Avalanche Hazard Mapping Using Numerical Voellmy-Fluid Models

Urs Gruber[1], Perry Bartelt[1] and Harold Haefner[2]

[1]*Swiss Federal Institute for Snow and Avalanche Research, Flüelastrasse 11, CH-7260 Davos-Dorf*

[2]*Institute of Geography, University of Zurich, Winterthurerstrasse 190, CH-8057 Zurich*

ABSTRACT

One- and two-dimensional numerical dense-snow avalanche dynamics models using a Voellmy-fluid constitutive flow law have been developed in Switzerland recently. In order to apply these models in practice, they have been embedded in a general Avalanche Hazard Mapping System. This system supports the preparation and specification of all necessary input, allows the choice between different simulation models, performs a detailed visualisation of the numerical results and generates the final avalanche hazard maps. Various avalanche events have been back-calculated using this system in order to identify the influence of the flow parameters, initial conditions and terrain undulations on predicted runout distances. The most important results of this system evaluation are stated in this paper. To illustrate the possibilities and limits of the numerical models, two examples are presented. The one-dimensional model is applied to a terrain terracing study in the Loetschental valley. The two-dimensional model is used to calculate a large-area avalanche hazard map in the Davos region. Both examples show that numerical models bring new and valuable capabilities into the avalanche hazard zoning process. On the other hand, some older problems remain, e. g. the importance of the "correct" assumptions in the release zone or the two-dimensional spreading of the avalanche over a flat open slope.

INTRODUCTION

In Switzerland the Voellmy-Salm model is officially used to calculate snow avalanche runout when preparing hazard maps (Salm and others, 1990). Recently, a one- and two-dimensional numerical depth-averaged continuum model has been developed that resolves many of the well-known shortcomings of the Voellmy-Salm model (Bartelt and others, 1997, Sartoris and Bartelt, 1998). The numerical model has been formulated such that it contains the same flow law – termed a "Voellmy-fluid" – as the older Voellmy-Salm model. Although alternative flow laws are possible to implement (see Bartelt and Salm in these proceedings), the Voellmy-Fluid law has the important advantage that a set of well-calibrated flow parameters exists. Recall that a Voellmy-Fluid law contains only two parameters: μ (dry-friction) and ξ (turbulent or viscous friction). Both the Voellmy-Salm model and the numerical models contain a third parameter, λ, the active-passive pressure coefficient (Salm, 1993).

Numerical models also have drawbacks. For example, they require a more detailed description of the avalanche release zone. They also generate large amounts of output data that is difficult to analyse. To be able to manage these new requirements, the numerical model has been integrated into a Avalanche Hazard Mapping System (AHMS). Because avalanches are a spatial phenomenon, the AHMS is based mainly on a Geographic Information System (GIS).

In order to judge the quality of the two implemented models and to calibrate the flow parameters, many extreme avalanches have been back-calculated. In this paper we present the important conclusions from this model evaluation. Two different examples for the model application are given: The one-dimensional model is applied to consider effects of terraces in a slope and the two-dimensional model is applied to perform a large-are avalanche hazard map in the Davos Region. In advance, we describe the AHMS that has been developed to work with the numerical models.

AVALANCHE HAZARD MAPPING SYSTEM

The kernel of the AHMS is a user interface that connects all different elements of the avalanche hazard mapping process. An overview of the system is given in Figure 1. The *Data Preparation*, the *Input Specification* and the *Hazard Mapping* tools are handled by the GIS-Software ARCINFO that provides also the main *User Interface*. The numerical simulation *Models* as well as their *Visualisation* tools are

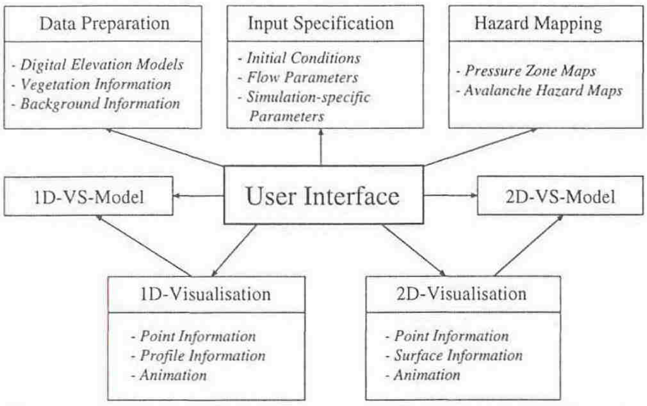

Figure 1:Overview over the Avalanche Hazard Mapping System (AHMS).

implemented using other software, but are directly connected to the *User Interface*. In the following sections, the different tools are described in more detail.

Data Preparation

A good digital representation of the topography is crucial for the accuracy of the model results. At present, in Switzerland a Digital Elevation Model (DEM) exists in a raster format with a spatial resolution of 25m (Swisstopo, 1998). During the evaluation it has been found that this resolution is not accurate enough – especially in steep gullies – for the numerical avalanche modelling, since important terrain characteristics are lost. Therefore, the DEM has to be improved in these regions by adding structure lines (rivers, ridges, gully bottoms) and additional altitude points.

As a second preparation feature, the AHMS allows the user to prepare all kind of thematic information (e.g. about forests, fields of large rocks) in order to easily assign this information directly to the flow parameter values.

An avalanche expert is accustomed to work with different maps as basic input. To give him the same background as when he would work with the analytical Voellmy-Salm model, it is possible to digitise and geo-reference maps. These can be projected on the background of the screen and enable the expert to define regions and lines on the screen in the same way as he would draw them with a pencil on a real map.

Input Specification

The input to the numerical Voellmy-fluid models can be divided into the following three categories:

(1) Initial conditions: Fracture Zone, Fracture Height.
(2) Flow parameters: Dry Friction μ, Turbulent Friction ξ, Active-Passive Pressure λ.
(3) Simulation specific parameters: Spatial Resolution of the Calculation, Time Step.

The AHMS allows the input specification for all parameters directly on the screen. The spatial parameters are determined using digitised map information as a background to ensure the correct spatial positioning. All spatial variable parameters are stored as ARCINFO files (ARCINFO, 1997).

For the initial conditions as well as for the flow parameter specification, the AHMS provides a semi-automatic procedure for every category. The principle of a semi-automatic procedure is: The expert must specify threshold values that are used by the AHMS to classify existing data, such as the DEM or vegetation information. Afterwards, the expert analyses the resulting classification. Based on this analysis, he can either restart the procedure using adapted threshold values or he can modify some part of the automatic classification interactively.

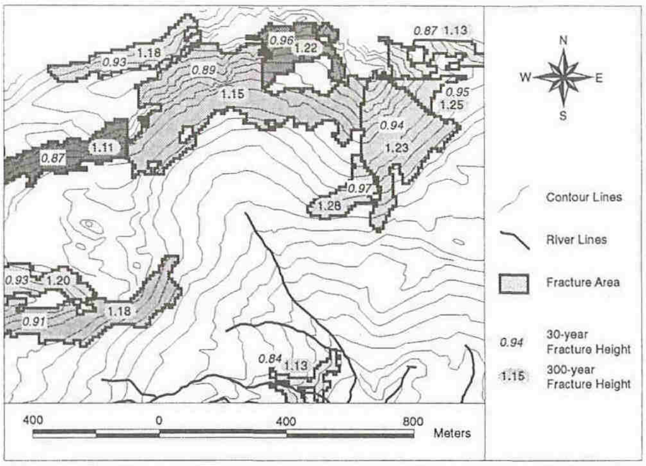

Figure 2: Example of a semi-automatic generated fracture zone definition. Topographic Data: © Swiss Federal Office of Topography.

The approach for the semi-automatic specification of the initial conditions will be illustrated using an example of the Davos region. The final result, providing information about the boundaries of several possible avalanche fracture zones as well as information about the assumed fracture height for an 30- and 300-year avalanche is shown in Figure 2. This classification is based on the threshold values listed in Table 1.

Lower/Upper Slope Limit:	30°/50°
Minimal Fracture Area:	5000m^2
Minimal Fracture Length:	50m
Fracture Area Separation Distance	20m
Maximal Snowfall Amount 30y/30	1.1m/1.5m

Table 1: Threshold values used for the semi-automatic initial condition definition approach in Figure 2.

The first four values are required to define the fracture zone boundaries using ARCINFO-GRID watershed and flow accumulation routines (for detailed description see Gruber, 1998). The maximal snowfall amount within a time period of 30 and 300 years are needed to calculate the fracture heights, which are based on the mean slope and altitude of every release zone (for exact calculation procedure see Salm and others, 1990).

Numerical Simulation Initiation and Visualisation

To start a numerical model, the user has to specify the required input in a form menu. For all constant parameters a number is required whereas for the variable parameters, the filename of the corresponding ARCINFO file has to be specified. For every simulation model one specific form menu exists that ensures a complete input. In a second step, the input data is converted into the format required by the chosen simulation program. After this conversion, the numerical model is initiated using the converted data as input. The conversion step has been implemented to be able to use exactly the same basic input files for all models.

To visualise the results of the one- as well as of the two-dimensional model, two different graphical visualisation tools have been developed. For the one-dimensional model, the results (i.e. flow-height, -velocity, -pressure) can be visualised along the profile (see Figure 3) and for the 2-dimensional model on a perspective surface representation (see Figure 4). It is also possible to check the exact values on every simulation element and to animate the flow of the avalanche.

Hazard Mapping

The most important result of the numerical models with respect to Avalanche Hazard Mapping is the spatial distribution of the maximal calculated dynamic pressures. The one-dimensional model gives only a distribution along the profile whereas the two-dimensional method provides also information about the thrust in all directions. A single pressure distribution of a simulation calculation can be classified into blue and red pressure zones (0.3kPa $\leq$ blue $<$ 30kPa $\leq$ red). The projection of these pressure zones on a topographic map is termed "Pressure Zone Map". To produce an Avalanche Hazard Map according to the Swiss Guidelines, it is necessary to combine the Pressure Zone Maps of 30-year avalanche simulations with the those of 300-year events (see Salm and others, 1990). All conversion and mapping steps can be easily performed using the AHMS. An example of a final Avalanche Hazard Map produced with the two-dimensional model is shown in Figure 5.

MODEL EVALUATION RESULTS

Both models have been evaluated in various avalanche sites (see Bartelt and others, 1997, Gruber, 1998). The results of these evaluations will be summarised in the following sections.

One-dimensional Model

A detailed description of the one-dimensional model is given in (Bartelt and others, 1998). Briefly, the governing differential equations describing avalanche motion are solved using upwinded finite differences schemes. The flow velocity and height are calculated for every point on the avalanche track. A model evaluation led to the flow parameter recommendations listed in Table 2 for large and small avalanche events. For comparison, the recommended parameter values of the Swiss Guidelines (Salm and others, 1990) are also listed.

Avalanche Volume [m^3]	Numerical Model		Swiss Guidelines	
	μ	ξ [m/s^2]	μ	ξ [m/s^2]
> 100'000	0.155	2000	0.155	1000
< 10'000	0.33	1200	0.3	1000

Table 2: Recommended Parameter Combination for the Use of the one-dimensional Numerical Model.

The numerical model uses almost the same μ-values as the classical Voellmy-Salm model, but a higher ξ-coefficient. There are several restrictions that must be made for the use of these parameters. Because of the fact that the numerical model is very sensitive to the fracture length, the recommended parameter combinations are only valid if the fracture length does not exceed 400m. For longer fracture zones, only the steepest 400m slope should be taken for the numerical calculations. Another result of the evaluation is that the above listed friction parameters are not valid for run-up calculations.

Two-dimensional Model

The two-dimensional model is a direct extension of the one-dimensional model. The implementation is described in (Sartoris and Bartelt, 1998). Although exactly the same flow laws are included, it is not possible to use the same flow parameter values as in Table 2. The main reason for this incompatibility is that the two-dimensional model is very sensitive to terrain.

In open slope, flat terrain, the two-dimensional model is not able to create one or more avalanche flow arms that follow a preferred flow direction. Instead of this, the model spreads out continuously over the whole unconfined area. For the avalanche hazard mapping process, this spreading can be seen as advantage, because it takes into consideration variations of the preferred flow directions. But physically, the model is incorrect since too much energy is lost during the spreading. The flow heights and dynamic pressures are underestimated. Therefore, to reach the runout distance of observed avalanches, it is necessary to decrease the friction to compensate for this effect.

In strongly confined terrain, on the other hand, the model accelerates the avalanche as it enters the channel and calculates too long runout distances. Bakkehøi (Bakkehøi and others, 1983) stated that the confinement of an avalanche track has no significant influence on the runout distance. He concluded that channelled tracks have higher friction. Following this assumption both friction parameters are increased in confined terrain configurations in order to reduce the velocity increase caused by the flow confinement.

During the evaluation work, the parameter combinations listed in Table 3 were found to be well suited for avalanche hazard mapping. Both parameters are strongly related to the terrain confinement. The planar curvature coefficient C serves to distinguish between different classes of confinement. It is calculated using the ARCINFO-GRID function "curvature" (ARCINFO, 1997). As for the one-dimensional model, parameters for large and small avalanche events are specified. For forested areas, the μ values

Confinement		> 100'000 m^3		< 20'000 m^3	
Description	$\lvert C \rvert$	μ	ξ [m/s^2]	μ	ξ [m/s^2]
channelled	> 3	0.33	1200	0.38	1200
confined	> 1.5	0.24	2000	0.30	1500
open, steep (>5°)	< 1.5	0.155	3000	0.25	2000
open, flat (<5°)	< 1.5	0.14	4000	0.23	3000

Table 3: Recommended Parameter Combination for the Use of the two-dimensional Numerical Model. |C|: Curvature Coefficient of the Terrain.

of Table 3 are chosen and a constant ξ-value of 400m/s^2 (according to the Swiss Guidelines (Salm and others, 1990)) must be specified independently of the terrain.

APPLICATION EXAMPLES

Two different examples have been chosen to demonstrate the wide range of application possibilities for numerical models. One example is a very specific study about the influence of terrain terraces to slow down an avalanche in a runout zone, whereas in the other example the two-dimensional model is used for large area hazard mapping.

Terrace Study in the Lötschental Valley

An avalanche track in the Lötschental-Valley frequently endangers an important road. Several possibilities to protect this road have been proposed by a local engineering office. One of this proposals was to terrace the terrain at the beginning of the runout zone. The one-dimensional model has been chosen to quantify the effect of this terraces, because it allows an easy integration of the planned terraces into the slope profile and a direct comparison of avalanche simulations with and without the terrain modifications.

The analysis has been performed for different avalanche frequency assumptions according to the Swiss Guidelines. For extreme avalanche events with return periods of equal or more than 30 years, it was found that the terraces have only a very minor influence on the runout distance. The velocity difference between the two simulations did not exceed 2m/s on the slope following the terraces: the road would be reached by the avalanche. However, for smaller avalanches – especially for avalanches with return periods of less than 5 years – the influence of the terraces is considerable. In Figure 3, a comparison of the simulations of a small avalanche with and without terraces is shown. The flow height of the avalanches is shown at two time steps (98.4s, 112.2s). In addition the maximum flow velocities along the profile of both calculations are overlaid. The terraces cause the avalanche to stop before the steep slope at the end of the profile section in Figure 3. The avalanche on the existing slope passes the flat area and accelerates on the steep slope again.

Based on these calculations we believe that on this particular avalanche track, terraces would help reduce the frequency that avalanches bury the road. However, in critical situations, where a large avalanche could occur, the road must be closed since the terraces provide no extra protection.

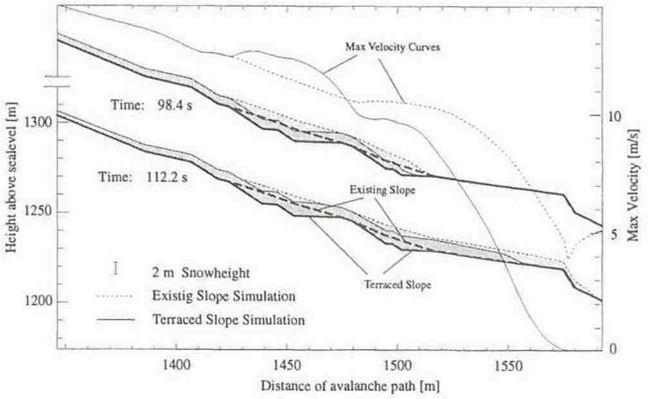

Figure 3: Comparison of a simulation with and without of terraced terrain of a small avalanche event.

Large Area Hazard Mapping in Davos

Due to the location of the SFISAR, the occurrences of avalanches in the Davos region have been well documented and allow a good estimate of the accuracy of an avalanche hazard map. Different types of terrain configurations, from steep gullies to open slopes exist, so that a model is also confronted with this different terrain characteristics. Additionally, the large extent of the Davos area demands a method that performs many steps automatically.

In a first step, the initial conditions have been defined for the whole area using the release zone procedures described above with the threshold values listed in Table 1. In all cases, the calculated fracture heights have been used for the numerical calculations. However, the automatic procedures often generate release zone areas that are either too small or too large. These areas had to be adjusted manually in order to make them realistic. Too large areas had to be split into smaller fracture zones; too small areas had to be merged together. After these modifications, all release zones are classified according to their fracture volume into large, medium and small avalanche events.

All parameter values have been calculated automatically using the DEM and information about the forests. For the 300-year avalanche simulations, the values of Table 3 have been chosen. For the medium avalanche event class, linearly interpolated values are used. For the 30-year avalanche simulations, the μ values of Table 1 were increased by 0.02, in order to take into account the smaller avalanche volume.

The numerical simulations were performed by the two-dimensional model because with the one-dimensional model it would have been necessary to specify for every release zone an avalanche width. This is problematic and time consuming. Out of all the calculations for every release zone, the large avalanche event of "Arelen" has been chosen to illustrate some results, since this track involves a confined as well as an open slope part and contains also forested areas. In Figure 4 the spreading of the avalanche is shown at the entrance into the open slope runout area. In Figure 5 the final avalanche hazard map resulting out of the combination of the 30- and 300-year avalanche simulation is shown. For comparison the boundary of an extreme

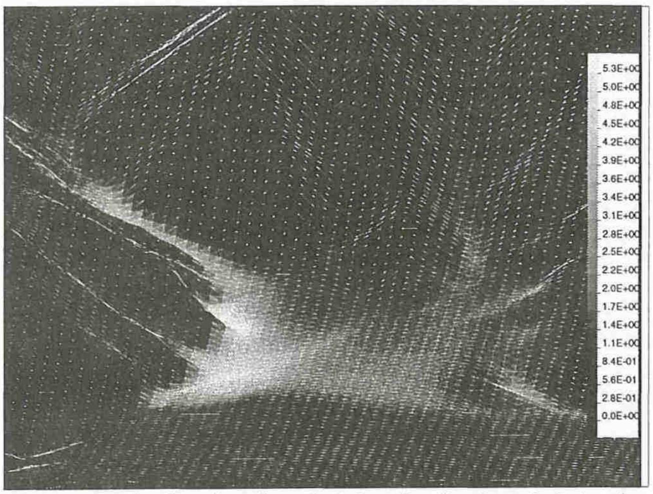

Figure 4: Avalanche flow height distribution [m] in the Arelen track at the entrance into the runout (60s after the release). Perspective view from east to west (see Figure 5). Topographic Data: © Swiss Federal Office of Topography.

avalanche event of the year 1968 is overlaid. The extent of the lateral spreading of the simulated avalanche is in good agreement with the real avalanche but the avalanche in 1968 had arm-like deposits. The simulation predicts a too continuous spreading in the runout zone.

Although the maximum runout distance of the avalanche of 1968 was underestimated by 100m, the simulation results provide a good idea to the avalanche expert how to define the avalanche hazard zones. The only "subjective" expert knowledge that was necessary to produce this map was to merge three release zones proposed by the semi-automatic procedure in order to release them simultaneously. This expert knowledge was based on the observations of the avalanche event of 1968.

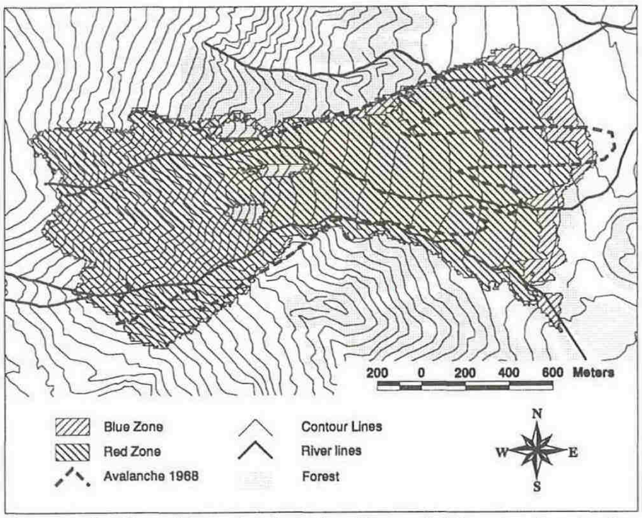

Figure 5: Resulting Avalanche Hazard Map in the Arelen Site, including an overlay of a real avalanche boundary of the year 1968. Digital Elevation Model: © Swiss Federal Office of Topography.

As in Arelen, the avalanche hazard maps in the other areas are in most cases in good agreement with observed avalanches. The problematic cases occur primarily in very flat runout zones, where the spreading is obviously too wide, or below steep gullies, where the flow parameters are not accurate enough.

CONCLUSIONS

In spite of the fact that the numerical model is using only a very simple Voellmy-fluid flow law, both the one- and two-dimensional models can be used as a tool by avalanche experts to estimate the degree of avalanche hazard. They can be applied in detailed studies as well as in large scale avalanche mapping tasks.

Different deficiencies of the classical Voellmy-Salm Model have been eliminated. For example, using the two-dimensional model, no assumptions regarding the width of the avalanche must be made. Together with the semi-automatic procedures to define the initial conditions and the flow parameters, the two-dimensional numerical model reduces tedious input of the avalanche expert to a minimum. Expert knowledge, however, is still very much required.

The development of the numerical models must carry on, especially with respect to the lateral spreading of the avalanches and the model behaviour in run-up zones. The Avalanche Hazard Mapping System contributes to this research by allowing the integration of other numerical or statistic-topographical models in a way that they can be compared to each other using the same input data.

REFERENCES

ARCINFO, 1997. ARCINFO Reference Manual, Version 7.1.2. Environmental Systems Research Institute, 380 New York Road, Redlands, CA 92373-8100, USA.

Bakkehøi, S., Domaas, U. and Lied, K., 1983. Calculation of Snow Avalanche Runout Distance. *Annals of Glaciology*, Vol. **4**, S. 24-29.

Bartelt, P., Gruber, U., and Salm, B., 1997. Numerical Modeling of Dense Snow Avalanches Using Upwinded Finite Difference Methods. *Internal Report of the Swiss Federal Institute of Snow and Avalanche Research*, No. 716, Davos, Switzerland.

Gruber, U., 1998. Der Einsatz numerischer Simulationsmethoden in der Lawinengefahrenkartierung: Möglichkeiten und Grenzen. *Dissertation*, Geographisches Institut der Universität Zürich.

Salm, B., Burkard, A. und Gubler, H.U., 1990. Berechnung von Fliesslawinen. Eine Anleitung für den Praktiker mit Beispielen. *Mitteilungen des Eidg. Inst. für Schnee- und Lawinenforschung*, Nr. 47, Davos.

Salm, B. 1993. Flow, flow transition and runout distances of flowing avalanches, *Annals of Glaciology*, **18**.

Sartoris, G. and Bartelt, P., 1998. Upwinded finite difference schemes for 2-dimensional dense snow avalanche modeling. *Internal Report of the Swiss Federal Institute of Snow and Avalanche Research*, Davos, Switzerland (in preparation).

Swisstopo. 1998. Swiss Federal Office of Topography. Product Information. *http://www.swisstopo.ch.*