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Norwegian Zoning tools

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Contact person: Mohamed Naaim, CEMAGREF
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For the Norwegian Geotechnical Institute

Project Manager:
Ulrik Domaas

Report prepared by: Ulrik Domaas, Carl Harbitz
Ulrik Domaas, Carl Harbitz

Reviewed by: Carl Harbitz, Ulrik Domaas

Postal address: P.O. Box 3930 Ullevaal Stadion, N-0806 OSLO, NORWAY Telephone: (+47) 22 02 30 00 Postal account: 0814 51 60643
Street address: Sognsveien 72, OSLO Telefax: (+47) 22 23 04 48 Bank account: 5096 05 01281
Internet: http://www.ngi.no e -mail: ngi@ngi.no Business No. 958 254 318 MVA

Summary

In Work Package 5, Task 2 of the EU-Program CADZIE (Catastrophic Avalanches, Defence Structures and Zoning in Europe), each participating country will contribute to Deliverable D9: Pre-standardisation of zoning tools.

The present report gives information on Norwegian legislation and building act in a historic perspective, today's practical hazard zoning principles, and the use of digital maps and calculational methods in hazard zoning.

The nominal annual probability of avalanches with corresponding return periods presented on the hazard maps is related to security classes and types of constructions in agreement with the Norwegian legislation (Norwegian Planning and Building Act). According to the Technical regulations in the law, three classes of avalanche and slide frequencies are usually taken into account. The building council of the municipalities has to follow the rules stated in the Act, and advises concerning hazard zones and protective measures are given by NGI (as consultant) in each case.

The scales (1:1 000 – 1:50 000) and contents (historic events and estimated hazard zones), as well as the production procedures, for different hazard maps are discussed.

The NGI Graphical User Interface used for hazard zoning is presented. This is an assembly for practical use of avalanche computational models based on more than 20 years of research. The interface reads terrain profiles produced by GIS from digital maps, and has links to model descriptions, database on Norwegian extreme avalanches and the Norwegian legislation internet pages.

Examples of use of the Graphical User Interface and of hazard maps are presented.

Contents

Review and reference document

1 INTRODUCTION

In **Work Package 5, Task 2** of the EU-Program CADZIE (Catastrophic Avalanches, Defence Structures and Zoning in Europe), each participating country will contribute to **Deliverable D9**: Pre-standardisation of zoning tools.

The present report gives information about:

- Legislation and building act in Norway in a historic perspective
- Legislation in Norway
- Today's practical hazard zoning principles in Norway
- Use of digital maps and calculational methods in hazard zoning with examples

2 LEGISLATION AND BUILDING ACT IN A HISTORIC PERSPECTIVE IN NORWAY

The Building and Planning Act in Norway has been under development since 1924 and the act was put into force for the whole country in 1966. The last revision was done in 1997. The building act is used when a detailed hazard plan is made with corresponding detailed maps. The ongoing hazard mapping on survey maps (scale 1:50 000) has been operative since 1979 and up till now approximately 110 maps are finished. It is still necessary to prepare 100 maps (each with an area of approximately 600 km^2), and we need another 15 years to accomplish this work. So far these maps has no legal liability, but will be used as a remedy for the municipalities in land use planning.

In 1980 a new act became operative in Norway which states that all objects with fire Insurance are also obliged to take out Natural Hazard Insurance. Damages caused by avalanches will normally be compensated in full unless the client has shown gross negligence. However, insurance companies will not initiate hazard evaluation or safety measures. For further description, see Hestnes (1990).

3 LEGISLATION IN NORWAY

The building council of the municipalities has to follow the rules stated in the Act, and advises concerning hazard zones and protective measures are given by NGI (as consultant) in each case. In cases where the avalanche-endangered houses date before 1966, the National Fund for Natural Disaster Prevention can give economical support to rebuild with protective measures or to move the houses.

The estimation of natural hazards is associated with the Norwegian Planning and Building Law. According to the Technical regulations in the law, three classes of avalanche and slide frequencies are usually taken into account, these are summarised in the Table 1.

Table 1. Nominal avalanche annual probability with corresponding return periods related to security classes and types of constructions.

Security class	Maximum nominal avalanche annual probability	Avalanche return period (years)	Type of construction
1	10^{-2}	100	Garages, smaller storage roms of one floor, boat houses
2	10^{-3}	1000	Dwelling houses up to two floors, operational buildings in agriculture
3	$<10^{-3}$	<1000	Hospital, schools, public halls etc.

In addition, the Building regulation states that rebuilding after fires or other kinds of reparation may be done for class two, when the nominal annual frequency is less than $3x10^{-3}$, i.e. return period of 333 years.

By using the word «nominal», as opposed to «real», one admits that exact calculation of avalanche run-out distance for the given frequencies is not possible, and use of subjective judgement is therefore necessary.

4 TODAY'S PRACTICAL HAZARD ZONING PRINCIPLES IN NORWAY

4.1 Hazard map scale

Hestnes and Lied (1980), and Lied et al. (1997) describe the principles of natural hazard zoning maps in Norway. The Norwegian Geotechnical Institute has conducted hazard zoning of areas exposed to rockfalls and snow avalanches since 1980.

The maps are divided into two categories according to mapping standard:

- survey maps
- detailed maps

4.1.1 Survey maps

The work is performed jointly with the client the Statens Kartverk (The Norwegian Mapping Authorities).

The maps used are standard topographic maps in scale 1:50.000, with a contour line interval of 20 m. Since 1982 the 1:50.000 maps have been available in digital form in Norway, and since then the hazard zoning process has been computerized.

Survey maps are meant to give general information on hazards. The production covers a fairly large area in a short time at low costs. It is estimated that each map sheet covering an area of approximately 600 km^2 , should be evaluated in 4 weeks.

For the purpose of hazard zoning, a digital terrain model TERMOS was developed by NGI in 1984 (Toppe, 1987), and this model has been in use until 1996. In this system, the topographical/statistical model described in App. A is TERMOS into a semi-automatic computerized hazard zoning method.

The main advantage with this system is that extensive areas may be surveyed for avalanche risk in a short time. The applied statistical avalanche run-out model is based on topographical parameters identified by the computer, from the information given in the map.

At present, this method of hazard zoning is performed by a commercial GIS system (PS GIS), and by the commercial digital terrain modelling system SURFER, for the computation of avalanche run-out, storage of avalanche data in a relation database, and for the graphical presentation of hazard zones.

4.1.2 Detailed maps

These maps should have a high degree of accuracy and therefore demand comprehensive field - and computational work and they are time-consuming to produce. In Norway such maps are based on the Norwegian economic map series at a scale of 1:5000, with 5 m contour line interval, or for certain areas in scale 1:1000, with 1 m contour line interval. In this zoning process, each avalanche path is examined in detail; both rupture area, track and run-out zone are evaluated carefully, first of all to identify the magnitude, frequency, and run-out distance of slides and avalanches.

4.2 Hazard map contents

Depending on map contents and methods used in data collection and data processing, NGI found it appropriate to distinguish between three types of hazard maps:

Hazard registration maps. Maps containing historically known slides and avalanches, compiled from literature and documents, interviews and field work.

Geomorphic hazard maps. Maps containing information of hazard prone areas identified by geomorphological investigations in the field, and by the use of topographic maps and air photos.

Hazard zoning maps. Maps that define risk areas compiled on the basis of known historic events, geomorphological investigations and the use of frequency/run-out calculation models. The hazard zones should correspond to the safety requirements in the national building regulations, or specify other frequency/magnitude conditions of the hazard zone.

4.3 Hazard zoning procedures

4.3.1 Survey maps

As a first step, all potential hazard zones are identified regardless of the frequency of avalanches and rock falls. The hazard zones are divided into two areas:

- Starting zones
- Run-out zones

The starting zones include all areas on the map, which are steeper than 30°. For snow avalanches, areas covered with dense forest are not considered.

The identification of the starting zones is done automatically by the computer, using vector information. On a map sheet with a surface area of 600 km^2 this process is completed within a few hours.

Using the terrain profile in each slide and avalanche path identifies the run-out zones. Each profile is drawn as a line on the computer screen, from the top of the starting zone, along the path to the valley floor. Based on the information from this terrain profile, the run-out distance is calculated by the computer in a few seconds by the topographical/statistical model for snow avalanches, App. A., and rock falls according to the empirical model developed by Domaas (1994).

After completion of the hazard map on the computer, the map is checked and corrected by inspection in the field.

Zoning of debris flow hazard has been tried out following the same procedures as for snow avalanches and rock falls. For the time being, NGI´s experience is that debris flow hazard is too complicated to be solved in a survey hazard zoning procedure, as the investigation of this type of hazard needs more basic field work than potential snow avalanche- and rock fall areas. Hazard zoning of debris slides is therefore performed by detailed zoning procedures only.

4.3.2 Detailed maps

Three different sources of information are used to complete a detailed hazard map:

- historic records of avalanches
- geomorphic analysis of the avalanche path

- computational models for run-out calculation

All information of known avalanches and slides, their run-out distance, damage, weather conditions connected to the release etc., are collected. Both oral information and written records are used.

Geomorphological evidence of avalanche frequency and run-out is studied in the field. First of all how vegetation is influenced by avalanche activity, and how loose deposits are eroded, transported and accumulated in the avalanche track.

Bedrock type and quality is investigated, together with the distribution of and type of loose deposits.

Debris flow hazard is identified mainly in terrain formations at, and nearby river fans. Soil profiles from test pits are used also to identify and date type and frequency of slides.

Run-out models for avalanches and slides are an important tool concerning the establishment of the hazard zones. Each avalanche and slide path is modelled in detail by using digital maps and terrain models. The run-out models are used to calculate the hazard zones corresponding to the national safety requirements for natural hazards.

Calculation of the run-out distance of debris flows has up to present been done manually.

5 USE OF DIGITAL MAPS AND CALCULATIONAL METHODS IN HAZARD ZONING

5.1 Digital maps (GIS)

The avalanche path is described by a longitudinal terrain profile shown as a red line on the map, Figure 1. The α/β-model is implemented in the PS GIS tool and will automatically execute a calculation of the run-out into the valley along this profile.

The method above is used for rapid hazard zoning covering large areas. From a longitudinal avalanche path profile we get the three-dimensional co-ordinates (xyz file) and automatically produce a two-dimensional (sz file) describing the longitudinal terrain profile, Table 2.

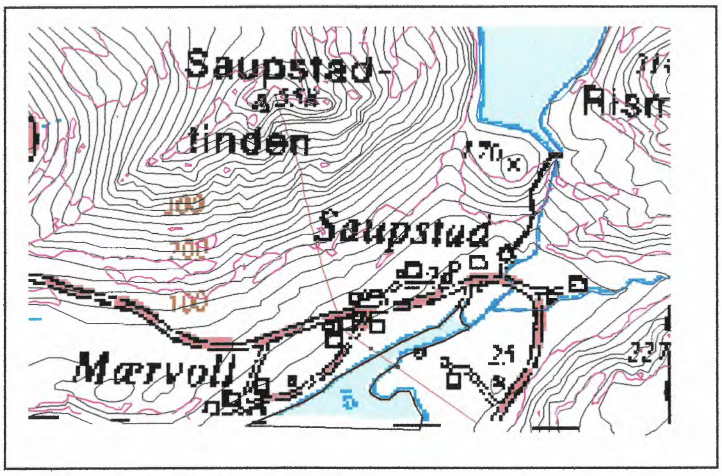


Figure 1. Digital map with terrain profile (red line).

Table 2. Longitudinal avalanche path profile with three-dimensional co-ordinates (x,y,z) as well as accumulated horizontal distance (s,z).

```
TYPE: Avalanche
Point number      x            y             z       akk.hor.distance
    1        -55987.60    1236418.67      1160.00            0.00
    2        -55988.46    1236398.19      1140.00           20.50
    3        -55988.47    1236368.79      1120.00           49.90
    4        -55989.36    1236336.31      1100.00           82.39
    5        -55989.36    1236302.03      1080.00          116.67
    6        -55990.25    1236279.46      1060.00          139.26
    7        -55990.26    1236251.66      1040.00          167.06
    8        -55991.14    1236214.73      1020.00          204.00
    9        -55991.14    1236183.39      1000.00          235.34
   10        -55992.03    1236153.83       980.00          264.91
   11        -55992.03    1236121.75       960.00          296.99
        -
        -
        -
        -
   60        -55025.62    1233910.05       205.00         2742.73
   61        -55003.57    1233872.97       200.00         2785.87
   62        -54994.32    1233857.28       195.00         2804.09
   63        -54975.85    1233826.48       190.00         2840.00
   64        -54932.03    1233752.27       185.00         2926.18
   65        -54907.24    1233710.66       185.00         2974.62
   66        -54846.07    1233630.75       190.00         3075.25
   67        -54319.30    1233127.13       240.00         3804.03
```

The NGI Graphical User Interface described below reads the resulting table.

5.2 Calculational methods — NGI Graphical User Interface

The preceding EU-Programs SAME (Avalanche Mapping, Model Validation and warning systems) and TIGRA (The Integrated Geological Risk Assessment) resulted in five deliverables on avalanche computational models and hazard zoning:

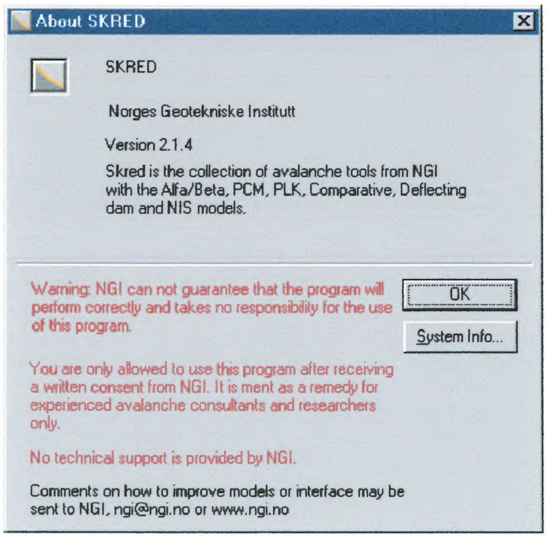
- Avalanche maps and databases in Europe (Burnet and Marti, 1998)
- Integration of different avalanche models in a single, GIS based user interface (Naaim and Gruber, 1998)
- Application and evaluation of different avalanche models at five real sites in Europe (Barbolini et al., 1998)
- A survey of computational models for snow avalanche motion (Harbitz et al., 1998)
- Hazard Zoning Methods of Snow Avalanches, debris Flows and Rock Falls (Lied et al., 1997)

This work gave a motivation to produce at NGI a common graphical user interface covering:

- Statistical and dynamical computational models for consulting work (α/β-, PCM-, PLK-, NIS1- & NIS2-, comparative- and deflecting dam models)
- Use of terrain profiles from digital maps (GIS)
- Model descriptions (cf. App. A)
- Database on extreme avalanches
- Link to the Norwegian legislation internet pages.

Basicly, the new NGI Graphical User Interface is an assembly for practical use of avalanche computational models based on more than 20 years of research. The top-level tool-bar is revealed in Figure 2 and the opening page in Figure 3.

Figure 2. Top-level toolbar for the NGI Graphical User Interface 'SKRED'.



SKRED

Norges Geotekniske Institutt

Version 2.1.4

Skred is the collection of avalanche tools from NGI with the Alfa/Beta, PCM, PLK, Comparative, Deflecting dam and NIS models.

Warning: NGI can not guarantee that the program will perform correctly and takes no responsibility for the use of this program.

You are only allowed to use this program after receiving a written consent from NGI. It is ment as a remedy for experienced avalanche consultants and researchers only.

No technical support is provided by NGI.

Comments on how to improve models or interface may be sent to NGI, ngi@ngi.no or www.ngi.no

Figure 3. Opening page of the NGI Graphical User Interface 'SKRED'

From the models we can calculate the run-out distance and velocity profiles based on the length profile, Figure 4.

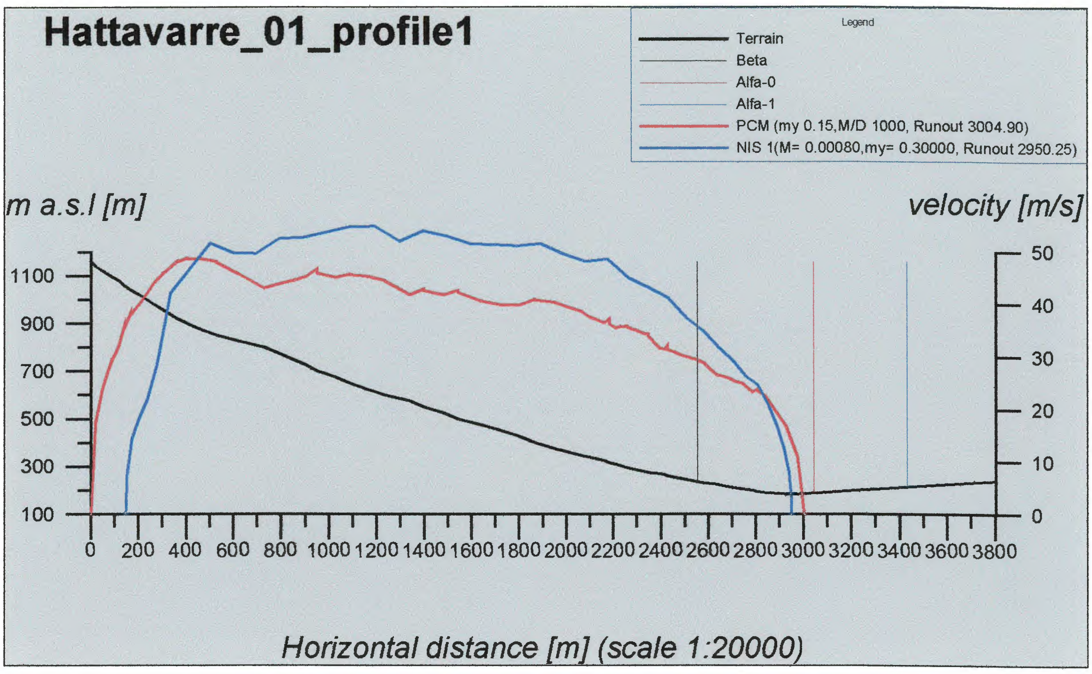
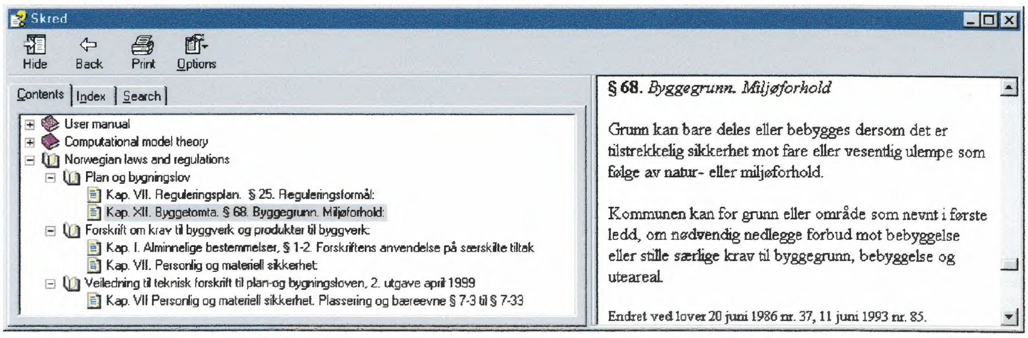


Figure 4. Example of run-out distance and velocity profile calculations by the NGI Graphical User Interface.

The Graphical User Interface is also linked to Norwegian legislation internet pages, Figure 5.



- User manual
- Computational model theory
- Norwegian laws and regulations
  - Plan og bygningslov
    - Kap. VII. Reguleringsplan. § 25. Reguleringsformål:
    - Kap. XII. Byggetomta. § 68. Byggegrunn. Miljøforhold:
  - Forskrift om krav til byggverk og produkter til byggverk:
    - Kap. I. Alminnelige bestemmelser, § 1-2. Forskriftens anvendelse på særskilte tiltak
    - Kap. VII. Personlig og materiell sikkerhet:
  - Veiledning til teknisk forskrift til plan-og bygningsloven, 2. utgave april 1999
    - Kap. VII Personlig og materiell sikkerhet. Plassering og bæreevne § 7-3 til § 7-33

§ 68. *Byggegrunn. Miljøforhold*

Grunn kan bare deles eller bebygges dersom det er tilstrekkelig sikkerhet mot fare eller vesentlig ulempe som følge av natur- eller miljøforhold.

Kommunen kan for grunn eller område som nevnt i første ledd, om nødvendig nedlegge forbud mot bebyggelse eller stille særlige krav til byggegrunn, bebyggelse og uteareal.

Endret ved lover 20 juni 1986 nr. 37, 11 juni 1993 nr. 85.

Figure 5. Link from the Graphical User Interface to the Norwegian legislation internet pages.

5.3 Examples of hazard zoning

The results from the calculations with the different models together with the fieldwork and historical information give sufficient information to make the hazard-zoning map.

The large avalanches and the historic records of damages due to avalanches in Geiranger have led to a hazard zoning for the whole village (Domaas et al., 1997). Figure 6 reveals an example of the historic records of avalanches in Geiranger, Møre and Romsdal County.

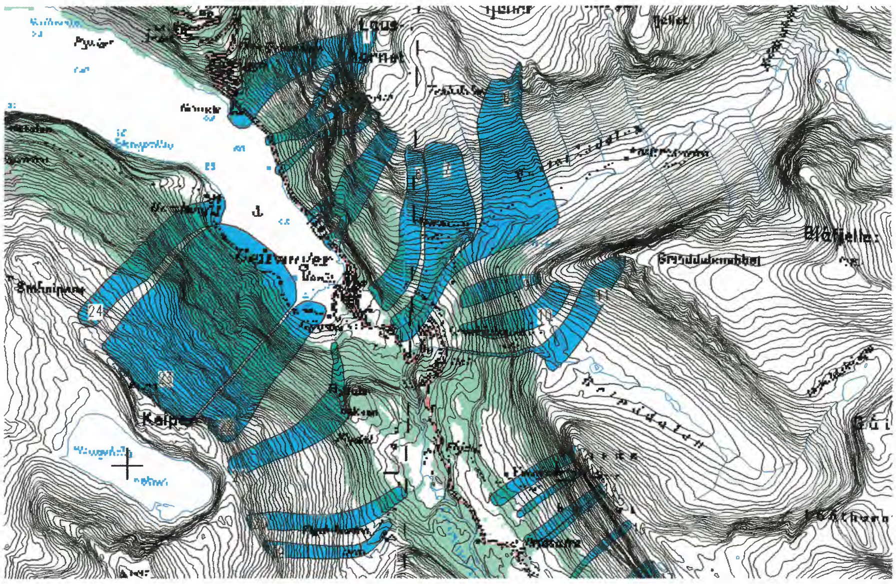


Figure 6. Map showing historic avalanches close to the Geiranger village.

Figure 7 shows a hazard map of the village centre. The red zone represents a nominal annual avalanche probability of 1/100, the blue of 1/300 and the green of 1/1000.

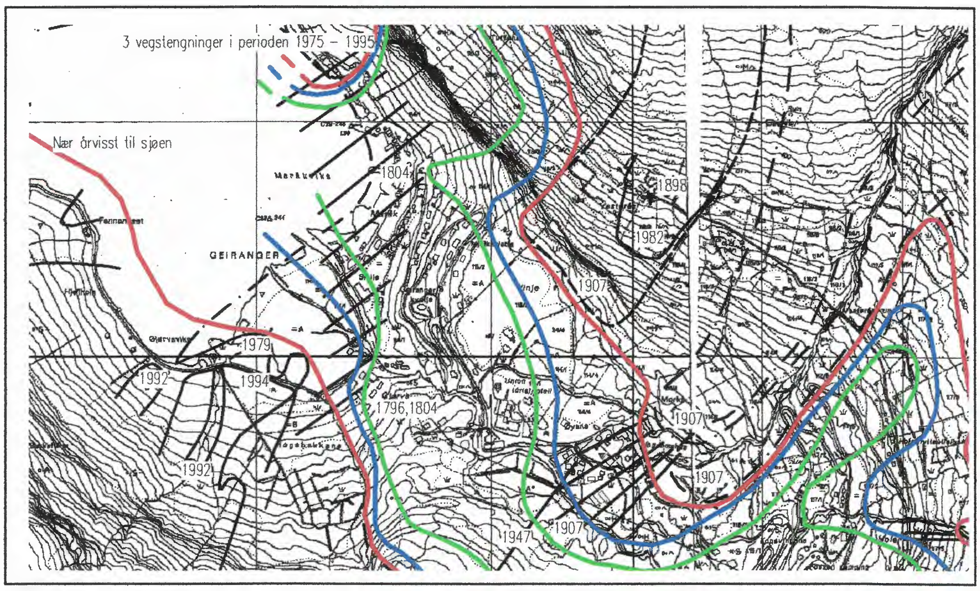


Figure 7. Avalanche hazard map with historic events estimated return periods corresponding to the Norwegian legislation for Geiranger village.

The vulnerability analysis of the living areas exposed to avalanche hazard led to areas of evacuation in situations with high avalanche danger. On the map in Figure 8 the area to be evacuated is indicated. The people from this area of the village will evacuate to the hotel nearby, when given the evacuation order from the local police. The system was successfully applied the winter 2000.

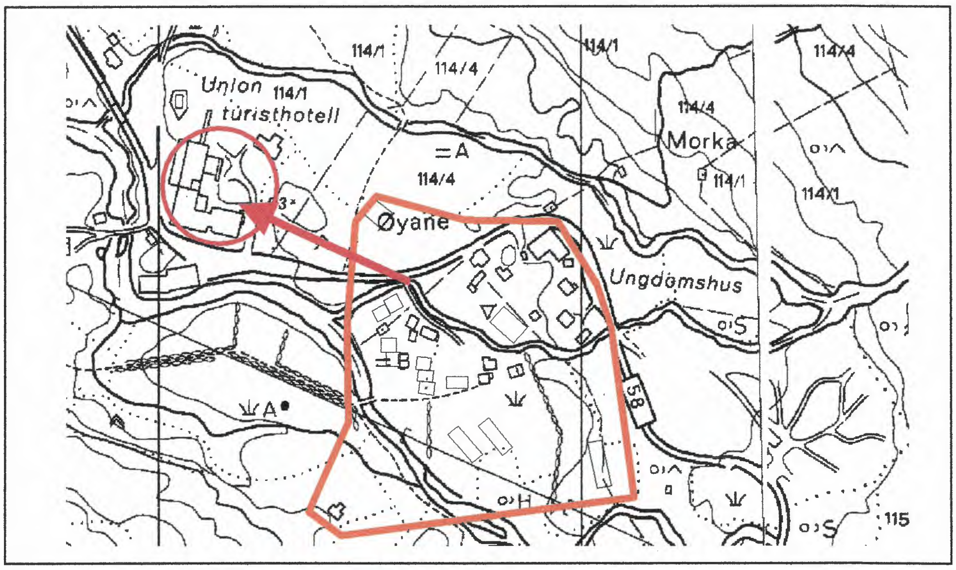


Figure 8. The housing area within the avalanche hazard zone with annual probability of being hit larger than 1/300 (orange). The police and municipality will evacuate this area to a hotel nearby (red) when the avalanche hazard is high.

6 REFERENCES

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Burnet, R. and Marti, G. 1998. Avalanche maps and databases in Europe. (Deliverable D1 of the EU project SAME) http://same.grenoble.cemagref.fr/

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Appendix A - Description of computational models

CONTENTS

A1 COMPUTATIONS OF SNOW AVALANCHE MOTION

A1.1 Avalanche dynamics

An avalanche consists of up to four layers. The basal *dense snow layer* is a gravity flow and normally represents the majority of the mass. The particles are in close contact and the density is high (assumed to be almost constant).

Above the dense snow layer is the transitional *saltation layer,* where the particles are transported in jumps similar to saltating particles in drifting snow. The density is reduced to the power of three against height in the saltation layer.

Then follows a turbulent *suspension layer*, referred to as an (airborne) powder snow avalanche, driven by the extra weight of small snow particles (< 1 mm) suspended in the air. The suspension layer constitutes the "snow cloud" of the avalanche. Here the density and the velocity are reduced almost linearly with height.

Above and around the avalanche is a backflow of air named the *recirculation layer*, with a height one to three times that of the suspension layer.

Since the material properties differ, there is a useful distinction between wet snow avalanches (generally cohesive with possible snowball and shear plane formation), and dry snow avalanches (no free water content). Dense snow avalanches can occur under both wet and dry snow conditions. An overriding suspension layer is normally generated in both circumstances, especially in steep slopes. Pure powder snow avalanches require dry snow conditions.

The type of rupture of the snow cover depends on the state of intergranular cohesion. In loose, low-cohesive snow a point fracture occurs and a loose snow avalanche is generated, whereas sufficient intergranular cohesion favours line fracture and the resulting avalanche moves initially as a slab before it begins to break up.

Increased human activity in mountain regions, deforestation from pollution, forestry and ski resorts, as well as an increased desire to exploit exposed areas combined with a reduced acceptance of risk, have caused a growing need for protection against avalanches. Both empirical procedures including statistical/topographical and comparative models for runout distance computations, as well as dynamics models for avalanche motion simulations are now in existence. The empirical procedures permit an assessment of runout distance only, while the more advanced dynamics models give much additional information concerning the nature of the sliding event (flow heights, velocities, etc.). This information is crucial for improved understanding of avalanche dynamics, and for the calculation of impact pressure upon obstacles, run-up heights on protective dams, etc. However, no universal model has so far been developed. The dynamics of avalanches are complex, involving properties similar to those employed in fluid, particle and soil mechanics. The limited amount of data available from real events makes it hard to evaluate or calibrate existing models. Often several models with different physical descriptions of the avalanche movement can be used to replicate the information contained in the available, deficient, recorded observations.

A1.2 Empirical models

Empirical models for snow avalanches are based on statistical/topographical models or comparative models for estimation of avalanche runout distance. In statistical/topographical models the runout distance relations are normally found by regression analysis of data from observed events. Comparative models are based on methods for evaluating the similarity between path profiles. An alternative approach is to present pure limiting criteria for flow behaviour, as from considerations of subaerial debris flow behaviour.

Empirical procedures are normally applied to dense snow avalanches. However, in principle, there is no reason why they could not be applied to slush flows and powder snow avalanches if a sufficient number of precise observations are available.

A1.3 Dynamics models for the dense snow layer

Most models for dense snow avalanches describe the flow as: 1) lumped mass (centre-of-gravity consideration); 2) rigid body or flexible “blanket” following the terrain; 3) two-dimensional depth-averaged deformable body models (two-dimensional continuum). Models including also a lateral dimension are now being developed to analyse distribution and deflection of the flowing masses.

The sliding block (lumped mass or rigid body), models describe the slide initiation well. Due to their simplicity they are also widely applied to the rest of the avalanche motion.

Deformable body models describe the dense snow avalanche as a continuum. Difficulties are related to a proper description of the material properties, the boundary conditions, and the initial conditions.

A1.4 Dynamics models for the suspension layer

The "PSA" (powder snow avalanche) models are either density current models or binary (two-phase solid/fluid) mixture models. They disregard the interaction with the dense layer and thus are not able to model the early stages of suspension layer formation.

Three-dimensional PSA models are now being developed into tools for avalanche hazard mapping in France, Switzerland and Austria. A few coupled models, including both the dense and the powder snow part of the avalanche, also exist.

A1.5 Computational models — a remedy only

Both empirical and dynamical computational models estimate avalanche runout distance with a certain probability. The probability has to be estimated for each avalanche path, and is a combination of the probability of occurrence and the probability of a certain runout distance. Where a sufficient number of reliable observations do not exist, the meteorological conditions and the exposition of the site relative to the direction of snow-bringing winds are applied to estimate the probability of avalanche occurrence. The probability of a certain runout distance is determined by the statistical distribution of the parameters included in the computational model. In the case of two otherwise similar avalanche paths, the probability of long runout is higher in the path on the leeward snow-accumulating mountain side, than in the windward non-accumulating mountainside. Buildings and vegetation will also influence the runout distance. However, the maximum conceivable runout distance in the two avalanche paths over an infinite period of time will be the same.

To relate avalanche runout to a certain probability, e.g. an annual probability of 10^{-3}, is a difficult task. However, the models are a good remedy to estimate the right order of magnitude for both avalanche frequency and avalanche runout distance.

Even though a house is located beyond a defined avalanche hazard zone, there is still a possibility of being hit by an avalanche. If the hazard zone mirrors an annual probability for an avalanche to reach the area larger than 10^{-3}, an avalanche should reach outside the hazard zone in average once every thousand years. In other words, there is a 1 % chance that the avalanche will reach beyond the hazard zone during a period of ten years. In a municipality with 100 buildings that have this chance of being hit by an avalanche, i.e. are built on the boundary of the hazard zone; in average one of these houses will be hit by an avalanche every ten years.

A2 THE α/β-MODEL

The statistical/topographical α/β-model was developed at NGI and governs maximum runout distance solely as a function of topography. The runout distance equations are found by regression analysis, correlating the longest registered runout distance from more than 200 avalanche paths to a selection of topographic parameters. The parameters that have proved to be most significant are presented in Table 2-1 , cf. Figure 2.1:

Table 2-1 Topographic parameters governing maximum runout distance

Symbol of parameter:	Parameter description:
β (deg.)	Average inclination of avalanche path between starting point and point of 10° inclination along terrain profile.
θ (deg.)	Inclination of top 100 vertical meters of starting zone.
H (m)	Total height difference between starting point and lowest point of best-fit parabola $y=c_2x^2+c_1x+c_0$, where c_0, c_1, and c_2 are constants.
y'' (m^{-1})	$y''=2c_2$, related to curvature of avalanche path.

The β-angle is empirically found to be the best characterisation of the track inclination, and regression analysis has revealed that the β-angle is also the only statistically significant topographic parameter. A β-point is accepted only if it is inside the section of the profile where the angle between the tangent of the best-fit parabola and the horizontal plane is between 5° and 15°.

The inclination θ of the top 100 vertical metres of starting zone indirectly governs the rupture height, and thereby the slide thickness, which is greater in gentle slopes than in steep slopes. Hence smaller values of θ give longer runout distances or smaller average inclination of the total avalanche path, α.

Smaller values of the product Hy'' mean smaller values of β. This results in theoretically longer runout distances, (smaller values of α), because the avalanches run with lower velocity, and the velocity-dependent frictional transformation of potential energy into heat is reduced. Hence, the avalanches have an apparently lower coefficient of friction.

The topography, the width and the degree of lateral confinement in the starting zone, as well as the drifting snow transport into the starting zone, have little influence upon the runout distance. No tendency is found that an avalanche with a wide rupture zone that is channelled into a narrow track, has a longer reach than an avalanche following an unconfined path.

The model is most appropriate for travel distance analysis along longitudinally concave profiles. The calculated runout distances are those that might be expected under snow conditions favouring the longest runout distances (i.e. loose and dry snow along the entire path).

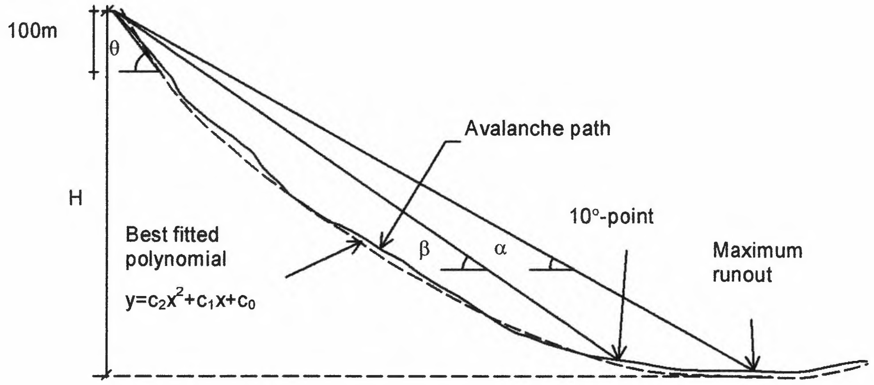

Figure 2.1 Topographic parameters describing terrain profile.

The assumption of small variations in the physical snow parameters giving the longest runout distance is only valid within one climatic region. The Norwegian avalanche database of NGI contains at present 230 events. Both the statistical/topographical and the dynamics models are occasionally recalibrated. The most usual form of the α/β-model based on the Norwegian database is that of a simple linear regression relation: $\alpha = 0.96\beta - 1.4^o$. The standard deviation is 2.3^o and the correlation coefficient is 0.92.

An analysis of 45 paths in Iceland with reliable records, (25 of which terminate on land and 20 in the sea), is used to produce an Icelandic α/β-model. A least-squares regression analysis found that the intercept term was not statistically significant and it was omitted from the model to $\alpha = 0.85\beta$. This equation had a standard deviation of 2.3^o and a correlation coefficient of 0.71.

The regression analysis for the α/β-model has also been accomplished in Austria. The simple regression relation based on the Austrian database is $\alpha = 0.946\beta - 0.83^o$. The standard deviation is 1.5^o and the correlation coefficient is 0.96.

An extended summary of the α/β-model is presented in:

Harbitz, C.B. 1998. A survey of computational models for snow avalanche motion. *(Deliverable D4 of the EU project SAME) Norwegian Geotechnical Institute*, report no. **581220-1**.

Literature:

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Bakkehøi, S. and Norem, H. 1994. Sammenlikning av metoder for beregning av maksimal utløpsdistanse for snøskred (Comparison of methods for calculation of maximum avalanche runout distance). *Norwegian Geotechnical Institute*, report no. **581200-30** (in Norwegian).

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A3 THE COMPARATIVE MODEL

The comparative model computes the avalanche runout angle, α (average gradient of the avalanche path) by comparing the actual path profile with more than 200 other paths with registered avalanche runout. The average inclination of the avalanche path between starting point and point of 10° inclination along terrain profile, β, is considered the most important parameter governing the runout angle. Thus avalanche path profiles in the register with β-values differing more than two degrees from the actual profile, are excluded from the investigation. Each remaining avalanche path profile and its best-fit parabola are then described by the characteristic parameters presented in Table 3-1 (cf. the statistical/topographical α/β-model). All parameters are weighted by suitable coefficients w_i.

When comparing the actual profile with a profile from the avalanche data register, the seven parameters in Table 3-1 will assume different values for the two paths, x_{i1} and x_{i2}, i=1,2,...,7, respectively. The 7-dimensional weighted distance

$$d = \sqrt{\sum_{i=1}^{7} w_i (x_{i1} - x_{i2})^2}$$

expresses the similarity between the two paths. A small value of d indicates a high degree of similarity. The actual runout angle is finally calculated as the average of the runout angles of the five most similar registered avalanche path profiles.

Table 3-1 Parameters describing avalanche path profile

Symbol of parameter x_i:	Parameter description:	Weight coefficient w_i:
θ (deg.)	Inclination of top 100 vertical meters of starting zone.	0.3
H (m)	Total height difference between starting point and lowest point of best-fit parabola $y=c_2x^2+c_1x+c_0$, where c_0, c_1, and c_2 are constants.	0.04
y'' (m^{-1})	$y'' = 2c_2$, related to curvature of avalanche path.	0.3
z (m)	Altitude of runout area (m a.s.l).	0.03
H y'' (-)	Determines β angle for a parabolic slope by $\beta = \tan^{-1}\left(\sqrt{\frac{Hy''}{2}} + \frac{\tan 10^\circ}{2}\right)$	0.7
σ (m)	Standard deviation of best-fit parabola from the co-ordinates of the given path profile.	1.0
Q (m)	Standard deviation of the variations of the deviations between best-fit parabola and the co-ordinates of the given path profile. Q expresses the roughness of the path profile.	2.0

The standard deviation of the calculated runout angle from the observed runout angle for all the registered avalanches is 1.86°. This is better than the standard deviation for both the statistical/topographical α/β-model and the dynamical NIS1 model, which is 2.2° and 2.3° for the whole avalanche register respectively.

The comparative model also affords the opportunity to study the background material of the most similar registered avalanche events with regard to topographical conditions, region, climate, return period, etc. Hence it is possible to attach greater importance to selected registered events.

An extended summary of the comparative model is presented in:

Harbitz, C.B. 1998. A survey of computational models for snow avalanche motion. *(Deliverable D4 of the EU project SAME) Norwegian Geotechnical Institute*, report no. **581220-1**.

Literature:

Bakkehøi, S. and Norem, H. 1993. Comparing topographical and dynamical run-out models by ideas of "Nearest Neighbour Method". *2nd Avalanche-Dynamics-Workshop in Innsbruck.* Preliminary.

Bakkehøi, S. and Norem, H. 1994. Sammenlikning av metoder for beregning av maksimal utløpsdistanse for snøskred (Comparison of methods for calculation of maximum avalanche runout distance). *Norwegian Geotechnical Institute*, report no. **581200-30** (in Norwegian).

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A4 THE PCM BLOCK MODEL

The PCM model describes the avalanche as a block moving on a path of varying inclination. The reference point is the initial rest position of the block's centre-of-mass. The equation of momentum includes gravity, velocity-independent dry (Coulomb) friction as well as the centrifugal force due to curvature of the path, dynamic drag and inertia-resistive ploughing of snow masses in the front. The three latter contributions are implemented together as the velocity squared, divided by the "mass-to-drag" ratio. The momentum equation is solved by an iterative solution procedure, dividing the slope into small linear segments of different inclination.

The usefulness of the model depends on knowledge of the two adjustable parameters (dry friction coefficient and mass-to-drag ratio) that can vary considerably. These values have been limited to some extent by testing the model statistically.

An extended summary of the PCM model is presented in:
Harbitz, C.B. 1998. A survey of computational models for snow avalanche motion. *(Deliverable D4 of the EU project SAME) Norwegian Geotechnical Institute*, report no. **581220-1**.

Literature:

Bakkehøi, S., Cheng, T., Domaas, U., Lied, K., Perla, R.I. and Schieldrop, B. 1981. On the computation of parameters that model snow avalanche motion. *Canadian Geotechnical Journal* **18(1)**, 121-130.

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A5 THE PLK PARTICLE MODEL

The PLK model is an alternative to the PCM model. The block model is abandoned and instead an avalanche is modelled as a collection of approximately 1000 particles. Each particle is allowed to move with only one degree of freedom along straight-line segments parallel to the avalanche path. The particles move independently, and are subjected to gravity and resistive forces as in the PCM model in addition to a force that is proportional to the velocity of the particle and has a random direction (positive or negative) determined by Monte Carlo-simulation. In essence, the model uses the equation of motion for each particle mass-centre, and in no way requires that the particles, taken together, form a continuum within a defined boundary. The model includes entrainment at the avalanche front. Furthermore, the model includes the possibility of varying resistive parameters with speed and slope position.

The random force seems to improve the distributions, but was introduced in an ad hoc manner and appears to lack a physical interpretation. However, the factor of proportionality has the denomination s^{-1} (Hz), and may be interpreted as particle collision frequency.

An extended summary of the PLK model is presented in:

Harbitz, C.B. 1998. A survey of computational models for snow avalanche motion. *(Deliverable D4 of the EU project SAME) Norwegian Geotechnical Institute*, report no. **581220-1**.

Literature:

Perla R., Lied K., and Kristensen, K. 1984. Particle simulation of snow avalanche motion. *Cold Regions Science and Technology* **9**, 191-202.

A6 THE DEFLECTING DAM MODEL

The deflecting dam model describes the motion of the avalanche centre-of-mass along the side of a retaining dam. Strictly speaking, the centre-of-mass is that of a representative frontal part of the slide projected onto the terrain, (the total avalanche centre-of-mass may not even reach the dam). The equations are derived from classical mechanics, including a resistance force represented by a dynamic drag and a dry (Coulomb) friction, and are solved numerically by a fourth order Runge-Kutta procedure.

However, a lumped mass consideration does not include any effects of the avalanche extension on the dynamics. Hence, the model results will in any case be encumbered with obvious restrictions. Instead of a sophisticated digital terrain model, it was therefore preferred to perform a simplified geometry study of the influence of avalanche impact velocity, terrain inclination, dam configuration, and dam orientation on avalanche course deflection and run-up height along a deflection dam. An additional advantage of a simplified geometry study is that the deflecting dam does not have to be superimposed on a complex digital terrain.

The simplified dam geometry consists of a plane terrain of inclination β and the upper plane wall of the deflecting dam, oriented by its angle relative to the terrain, ψ, and the angle between the base line of the wall (the x-axis) and the terrain contour lines, φ, Figure 6.1.

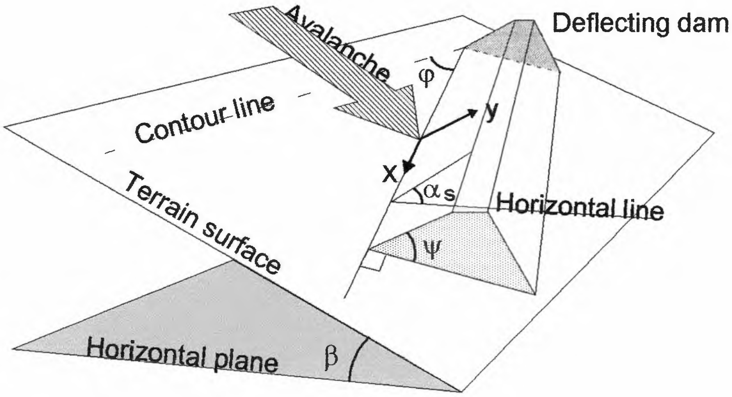

Figure 6.1 Simplified geometry configuration for centre-of-mass model.

The avalanche impact velocity on the dam is normally found by running the PCM model. The effects of energy loss due to impact may also be investigated by the deflecting dam model.

To overcome the model deficiencies introduced by a lumped mass consideration, a best-fit line between the observed and the calculated run-up heights is applied in practical dam design.

Literature:

Domaas, U. and Harbitz, C.B. 1998. Avalanche run-up heights on deflecting dams: Centre-of-mass computations compared to observations. *25 Years of Snow Avalanche Research at NGI, Anniversary Conference, Voss, Norway, 12–16 May, 1998, Proceedings. Norwegian Geotechnical Institute*, publication no. **203**.

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Irgens, F., Schieldrop, B., Harbitz, C.B., Domaas, U. and Opsahl, R. 1998. Simulations of dense snow avalanches on deflecting dams. *Annals of Glaciology* Vol. **26**. Also in: *Norwegian Geotechnical Institute*, publication no. **143** and report no. **581210-3**.

A7 THE NIS1 DEFORMABLE BODY MODEL

The NIS1 model describes the avalanche as a deformable body model of which velocity and flow height are a function of both space and time. The snow is described as a visco-plastic material with dispersive pressure (i.e. the normal stresses depend on the shear rate) forming a shear flow with or without a basal slip velocity. Varying inclination produces centrifugal forces. The model is one-dimensional as the equations are depth-averaged for a velocity profile assumed to be identical in form to the steady shear flow profile. The resulting equations for balance of mass and linear momentum are solved by a Eulerian finite difference mid-point scheme in space and a fourth-order Runge-Kutta procedure in time.

To simplify comparison with other models, four program options are implemented:

- varying flow height with slip velocity conditions
- varying flow height with no-slip velocity conditions
- varying flow height, but uniform velocity profile in a vertical cross section
- constant flow height and velocity profile along the whole slide with no-slip velocity conditions

The latter can be compared with the PCM model.

Several input parameters are required. The most important are the material friction coefficient and the initial flow height (thickness) of the avalanche. A default value is presented for the latter, based upon the fact that an unstable situation occurs when the actual shear stress equals the yield strength of the snow.

For the initial length of the avalanche slab, it is recommended that the corresponding vertical extension comprises one sixth of the total height difference of the slide path, with a maximum value of 100 m.

On the free surface, the normal stress must be equal to the atmospheric pressure, which is assumed to be equal to the pore pressure. The shear stress is neglected.

The model is validated by comparison with laboratory and full-scale experimental data of avalanches, submarine slides and rock slides.

An extended summary of the NIS1 model is presented in:

Harbitz, C.B. 1998. A survey of computational models for snow avalanche motion. *(Deliverable D4 of the EU project SAME) Norwegian Geotechnical Institute*, report no. **581220-1**.

Literature:

Bakkehøi, S. and Norem, H. 1994. Sammenlikning av metoder for beregning av maksimal utløpsdistanse for snøskred (Comparison of methods for calculation of maximum avalanche runout distance). *Norwegian Geotechnical Institute*, report no. **581200-30** (in Norwegian).

Irgens, F. in review. Simplified simulation model of snow avalanches and landslides. *Submitted to Journal of Glaciology*.

Locat, J., Norem, H. and Therrien, P. 1992. An approach to rock avalanche dynamics. *Norwegian Geotechnical Institute*, report no. **585000-10**.

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Norem, H., Irgens, F. and Schieldrop, B. 1989. Simulation of Snow-Avalanche Flow in Run-Out Zones. *Annals of Glaciology* Vol. **13**, 218-225.

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Norem, H. and Schieldrop, B. 1991. Stress analyses for numerical modelling of submarine flowslides. *Norwegian Geotechnical Institute*, report no. **522090-10**.

A8 THE NIS2 DEFORMABLE BODY MODEL

The NIS2 model is an extension of the NIS1 model. The same one-dimensional equations as for the NIS1 model are applied, but motion in a three-dimensional terrain is considered. The avalanche is assumed to flow in a depression approximated by a set of volume elements with varying widths, compensating for converging and diverging effects in a real avalanche flow. Furthermore, horizontal centrifugal effects due to the curvature of the horizontal projection of the path are taken into account. A circular segment approximates the cross section (perpendicular to the bed) of the flowing material. Owing to centrifugal forces the free surface in the cross section will be inclined with respect to the horizontal plane. The main feature of the model is the fact that the centre line of the avalanche is a space curve, which is determined by the terrain and also by the dynamics of the flowing material itself.

For the sake of simplicity, the complete version of the simulation model presents two options for the properties of the flowing material: 1) for highly cohesive material, active and passive pressure contributions are included and a vertically uniform velocity distribution is assumed; 2) when cohesion may be neglected, active and passive pressure contributions are not included and a shear flow with no-slip basal conditions is assumed.

An extended summary of the NIS2 model is presented in:

Harbitz, C.B. 1998. A survey of computational models for snow avalanche motion. *(Deliverable D4 of the EU project SAME) Norwegian Geotechnical Institute*, report no. **581220-1**.

Literature:

Irgens, F., Schieldrop, B., Harbitz, C.B., Domaas, U. and Opsahl, R. 1998. Simulations of dense snow avalanches on deflecting dams. *Annals of Glaciology* Vol. **26**. Also in: Norwegian Geotechnical Institute, publication no. **143** and report no. **581210-3**.

Irgens, F. in review. Simplified simulation model of snow avalanches and landslides. *Submitted to Journal of Glaciology.*

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