Snow avalanche experience through 25 years at NGI

KARSTEIN LIED,
Norwegian Geotechnical Institute, P.O. Box 3930, Ullevaal Hageby, N-0801, Oslo Norway

INTRODUCTION

This year it is 25 years since the Norwegian Parliament decided that NGI should be the institution responsible for snow avalanche research and consulting work in Norway. Because of several major snow avalanche accidents in the late sixties and early seventies when many persons were killed and constructions damaged, an official comity appointed by the Department of Industry, came to the conclusion that NGI was the best fitted institution to handle snow avalanche problems in our country.

As NGI is situated in Oslo where few snow avalanches occur, it was necessary to build a research station in mountainous terrain where the scientist could study avalanche behavior throughout the winter, and where personal and practical experience could be gained directly in the field. Such field experience is especially important in snow avalanche work where theoretical models must be combined with the practical experience of the scientist. A nice location for the research station was found in the community of Stryn, 950 m a.sl., nearby a new main road which is kept open for winter traffic.

Although some snow avalanche work earlier had been performed by different persons and institutions in Norway, a main goal in 1973 was to educate a new generation of avalanche scientists and consultants which should be able to give professional advices to persons, institutions and organizations throughout the country.

The main task for the newly established research group was to find an answer to the following questions:

- Where do avalanches occur?
- What weather and snow conditions favor avalanche release?
- Which kind of safety measures may be applied to protect human life and property?

Although these problems had been studied for many years abroad, we had to find out what kind of conditions that were special for Norway, and which results from other countries that could be applied in our country.

AVALANCHE TOPOGRAPHY AND RUNOUT MODELS

In what terrain formations are avalanches released, and what runout distance do they obtain with a certain frequency? These are the most important questions in the field of snow avalanches in Norway, and the most difficult to answer. From the beginning of our avalanche research work, this topic was therefore our main research activity. For young scientists without too much experience with snow avalanches, the question of avalanche topography, -magnitude and -frequency was a natural starting point.

To solve this question, a detailed mapping and registration of major avalanche paths were started, both in the valleys nearby the research station, and first of all in the populated parts of the avalanche districts of Western Norway. All major paths were mapped in their maximum known extent. By this work we collected information of about 1000 avalanche paths. Based on this "avalanche library" it was possible by statistical methods to predict in what terrain avalanches were likely to occur, and to a certain degree of accuracy, to predict how far they would run in the valley bottom.

The problem of avalanche runout is the most difficult to solve, and many models have been applied for this purpose. Voellmys hydrodynamic model (1995) is well known, but to apply the model one have to collect empirical knowledge about the friction parameters, and also about the rupture height of the slab. Slight changes of the parameter values will cause great differences in runout distance, which makes the model difficult to use in practical work.

In lack of such numbers for the mentioned constants, we tried out a topographic method where the parameters which describe the snow conditions were left out. The reason for this was that all the avalanches treated in our model, had been known for about 100-300 years, a runout which represented a "near-maximum" runout. By assuming that the snow condition were optimal and equal for a maximum runout in every avalanche path, we could concentrate the work to identify the topographic factors that were most important for the runout. By regression analysis, four topographic factors were identified, see fig.

(1) and (2). (Lied and Bakkehøi 1980, Bakkehøi, Domaas and Lied 1983).

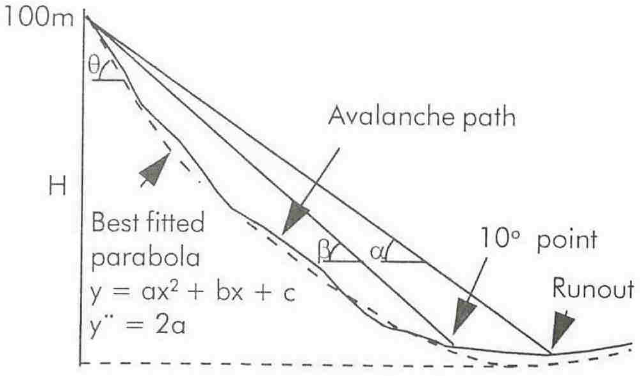


Fig 1 Topographic parameters to predict runout distance

$$\alpha = 0{,}96\,\beta - 1{,}4^\circ \quad R = 0.92,\ S.D\ 0\ 2.3^\circ \qquad (1)$$

$$\alpha = 0{,}92\,\beta - 7{,}9 \cdot 10^{-4}\,H + 2{,}4 \cdot 10^{-2}\,Hy''\,\theta + 0{,}04 \qquad (2)$$

The main topographic factor in this respect is the angle β, which is the straight line combining the point in the path where the terrain inclination is 10 degrees, with the point of rupture. The 10-degree point was chosen because this point represents more or less the point on the slope where big, dry avalanches starts to retard. The relation between α, which represents the longest avalanche in each path, and β, is expressed in equation (1). The correlation between the two parameters is surprisingly high, for such a simple model.

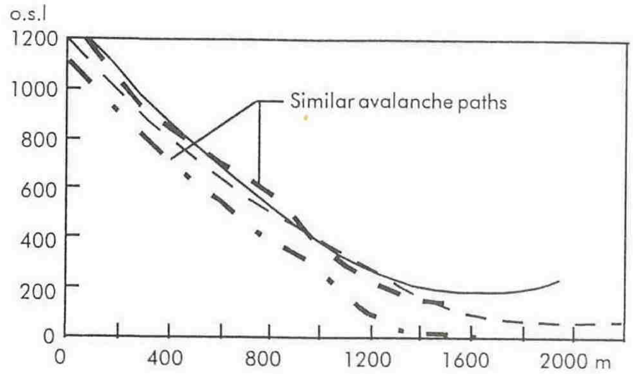
The four parameters model, (2) use; the total vertical fall, H, the inclination of the starting zone, θ, and the second derivative of the slope function;
$y = ax^2 + bx + c$. The second derivative $y'' = 2a$, describes the curvature of the slope. The introduction of four parameters improved the prediction of the runout to a minor degree, and the two-parameter model is therefore the one which is mostly used.

By this topographical/statistical method it is possible to predict the possible runout of a given avalanche by a probabilistic method with fairly high accuracy. But we still have to improve the accuracy of the runout prediction, and to combine the topographic model with dynamical/numerical models to obtain the best possible answer.

An extension of the topographical model was developed by Bakkehøi and Norem (1994). In this model the four most similar avalanche path profiles are compared to the avalanche profile in examination.

The most equal profiles are found by the "nearest neighbor" method. The advantage by this model is the possibility to compare avalanche paths with equal curvature and "outlook", see fig 2.

The dynamical model developed by Perla, Cheng and McClung (1980), has been extensively used by NGI. This is a two-parameter, finite mass model, where the avalanche is described as a one-dimensional block moving on a path of varying curvature. The model is based on two n parameters; the dry friction parameter, and a ratio mass - to - drag.



Calculations

	Calculated	
α - observed	α - topographic model	α - NIS model
——— 33.0	33.16	35.03
— — 32.0	32.20	35.31
— · — 35.0	35.08	36.02
- - - - 34.5	34.12	33.18
	35.08	35.94
α - average 33.7 St. dev. 1.2	33.92 1.25	34.69

Fig 2 Comparison of the most equal avalanche paths

By dividing the avalanche path into short segments with constant inclination, the equation is solved numerically. Like Voellmys model, this model also is encumbered with two friction parameters of unknown numerical quantity, and combinations of different parameter values may match any observed avalanche runout.

To find the best fitted pairs of parameter values, the PCM-model was tested statistically with the 200 avalanches in the topographic model. By this combination of a topographical and numerical runout model it was possible to increase the accuracy of the runout prediction, and to calculate the avalanche velocity along the path.

In 1986 NGI presented a dynamic avalanche model (Norem, Irgens and Schieldrop), where the avalanche mass is modeled as a non-linear visco-elastic continuum. The model is based on the parameters:

- Avalanche rupture height
- Avalanche length
- Friction parameter
- Viscosity parameter

The continuum equations for the stationary part of the avalanche movement is given by eq. (3) and (4), and the maximum velocity by (5).

$$\sigma_y = p_u + p_c + \rho\, v_z \left(\frac{dv}{dy}\right)^2 \quad (3)$$

$$\tau_{xy} = c + \mu p_e + \rho m \left(\frac{dv}{dy}\right)^2 \quad (4)$$

$$v_h = v_0 + \frac{2}{3}\left[\frac{gh^3 (\sin\psi - \mu\cos\psi)}{m - \mu v_z}\right]^{\circ/\infty} \quad (5)$$

Parameters in the NIS-model:

σ_y	=	normal stress
τ_{xy}	=	shear stress
p_u	=	porepressure
pe	=	effective pressure
ρ	=	density of granular material
υ	=	normal viscosity
v	=	velocity
c	=	cohesion
μ	=	coefficient of friction
m	=	shear viscosity
v_0	=	avalanche velocity at ground level

The model takes into account normal and shear stress in the moving snow, pore pressure and effective pressure, snow viscosity and snow friction. Compared to the PCM-model, the NIS-model uses both the flowing height and the length of the avalanche, in combination with physical properties of the avalanche snow, which is a much better representation of the avalanche. As this model contains a number of variables where the quantitative numbers are unknown, it must be tested on real avalanches. Such tests have been performed both towards the topographical model, and in the full-scale Ryggfonn avalanche project, performed at NGIs avalanche research station.

FULL-SCALE EXPERIMENT ON AVALANCHES

In 1980 a 16 m - 17 m high and 100 m long retaining dam was built in one of the major avalanche paths, Ryggfonn, nearby the avalanche research station, with the purpose to study the effect of protection measures.

The Ryggfonn avalanche has a vertical drop of about 900 m and a horizontal length of 2100 m. Usually the avalanche runs 2-3 times every winter, and may contain as much as 500.000 m^3 of snow.

In addition to the dam other constructions were built in the avalanche path:

- On the top of the dam a 6,6m steel mast with strain gauges, and one 1,0 m high mast with a load cell.
- 200 m upslope from the dam three transmission line conductors across the track, 8, 12 and 16 m above the ground with tension recorders at the end if the lines.
- 230 m upslope from the dam, a 4,5 m high concrete structure with three load cells, each 0.72 m^2 in area.
- 320 m upslope from the dam, a 26 m high tubular steel Y-tower with strain gauges, accelerometers, and mechanical pressure indicators. In 1990 a major avalanche destroyed the mast and it was therefore replaced by a 10 m high cylindrical steel mast.

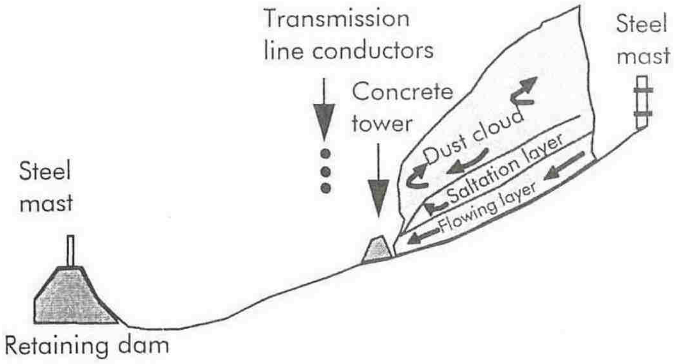


Fig. 3 Principle sketch of Ryggfonn installations

- In 1993 this mast also was damaged by an avalanche, and had to be rebuilt.
- Geophones 50 m and 100 m upslope from the dam, sensing the vibrations from passing avalanches.

Fig. 4 Concrete tower with pressure transducers in Ryggfonn

The avalanche is either triggered by explosives via radio signals or it releases naturally. The installed instruments record continuously the avalanche passage, and the signals are digitized and stored in PCM format at a tape recorder. The instrumentation is designed and performed by NGI's Instrumentation division.

The Ryggfonn full scale project has been a success, and a lot of valuable information is gained about the avalanche behavior. Maximum velocity is recorded to 60 m/s for dry, flowing avalanches, wet snow avalanches seldom exceeds 30 m/s. Maximum recorded impact pressure is 540 kPa for a wet snow avalanche and 445 kPa from a dry snow avalanche.

Maximum recorded tension in the transmission line conductors is 108 kN. The load on the transmission lines is quickly reduced with the height above the ground. 16 m above the ground, the load is 10% of the load at 8 m height, (Norem 1980).

Fig. 5 The Ryggfonn avalanche as it passes over the retaining dam

The effect of the retaining dam seems to be negligible for major avalanches of several 100 000 m^3 , with velocities of about 35-40 m/s at the location of the dam. For medium sized avalanches (~50 000 m^3) with velocities not exceeding 20 m/s the dam seems to stop the snow mass, although the snow cloud may surpass the dam by about 200 m.

Further tests and investigations are needed, to develop general dimension criteria for such retaining dams. Preliminary results (Lied and Kristensen 1998), from the study of the retaining effect of the dam for dry, medium sized avalanches indicates $\lambda = 1,2$, in the runup equation:

$$H = v^2/2g\lambda \qquad (6)$$

In 1997 NGI started a project on deflecting dams. Deflecting dams are an important method in avalanche protection, but the dimension criteria for such dams are scarce. The problem of dimensioning deflecting dams was looked into both from a theoretical viewpoint, and from a practical, empirical point of view. In Irgens et. al. (1998), the PCM - model was used to describe the avalanche path along the deflecting wall, a study mainly performed by mechanical engineer B. Schieldrop. In the same work prof. F. Irgens at the Norwegian Technical University in Trondheim developed a quasi-three dimensional method for the movement of the avalance body in a curved path. Extensive field measurements of the effect of natural deflecting dams have been done through the last two years by Domaas and Harbitz (1998), with promising results.

FULL SCALE EXPERIMENT ON SNOW CREEP PRESSURE

Snow creep forces at constructions on inclined slopes represent an important problem, both for supporting constructions made to prevent the release of avalanches, and for other constructions, as for instance power line masts built in mountainous terrain.

For about 20 years NGI has worked with these problems in a full scale experiment at the avalanche research station. Snow creep pressures are measured at two different types of supporting constructions, a cylindrical 6 m high steel tube, and a power-line mast. The snow- forces are monitored continuously by vibrating wires attached to the constructions, and data is stored in a local datalogger.

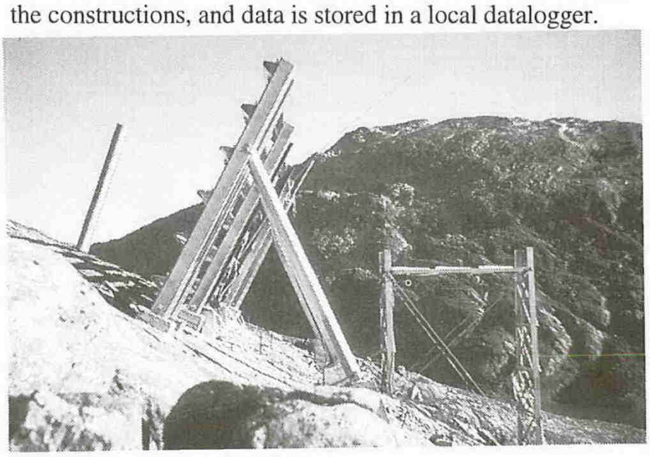


Fig. 6 Measurements of snow creep forces on steel structures

A theoretical model for the snow pressure against supporting constructions is developed, (Larsen et al.1988).

$$\sigma = P \cdot \rho \cdot g \cdot h \qquad (7)$$

$$P = \left[\left(\frac{2}{1-\nu}\right)\left(\frac{L}{H}+\frac{D}{H}\right)\right]^{\frac{1}{2}} \sin\psi + \frac{1}{2}\left(1-\frac{\nu}{1-\nu}\right)\cos\psi \qquad ....(8)$$

The results show that snow pressure in the Norwegian snow cover seems to be somewhat higher than in the Alps. This is mostly due to the denser snow in Norway which for dry, wind packed snow may exceed 500 kg/m^3.

An empirical method for the calculation of snow pressure against circular constructions is compiled also,

$$P = K \cdot f_{\psi} \cdot f_B\ Z^e\ (kN/m) \qquad (9)$$

where
Z = snow height
f_B = factor of structure width
f_ψ = factor of terrain inclination
K, e = empirical constants
The measurements confirm practical experience: slender constructions are exposed to comparatively higher loads than broader constructions, because of the effects of the shear strength of the creeping snow, see fig 7. As an example, for a 0,3 m broad construction, the snow load will increase by a factor of 2, if the width of the construction is increased by a factor of 3.

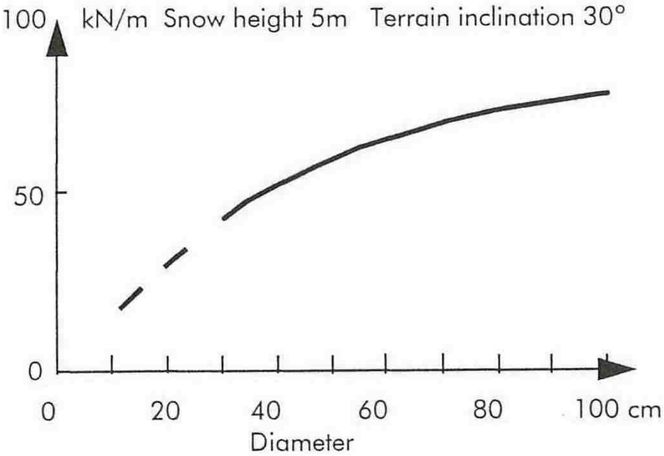


Fig .7 Snow creep forces related to the diameter of construction

AVALANCHE FORECASTING

The typical snow-pack structure related to an avalanche situation in Norway is the following: 1) Older snow with high density and strength above the ground. 2) A thin weak-layer with little strength covering the old snow. 3) New snow, moderately to strongly wind packed, 0,5-3 m thick at the top. Practically all catastrophic avalanches in Norway are direct actions as triggered during, or immediately after a snow storm.

The access to the rupture areas where measurements may be carried out during an avalanche situation is hazardous and for practical purposes not possible. All measurements and evaluations must be performed in safe areas with different snow and terrain conditions than in the actual rupture area. The evaluation of the day to day avalanche hazard is therefore based mainly on weather and snow observations and -statistics, in combination with practical experience and subjective judgment.

The main weather factors that control the avalanche danger is:

- Snow precipitation and intensity
- Wind speed and wind direction
- Air temperature

At NGI we have concentrated the work mainly to the connection between precipitation rates and avalanche occurrence. By plotting the precipitation in 3 and 5 days as a cumulative normal distribution, the possibility for an avalanche may be quantified, see fig. 8.

The method is tested for 5 different paths nearby the avalanche research station, with 25-37 avalanche events in each path. The straight line between the avalanche observations shows the strong connection between the amount of precipitation and the possibility for an avalanche, (Bakkehøi 1987).

Of other methods used for avalanche forecasting also, the Swiss "Nearest- neighbor" method (Buser 1983), is regarded to be very useful. Much effort has been done to put this method into practical avalanche forecasting in Norway, and the system is now used for avalanche forecasting by the road authorities.

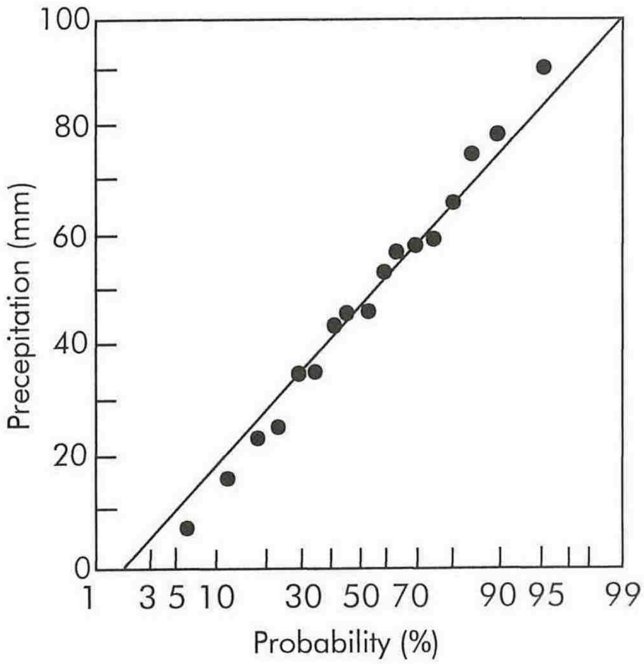


Fig 8 Cumulative 3-day precipitation related to avalanche probability

SLUSHFLOWS

Slushflows occur in most districts of Norway, and slushflows have caused extensive damage to lives and property.

Systematic research on slush flows was started at NGI in 1983, as a result of a catastrophic slushflow winter in 1979. The main efforts have been concentrated on what snow, weather and topographic conditions that favor slushflows, and what kind of mitigative measures that can be applied to reduce the slushflow hazard.

Slushflows are flowing mixtures of water and snow, and where the snow is oversaturated with water. The flow varies from laminar to fully turbulent, depending of the steepness and roughness of the path (Hestnes 1997). On the top of the dense layer one may find a saltation layer, and large slusflows may even also have an airborne part.

The most hazard prone areas are West- and North Norway, districts which are exposed to high syclonic activity during autumn and winter. Slushflows are released also by intense thaw in spring in the inland mountainous areas, and also in the Spitsbergen islands. The most frequent slushflow situations occur during October - December, but slushflows may occur during the whole winter season.

Starting zones on slopes exposed to wind during frontal passages will normally be most susceptible to release. Such areas receive the highest input of sensible and latent heat from the atmosphere, and therefore the highest amount of meltwater, often in combination with the highest precipitation rates. During spring thaw, catchment areas facing solar radiation represent the most favorable starting zones, (Hestnes et. al. 1994).

The topographic formations where slush flows may occur seems to be widespread, and within wide limits concerning terrain type and inclination. Slushes often start in shallow depressions and smaller drainage basins, and generally on more gentle inclined slopes than snow avalanches. The average runout angles is lower than for snow avalanches also. Slusflows occur within cultivated land, open forest, and in treeless mountainous terrain.

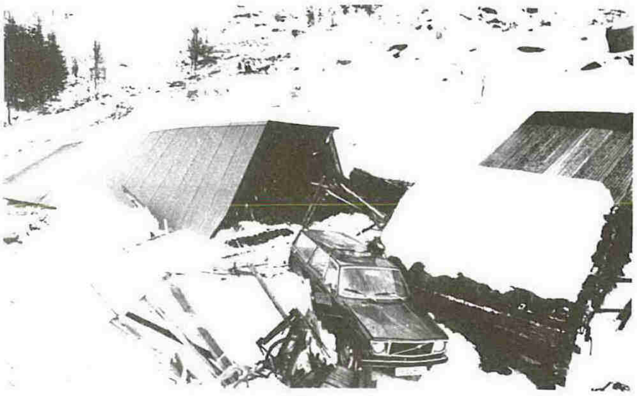


Fig. 9 Slusflow damage

The slushflows are most often released on bare rock faces, frozen ground, and icy surfaces, but release on unfrozen ground occurs as well. The rupture is usually found along brooks in locations where the gradient suddenly gets steeper. The outlet of ponds and bogs where abundant accumulation of water reduces the strength of the snow cover is another typical release locality (Hestnes and Sandersen 1987).

Snow conditions that favor slushflows are a loose, coarse grained snow pack, with depth hoar at its base, built up during extensive cold periods. When such snow is exposed to heavy rain, or melting by warm wind or radiation, big slusflows are likely to occur.

A fine grained snowpack is generally more stable than a coarse grained. Several icelayers in a compact snow pack also prohibit the formation of slushflows.

Slushflows often have long runout distances, mainly due to a high water content and a big snow volume. The inclination of the runout zones are normally less than 5°. Measured average inclination of the path from the starting point to the end of the debris varies between 3° - 20°, with an average of 12,5 °

AVALANCHE ZONING

In 1980 snow avalanche hazard zoning were started by NGI on the instructions of The National Fund for Natural Disaster Assistance. In this project, potential snow avalanche- and rock fall areas are identified based on simple topographic criteria and runout models developed by NGI.

To perform such a mapping project, a great research effort was done by NGI to make use of digital maps in combination with snow avalanche runout models. Digital maps and application of terrain models makes it possible to do runout calculations directly on the maps at the computer screen, a method which substantially rationalized the work the mapping procedure (Toppe 1987). The mapping is performed on topographic maps of scale 1:50.000, and will cover about 100.000 km^2, that is 1/3 of the land area. By the end of 1997, about 125 map sheets have been produced, corresponding to 75% of the total. The purpose of the maps is mainly to be an aid in municipal development.

From 1987 snow avalanche maps for the Norwegian army were produced by the same method. These maps will first of all be used during planning and execution of major army exercises in winter time, (Lied and Sandersen 1989).

During the last 5 years, geographical information systems (GIS), have been introduced in avalanche research and advisory work at NGI. Detailed hazard zoning are performed by use of GIS, where hazard maps are combined with databases of historic avalanche accidents and avalanche runout. Preparedness measures as local evacuation maps and hazard forecasting also benefits from the use of GIS. (Domaas et. al. 1997, Kristensen et al. 1997)

AVALANCHE ADVISORY WORK

As soon as the snow avalanche service was established at NGI, the demand for professional advice concerning snow avalanche problems became a reality. First of all, there was a need to investigate avalanche danger and protection measures for housing areas, roads, and construction works in mountainous terrain in connection to hydroelectric power station constructions. In these fields there were a considerable activity through the 70- and 80-ies.

Altogether, the avalanche group at NGI has handled about 2000 snow avalanche assessments, including snow avalanche evaluation, calculation of avalanche frequency, magnitude, runout distance, cost benefit analyses and defense structures. In this work it has been of vital importance that the staff at NGI working with avalanche problems, gradually gathered a considerable practical experience concerning danger evaluation and design of defense works. The author is convinced that one need scientists not only with a extensive theoretical background in snow mechanics, but also with a considerable practical experience. In this field one also need an extensive team work to be able to act as a professional avalanche adviser.

The problem of snow avalanche danger does not only have a technical side, it also has a political and public side. Politicians must be told what is the danger, i.e. the frequency and magnitude of the avalanche, and what possibilities there are to protect the endangered objects. Based on these terms, the politicians must decide what to do with the existing avalanche problem. As an avalanche expert one also have to convince the public, and the persons directly involved in an avalanche problem, that your evaluations and calculations as an adviser are correct, and that you prescript the best method to increase human safety. This part of the job is more important than often realized by experts, and should be given much attention.

INTERNATIONAL COOPERATION

During the last 5 years NGI has had the pleasure to be a partner in several internatinal research projects. Through the EU - research program Environment and Climate, NGI has taken part in 5 research projects within the field of slides and avalanches. Three of these project have dealt with snow avalanches. Through these projects extensive and valuable cooperation have been established, with scientists and institutions in all the countries of Europe where avalanches represent a threat to human life.

Bilateral projects and direct cooperation through many years between scientists from NGI and institutions in Austria, Canada, Island, Italy, Japan, Russia, Spain , Switzerland and USA have greatly improved NGIs ability to understand avalanche behaviour. In addition to the technical aspects of snow avalanches, many close personal contacts have been established. For both of these aspects NGI is very grateful.

AVALANCHE DISASTERS

Throughout the years the avalanche specialists at NGI have been through many difficult cases and experienced many tragedies. One of the worst cases was the avalanche accident during a NATO winter exercise in 1986 in North Norway, when 16 soldiers were killed in an avalanche in Vassdalen, nearby Narvik. The reason for this tragedy was first of all a combination of a very unstable snow cover that led to a severe avalanche situation in the area where the exercise took place, and misunderstandings and bad communication lines between higher and lower levels in the military command system.

During the winter of 1992/93, western part of Norway experienced severe winter weather in January. For a period of 20 days winds from west and south west of storm force hit the west coast. Combined with heavy precipitation and lower temperatures than normal, a great number of avalanches were released. The 3-day precipitation was recorded to maximum 107 mm, and fracture depths of 3 m in the starting zones were observed. Many of the avalanches were bigger than ever before observed, and in some cases the avalanche wind blast were responsible for most of the damage. Hundreds of avalanches blocked roads, powerlines were cut and destroyed, and dwelling areas were exposed to avalanche damage. Only one person were killed, but the material damage was extensive. In the community of Odda, which experienced the most severe damage, the cost of the defense structures for housing areas will amount to NOK 30 mill. In the winter of 1993/94 the same area was struck again by heavy avalanche activity and extreme avalanche runout.

The winter of 1996/97 brought a severe avalanche situation to North Norway. Record snow depths were observed in January, and several extreme avalanches hit this part of the country. In the community of Tromsø two persons were killed in their home, and about 200 persons were evacuated. Sevaral roads were blocked and powerlines were cut. In Hammferfest many people had to evacuate their homes at three occasions. NGI was heavily involved in most of North Norway during these periods, with day to day hazard forcasting, and advices concerning evacuation of houses, in close cooperation with the local authoroties and police forces.

Looking back into the history of severe avalanche winters in Norway, the statistics tells us that such winters have a return period of 11-13 years. In such winters 10-15 people are killed, and material damage adds up to NOK 100 mill. Damage will be done both in dwelling areas and in huts in the mountains. Numerous roads will be blocked, and many railway lines also. Power and telephone lines will be cut and torned down.

Based on this experience and statistics, one can conclude that the challenge from snow avalanches in this country will not disappear in the future. Likewise, there is a long way to go before all avalanche problems are solved. The most difficult tasks in this respect is the problem of avalanche runout distance, wind forces associated with avalanches, reliable models for avalanche forecasting, and dimension criteria for avalanche defense works.

NGI is involved in research- and advisory work connected to other kinds of slides also, like quick-clay slides, debris slides, rock slides and submarine slides. The snow avalanche activity at the institute clearly benefits from this situation, as many of the theories and methods developed for other kind of slides are applicable for snow avalanches.

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