushflow hazard is primarily tied to the size, velocity and runout of the masses. Thus, the basic ways to reduce the consequences of slush-flows are to reduce these factors or divert or control the flow. Such measures can principally be performed at any elevation in a slushflow path (Sandersen and Hestnes 1995). Reinforcement of constructions and special protections for communication-, power- and pipelines are also provided. Different types of safety measures will often supplement each other. The main methods applied are summarised in Table 3.

Due to modest international research on slushflows, basic data on velocities, superelevation along paths and impact forces, are limited. Thus, dimensioning is based on experiences, hydrodynamic theories and empirical formulas, e.g. Mannings formula, the forced vortex equation, the momentum equation etc. (Sæterbø et al. 1998, VanDine et al. 1984). The roughness coefficient of Mannings formula is normally chosen based on experiences from back-calculating actual events. Qualified estimations are made in each case, regarding the ratio of the mixture between snow and water, slushflow size etc. Large slushflows may reach velocities of 60 $msec^{-1}$. However, the impact of small slush-flows may also cause considerable damage due to the high density of the flow (Fig. 5).

Table 3 Mitigative measures along tracks and within runout zones and their objectives

Measures	Objectives
Size and runout control:	*Reduce the consequences of flows:*
· Afforestation	· Restrict influx of saturated snow
· Drainage of adjacent terrain	· Restrict influx - reduce size
· Improved & artificial channels	· Restrict influx - direct flow
· Remove snow from channels	· Prevent water accumu. and flow
· Control works, dams, walls etc.	· Control, divert and deflect flow
· Catching dams, walls, nets etc.	· Stop the flow
· Brakes of concrete, steel etc.	· Stop the snow, release water
· Snow barriers	· Temporary control measure
Reinforcement of construction:	*Prevention of buildings and objects:*
· Favourable design	· Reduce loads on constructions
· Dimensioning	· Resist destructive forces
· Adaptation terrain - structure	· Utilise hazardous areas
Mitigation of communication:	*Prevention of communication lines:*
· Tunnels & sheds	· Avoid hazardous areas
· Buried culverts for roads	· Acceptable safety to traffic
· Buried power and pipelines	· Reduce operational problems
· Elevated bridges	· Avoid destructive forces
· Enlarged culverts	· Adjust openings to mass-flux

Control of slushflow size

The principle way to restrict slushflow size is to prevent incorporation of mass along the track. Most methods described for improvement of snowpack stability in starting zone can be used along the track as well. Drainage and remodelling of adjacent terrain will prevent saturation of snowpack, afforestation and artificial levees can restrict the width of potential tracks, and trenching of snowpack will prevent saturation and snow masses from being swept along.

Improvement of the natural drainage channels, including removing bushes, turfs, stones and pools causing water accumulation along the drainage, are often advisable. Especially where there are problems of ice formation and freezing over adjacent terrain, because this is critical to enlargement along tracks.

Control, diversion and deflection of flow by artificial channels and direction control works, may also restrict such problems and thus the size of the slushflows. The most effective way to prevent critical slushflows is, however, to remove the snow from potential tracks prior to the critical weather periods (Fig. 4).

Fig. 5 Small slushflows may cause considerable damage. Heggland, Matre, West Norway 03.03.1979. (Photo Svein A. Eriksen, Aftenposten)

Control of velocity and runout

Control measures of slushflow velocity and runout may roughly be classified in four types: Channels, direction control works, catching dams and breaking constructions.

Channels are primarily used to guide and control the masses in a natural direction of flow. A normal venture is to improve the longitudinal and cross profiles of natural drainage channels, i.e. increase their capacity and ability of flow control. Artificial channels excavated in earth and rock or made by concrete, gabions etc., as well as erosion protection, is used when appropriate. Large control works of earth- and rockfill are used where the superelevation along flowpaths or the size of the flow, might be critical to built-up areas. Maintaining the velocity of masses past critical zones may often be the purpose of such measures.

Control works for diversion and deflection of slushflows are used in tracks as well as in runout zones. The methods are principally the same as for avalanches (Norem 1994). However, the design, dimensioning and erosion control, are based on the predicted dynamical behaviour of the potential slushflows and the runoff conditions (Sandersen and Hestnes 1995, Tómasson and Hestnes 1999) (Fig. 6). Temporary control works by snow and ice may sometimes be adequate.

Catching dams, concrete walls etc. are applied to restrict the runout of slushflows. The method is primarily used where the potential size and velocity of flows are fairly well known and where the consequences of overtopping will not be fatal to dwellings or constructions. Such barriers need specific by-pass arrangements for the runoff of water.

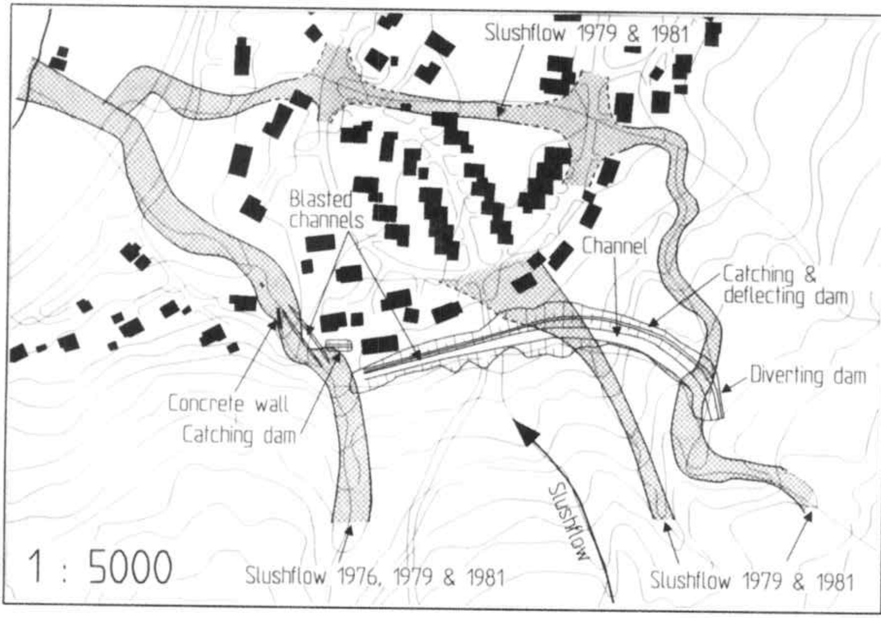

Fig. 6 Small streams with frequent slushflows, Kvernkroken Rana, North Norway. After critical slushflow occurrences in 1976 and 1979 it was decided to protect the housing area by diverting three of the slushflow tracks into Skreddalsbekken, the fourth slushflow path with a less problematic drainage course.

Many breaking constructions used in debris flow control would be suitable for retarding slushflows as well (cfr. Wahlmüller 1976) (Fig. 7).

Breaks of concrete and steel may be recommended where the track or runout is fairly well defined and the downward drainage can cope with a certain amount of mass. A row of smaller constructions are sometimes preferable instead of one large. The potential size of the slushflows and the critical mass-flux below the breaks, are basic factors to be taken into account in the design and dimensioning of such constructions. Basic ideas for the design are often sought from debris flow control (VanDine et al. 1984).

Small slushflows of low velocity may be retarded, reduced and stopped by one or a few wire-nets. A light net of small mesh will normally be put on the inside of the main net to reduce the amount of snow passing through.

Reinforcement of constructions

Buildings and structures can be designed and dimensioned to withstand forces from slushflows. Adjustment of constructions with earthfill, remodelled terrain etc. is sometimes preferable. Technical solutions and dimensioning are done in accordance with the introductory summarised principles. The complex dynamic behaviour and density of slushflows makes it a challenging task.

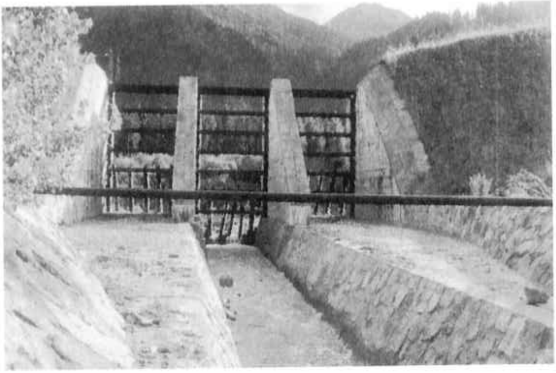

Fig. 7

A breaking dam for protection against debris flows in Austria, suitable for retarding slushflows as well. (Photo E. Hestnes, NGI,)

Mitigation of communication lines etc.

Supplementary mitigative measures like tunnels, sheds and buried culverts are used for elimination of the hazard problems to roads and railways. Bridges and culverts are often designed and dimensioned to resist impact loads and potential mass-fluxes. The safety to traffic and operational problems are often weighted against construction costs in cost-benefit analysis (cf. Norem 1994).

The worst slushflow situation in this century in Western Norway, occurred in 1928. Most bridges along the Bergen-Voss railway were badly damaged, 5 large ones where totally wiped out, and the embankment was washed away many places. It took 13 days to repair the damages and reopen the line. New tunnels, relocation of line segments and larger bridges and culverts have eliminated the majority of the problems, but there is still a potential hazard to the line in some places (Fig. 8) (Hestnes and Larsen 1989).

Power and pipelines crossing slushflow paths are also subjected to critical damage. The Alyeska Pipeline Service Company has partly solved their problem by burying the pipeline into the ground. Due to the erosive effect of large slushflows in fan deposits depths between 1-2 metres have been recommended (Reger 1975). Power lines may also be dug into the ground, or mast foundations relocated or protected.

Fig. 8

A small shed specifically built for protection against slushflows. Bergen-Voss railway, West Norway. (Photo E. Hestnes, NGI)

CONCLUDING REMARKS

Many methods applied in slushflow hazard mitigation are basically known from the control of other natural hazards, however, some methods are exclusively serving slushflow control. Prediction and mitigation of slushflow hazard are challenging due to the complex dynamic behaviour of water-saturated snow and the modest scientific research within the field.

Most countries having a seasonal snow cover experience the problem of slushflow hazard and there is an increasing encroachment of human activity into potential slushflow zones (Onesti and Hestnes 1989). Consequently, there is a rising demand for slushflow hazard prediction and control. It should be a challenging task for the scientific community of avalanches and debris flows to contribute to the knowledge of slushflows.

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