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AVAL-1D: AN AVALANCHE DYNAMICS PROGRAM FOR THE PRACTICE

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ABSTRACT

Avalanche hazard maps are prepared by engineers and land use planners. These experts rely both on practical experience and calculation models to predict avalanche runout distances and flow velocities. Both dense flow and powder snow avalanche dynamics models are using sophisticated numerical schemes to track the motion of avalanches from initiation to runout. Since avalanche experts are seldom numerical specialists, the software must be stable and user-friendly and model limitations must be clearly communicated. In this paper we present a new avalanche dynamics program called AVAL-1D that meets these requirements. This program is intended to be used by avalanche practitioners to supplement the well-tested Voellmy-Salm model. In the following we discuss the program structure and present an example calculation with the new program.

KEYWORDS: avalanche hazard maps, avalanche dynamics, numerical modelling, dense flow avalanche, powder snow avalanche

INTRODUCTION

The preparation of a hazard map involves six main steps:

1. Review of the historical avalanche cadastre.
2. Field visits and analysis.
3. Determination of climatic conditions such as new snow depths, main wind directions and snow drift conditions.
4. Determination of avalanche type and return period.
5. Avalanche dynamics calculations.
6. Final hazard map preparation based on all above mentioned steps. The practical experience of the expert plays an important role in this final analysis.

The extreme avalanche winters of 1951 and 1999 clearly demonstrated the importance of the fifth step, avalanche dynamics calculations, in preparing hazard maps for snow avalanches (SLF, 1951,

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2000). Since 1955 these calculations have been performed primarily using the analytical Voellmy-Salm model (Voellmy, 1955), (Salm, 1966, 1968). This model, after many years of validation and calibration, was finally embedded in the Swiss Guidelines for Avalanche Runout Calculation in 1990 (Salm et al., 1990).

The Voellmy-Salm model is well-liked by practitioners. Firstly, because it is simple to use. It requires only a few input parameters, i.e. the fracture depth, the slopes of the avalanche path (which is divided into three sections; release, acceleration and runout zones), the magnitudes of the model's two friction coefficients (dry friction ? and turbulent friction ?) and the location where the avalanche reaches it's terminal velocity (point P). Secondly, and perhaps more importantly, practitioners who solve avalanche dynamics problems do not have the expectation that a calculation model provide them with stupidly accurate velocity and runout results. In their opinion complicated models are not justified considering the uncertainties of an actual avalanche dynamics problem.

However, there are many cases where the model over-simplifies avalanche flow (one-directional flow with constant width, steady flow, constant mass, plug flow) by far. Another disadvantage of the Voellmy-Salm model is that it can not be used to calculate the dynamic pressures of powder snow avalanches. A practical, easy-to-use powder snow avalanche model has been failing in Switzerland and, in view of the damage caused by powder snow avalanches in 1999, is of considerable economic importance (SLF, 2000).

Flowing and powder snow avalanche models that supplement the Voellmy-Salm calculation procedure have been under development for some time (Issler, 1998), (Bartelt et al., 1999). These one-dimensional computer-based models have now reached a level of development where they can be introduced to practitioners.

PROGRAM REQUIREMENTS

In order to introduce a program into the practice, the software should meet – based on our experience in Switzerland - the following requirements:

- **Model Validation** : New calculation procedures cannot be introduced into practice without extensive model validation. Users must understand how the model functions in order to apply the model correctly. The limitations of the model must clearly be communicated, especially since both the flowing and powder snow avalanche models are based on many assumptions, several of which are debatable. Model validation implies defining parameter sets i.e. model guidelines that the user can refer to when solving actual problems.
- **User-friendliness**: Users are accustomed to working with "what you see is what you get" software. Tedious input procedures and non-graphic output are no longer acceptable. Furthermore, the calculations will be performed by land use planners and engineers who will not work exclusively with the software; they do not have time to relearn the program for every application. The program input - for example, the specification of the avalanche track - must be intuitive and self-explanatory. The results of the calculations will be placed in reports which will be read by non-experts in order to make political decisions. The program output - both graphical and hardcopy - must therefore be clear and understandable.
- **Program Stability**: Numerical solution procedures must be chosen to solve the system of partial differential equations which are both accurate and stable. Most avalanche professionals don't have the know-how required to resolve numerical difficulties.

- Another question which must be addressed is why develop and support a one-dimensional model when both two- and even three-dimensional numerical models with sophisticated GIS interfaces (Gruber et al., 1998) exist that could be applied to solve practical problems. Powder snow and unchannelled flowing avalanches are clearly two- and three-dimensional phenomena. Besides, one-dimensional models have the disadvantage that the user must select the avalanche path - often in very difficult three-dimensional terrain. Why not introduce more realistic models into practice? Our answer is threefold:
- **Conservative Calculations**: Observations of avalanche runout zones in 1999 often showed that when a flowing avalanche entered the runout zone it did not laterally disperse. Rather it flowed in one or more "arms" of almost constant width. The present generation of two-dimensional numerical models are firstly not able to model this effect and, secondly, underestimate the runout distance because the flow energy is not used to drive the avalanche forward, but to spread it too much sideways. Therefore, it is - and will probably always be - necessary to determine or, at least check, runout distances using one-dimensional models (see dense flow example). Two-dimensional models can be used to establish the course of the avalanche given a terrain and starting zone.
- **Cost Effectiveness**: Land use planning offices cannot afford the expensive hardware and software required for complicated two- and three-dimensional simulations. We doubt that the money generated from avalanche dynamics calculations alone would ever be enough to finance such a large investment. Larger firms clearly have an advantage over smaller firms. Since AVAL-1D is installed on a PC and it's price corresponds roughly to the cost of one engineering expertise, both large and small firms can afford the software. Our goal as a federal agency is to create fair competitive practices by allowing smaller (one man) firms to compete with larger companies. This practise arises because we previously supplied practitioners with hand calculation procedures that required no investment costs.
- **User Know-How**: It is likely that the future of avalanche dynamics calculations is with two- and three-dimensional models. However, at present, practitioners do not have the know-how to apply these models. We stress that avalanche hazard maps are not prepared solely on the basis of simulation results. Each of the six steps listed in the introduction are of equal importance. We do not want to change this well-based strategy. The application of two- and three-dimensional codes requires numerical specialists who are usually not familiar with the local terrain and meteorological conditions. We regard a one-dimensional program - which has many similarities with the old Voellmy-Salm model - as an important and essential first step in bringing practitioners into contact with numerical models.

The purpose of this paper is to present AVAL-1D, an avalanche dynamics program that we have developed at the SLF. We do not want to stress the details of the actual avalanche dynamics models - which have been presented elsewhere (Issler et al., 1998), (Issler, 1998), (Bartelt et al., 1999) - rather the software system as a whole. The problem we want to address directly is the difficulty of introducing numerical models in practice.

PROGRAM STRUCTURE

AVAL-1D consists of three components: a one-dimensional flowing and a powder snow avalanche calculation module connected by a graphical user interface. One-dimensional refers to the fact that a single velocity component parallel to the avalanche track is used to describe the motion of both the flowing avalanche or powder snow saltation and suspension layers. The avalanche track is described by a two-dimensional topography with known width (flowing avalanches) or unit width (powder snow avalanches). The two avalanche models, FL-1D and SL-1D, were developed in C. The graphical user-interface was programmed in IDL (Interactive Data Language), a portable software for data analysis and visualization.

Dense flow model (FL-1D)

FL-1D is a quasi one-dimensional, hydraulics-based, depth-averaged continuum model (see Fig. 1). It tracks the motion of the avalanche (velocities, snow heights, pressures) from initiation to runout. The model is based on several important assumptions:

1. Flowing snow is modelled as a fluid continuum of mean constant flow density.
2. The flow width is known.
3. A clearly defined top flow surface exists.
4. The flow height is the average flow height across the section, i.e. the flow height is level over the flow width.
5. The vertical pressure distribution is hydrostatic. Centripetal pressures which modify the hydrostatic pressure distribution are not accounted for.
6. Flow velocity and depth is unsteady and non-uniform.
7. The avalanche mass is constant and no entrainment processes are modelled.

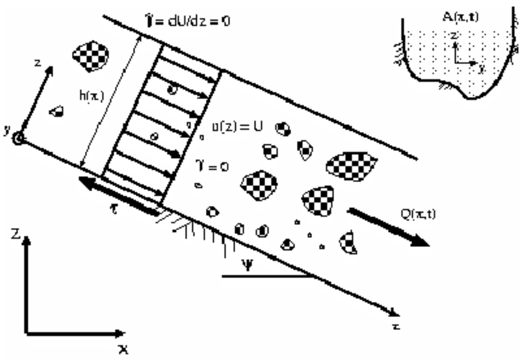

Fig. 1 Avalanche flow is described by two scalar fields A(x,t) and Q(x,t). The first field A(x,t) represents the cross sectional flow area at x and time t and the second field Q(x, t) gives the average snow discharge along the mountain profile (Bartelt et al., 1999). A Voellmy-fluid flow law is applied that assumes no shear strain-rates in the avalanche flow plug.

The differential equations are solved numerically using first and second order upwinded finite difference schemes. For details see Sartoris and Bartelt (2000).

The model employs a Voellmy-fluid flow law. This law assumes that the shear strains in the flow body are small and that the flow resistance is concentrated at the base of the avalanche. This resistance is given by a dry-Coulomb type friction (?) and a velocity squared (Chezy) friction (?). The magnitude of the two friction parameters is defined and based on extensive model calibration with observed field events, see Bartelt et al. (1999). Tensile and compressive longitudinal straining of the flow plug is resisted by active and passive pressures, respectively.

The primary difference between the numerical model and the analytical Voellmy-Salm calculation procedure is that the avalanche flow is instationary. The location of the terminal flow velocity must not be selected by the user. Flow heights, especially in the runout zone are smaller. The model has been extended to include other flow laws - including the Russian and Norwegian models. For more details, see Bartelt et al. (1999).

Powder snow model (SL-1D)

Following Norem's description of powder snow avalanche formation and structure (Norem, 1995), SL-1D consists of a suspension layer and a so-called saltation layer (see Fig. 2). The latter is only a few meters deep and is modelled by depth-averaged mass and momentum balances. In the suspension layer, the mass and momentum balance equations for the mixture are supplemented by the snow mass balance and the transport equations for turbulent kinetic energy and dissipation. Mass and momentum exchange between the two layers is determined by particle settling, turbulent diffusion against the concentration gradient, and aerodynamic shear forces. The net erosion or deposition rate is a function of the kinetic energy of the impacting particles. The saltation layer acts back on the suspension layer in that saltating particles extract momentum from the air flow. The preliminary estimates of the model parameters can be refined by means of saltation trajectory simulations. Three-dimensional simulations with a simplified model clearly showed the importance of snow erosion and deposition in practical applications. This approach is well suited for coupling to a dense-flow avalanche model. For more details about the model and the validation see Issler et al. (1998), Issler (1998) and Förster (2000).

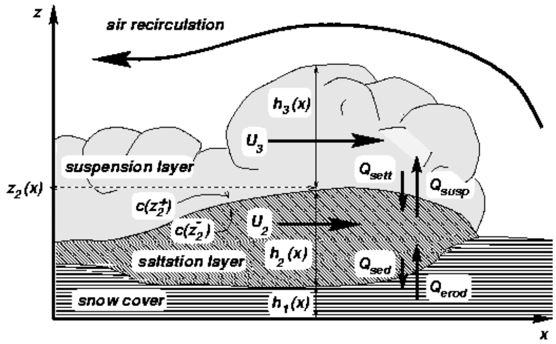

Fig. 2 Schematic view of the structure of a powder snow avalanche according to Norem (1995). Some quantities relevant to the model are also indicated. Subscripts 1, 2, 3 on field variables generally refer to the snow cover, saltation layer and suspension layer, respectively (Issler 1998).

Graphical user interface

Emphasis was placed on developing an easy-to-use graphical user interface, containing both the possibility to calculate dense flow or powder snow avalanches. It is used to specify the required input data (topography, model and calculation parameters, initial conditions) and visualize output results, such as runout distances, dynamic pressures and flow velocities.

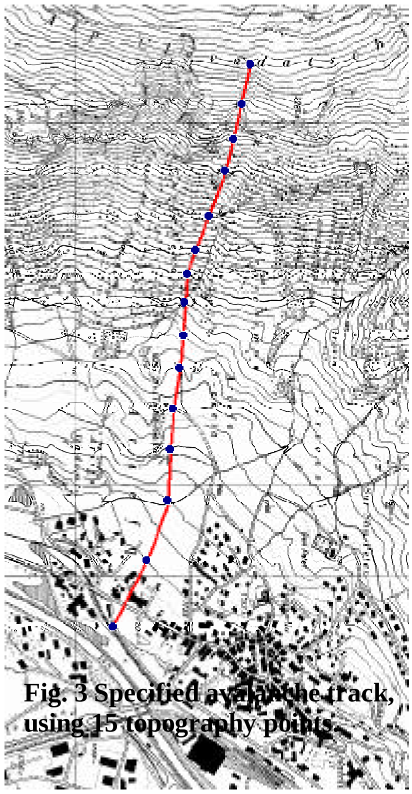

Fig. 3 Specified avalanche track, using 15 topography points

Program input

There are three possibilities to specify a new topography:

1. By studying the avalanche track on a map, writing down the elevation and coordinates of all the topography-points and using the topography editing dialog window to specify all the points, interactively one by one.
2. By studying the avalanche track on a map, writing a text file on the computer (containing the elevation, the coordinates and the width of the avalanche in every point) and reading this text file with AVAL-1D.

3. By using a digitalized map of the avalanche area and specifying the avalanche track directly (see Fig. 3). Therefore the digitalized map has to be georeferenced by four points and AVAL-1D executes a coordinate-transformation. The user has then to click along the contour lines and to enter the altitudes manually, because no digital terrain-model is used.

Figure 3 illustrates the third possibility to create a new topography, showing the selected avalanche track with all the topography points marked.

After the terrain has been specified, the model parameters (which differ between dense flow and powder snow problems) must be defined using a dialog window as shown in Fig. 4. In another dialog window the calculation parameters can be changed in order to refine the element size along the avalanche track or to adapt the calculation time or time step. By pushing a calculation button, either a dense flow or a powder snow calculation will be performed, displaying the results after the calculation directly within the user interface.

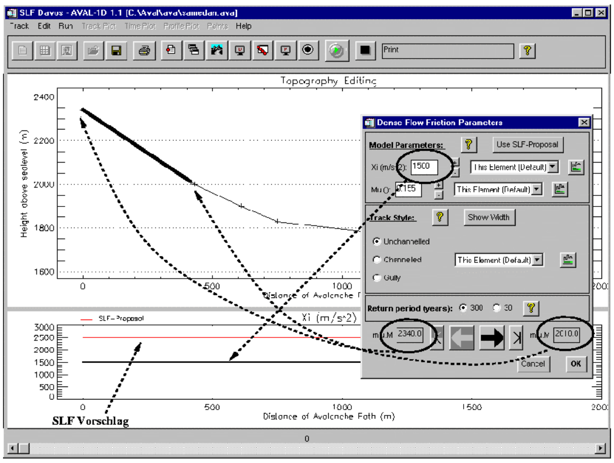

Fig. 4 Top: Topography window, points are marked with crosses; Bottom: parameter window, model parameters can be visualized.

Program output

Some of the most important output features of AVAL-1D are:

- Possibility to stop the simulation at a certain altitude and continue with decreased or increased amount of snow-mass (see dense flow avalanche example). Simulations of ‘avalanche arms’.
- Results are provided along the entire avalanche track, not only at specific points (in contrary to the analytical Voellmy-Salm model).
- Animation of avalanche flow.
- XY-Plots at user-selected points along the avalanche track (plots over time).
- Profile plots at user-selected points (only for powder snow avalanches).
- Possibility to overlay different simulation runs to visualize sensitivity studies.
- Log-files to summarize the most important simulation results.
- Possibility to create TIFF-, GIF-, BMP- and EPS-files of all output results.

Of course additional functions like zooming, scaling and annotations are also possible to adapt a graph to individual demands.

Program help

AVAL-1D provides the user with a help menu, where he can find information on how to use AVAL-1D, and help on choosing the model parameters. More help is available in the user manual and on the internet, where an AVAL-1D-Homepage exists with frequently asked questions (FAQ) and problem descriptions. Example calculations show how to use the program in difficult situations.

EXAMPLES

Dense flow avalanche: Holderlilaui, Canton Bern, Switzerland

The Holderlilaui avalanche occurred on February 1999. In this example calculation we have tried to back-calculate the avalanche perimeter of above event. At the beginning of the runout zone (at an altitude of 1160m a.s.l.) the Holderlilaui avalanche split into three paths. This clearly is a two-dimensional problem, which until now could not be solved satisfactorily. AVAL-1D is able to treat this problem and provide a solution for practitioners.

The paths are numbered 1 to 3 from west to east (see Fig. 6). It was assumed that after the avalanche emerged from the channelled path at 1160m a.s.l., the total mass was divided between these three distinct paths. A control simulation was run where the entire release mass ran down the centre path. The total fracture depth was assumed to be 1.22m according to the Swiss Guidelines. Test runs have indicated that it is not realistic to model the three paths separately using an estimated (reduced) release fraction of snow for each avalanche path. The velocities of the simulated avalanches will be too low and the avalanches may be underestimated.

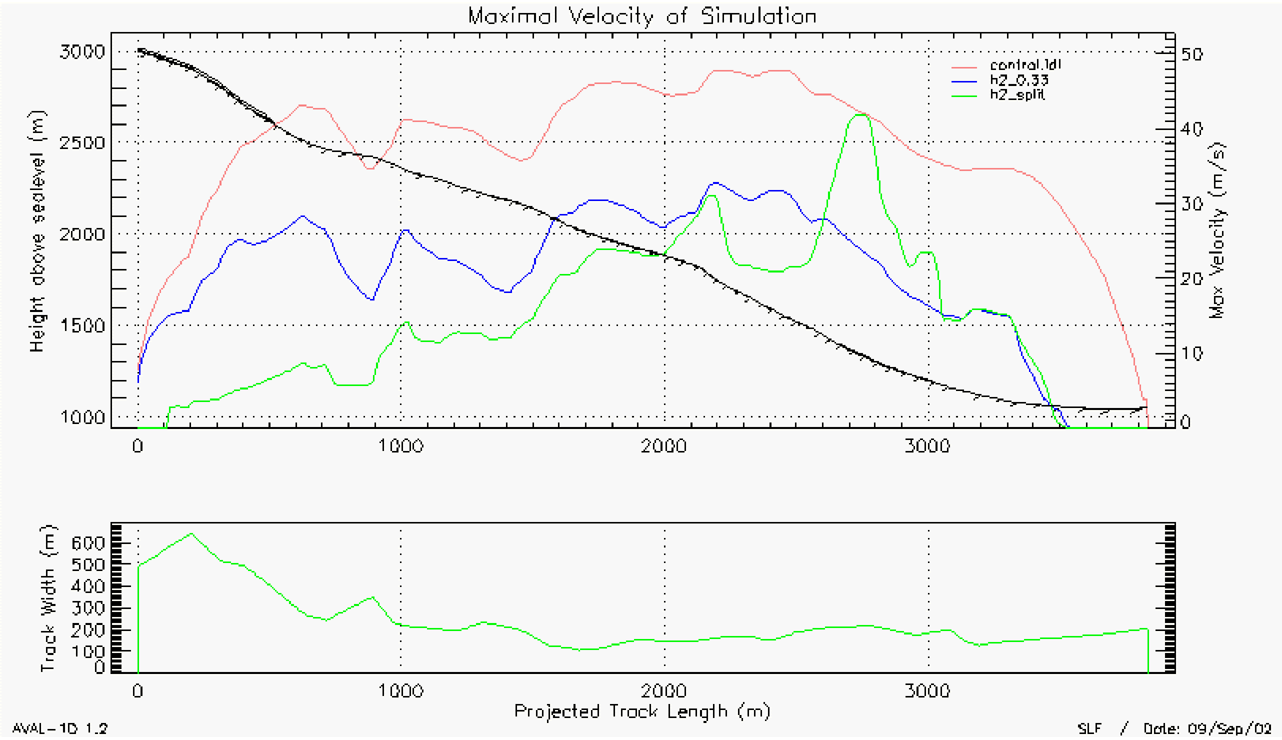

Fig. 5 A comparison between maximum velocities of control simulation (control.idl), a run with reduced (33%) release mass (h2_0.33) and the split simulation (h2_split, 15% from point 1160m a.sl.).

AVAL-1D solves this split avalanche path problem by running the simulation using all the snow mass in the release zone, as for a normal avalanche calculation, then stop the simulation at the point where the avalanche paths diverge. The snow depths and velocities can then be exported, the snow depths reduced (while keeping the same velocity) and the simulation restarted along one of the new paths. The reduction of snow depth is done according to the amount of snow that can be estimated to go into one of the new directions. In this calculation it was assumed that 35% will go into path 1, 15% into path 2 and 50% into path 3 (a comparison between the control simulation, a simulation with reduced release mass and the split avalanche for path 2 is shown in Fig. 5). This simulates avalanche splitting more realistically since the avalanches will have the same initial velocities after the divergence point. The three paths and the stopping points of the simulations down each path as well as the stopping point of the control simulation using the complete snow mass from the release zone is shown in Fig. 6. The simulation results show a very good agreement with the observed avalanche perimeter from 1999.

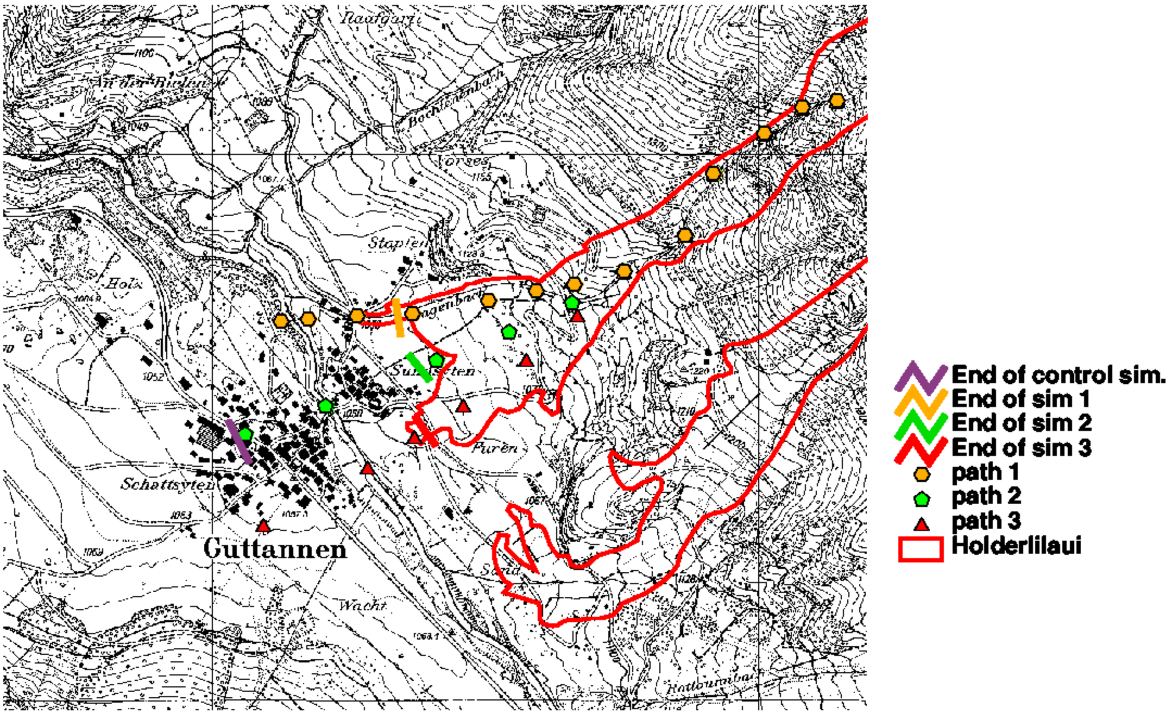

Fig. 6 Map showing the three paths in the runout zone of Holderlilaui. The stopping points of the control simulation and the split simulations are marked.

Powder snow avalanche: Avalanche Test Site 'Vallée de la Sionne, Switzerland'

Vallée de la Sionne is located immediately to the north of the Canton capital of Sion in the French speaking western part of the Canton of Valais. The test site is used to study basic processes in avalanches (flow regimes, snow entrainment and deposition, etc.) in order to improve avalanche dynamics models. In this example calculation two simulation runs were performed, in an attempt to back-calculate the velocities of the avalanche dated January 30th 1999.

Ideally the initial conditions for a powder snow avalanche calculation would be the same as for a flowing avalanche calculation, i.e. the specification of the fracture slab dimensions. The fracture depths of 1.0m for a 30 year return period and 1.4m for a 300 year avalanche were defined according to the Swiss Guidelines. In AVAL-1D the initial mass of both the saltation and suspension layers must be specified by assuming an initial snow density and suspension rate. These values depend on geographic region, elevation, slope angle, snow properties and flow velocities (recommended values are provided with AVAL-1D).

The two simulations were (1) a 300 year avalanche and (2) a 30 year avalanche. The initial density was assumed to be 200 kg/m^3, the suspension rate 10% and the erodible snow height was estimated to be 1m overall. The density of the erodible snow layer was also 200 kg/m^3. The erodibility was chosen according to the SLF-recommendations.

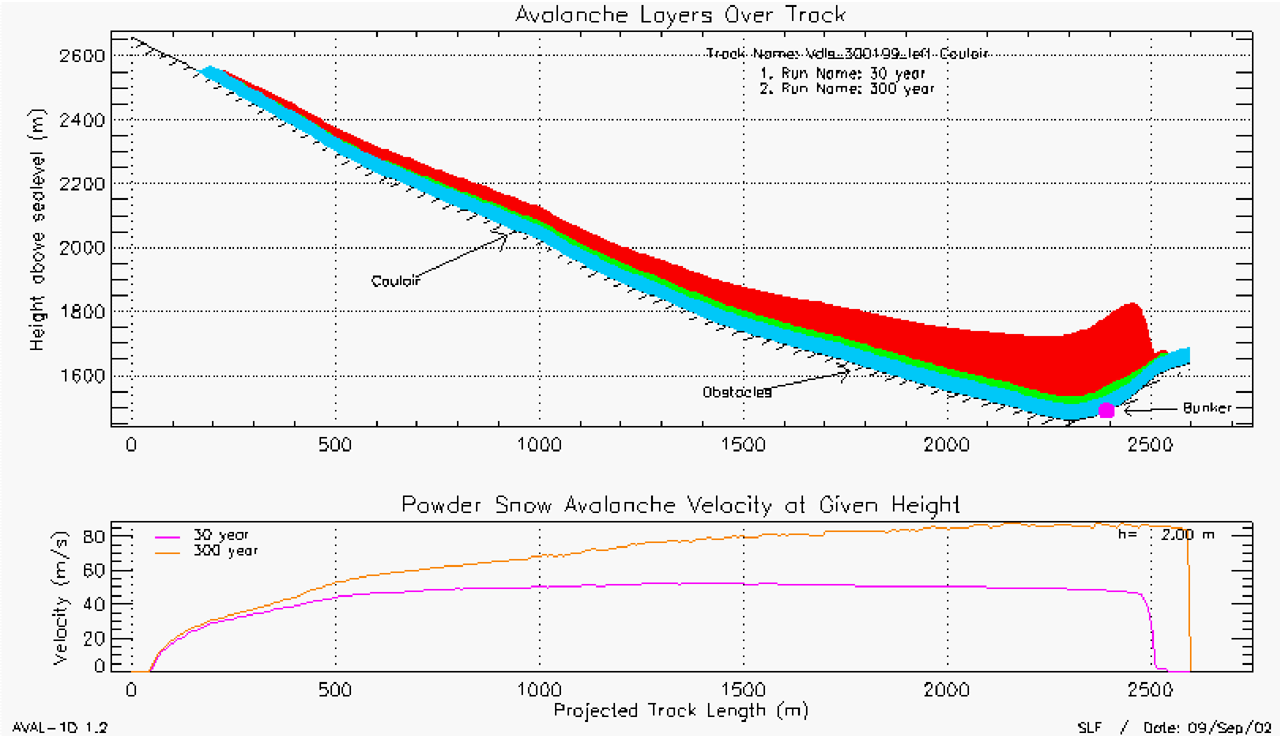

Fig. 7 Upper window: Snowcover (blue), saltation layer (green) and suspension layer (red) with three points of interest (couloir, obstacles and bunker). Lower window: Maximum velocities at a height 2m above the ground for 30 year and 300 year avalanche.

Table 1, Fig. 7 and Fig. 8 show the simulation results. Fig. 7 is typical program output. The upper window illustrates the three snow layers; snow cover, saltation layer and suspension layer. In the lower window the maximum velocities at a height 2m above the ground are compared for 30 and 300 year avalanche simulations.

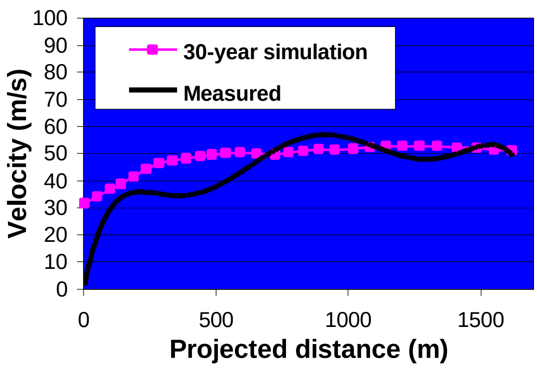

Fig. 8 Measured and simulated velocities along the Vallée de la Sionne avalanche track.

Comparing the simulated and measured velocities in Fig. 7 and Table 1, we recognize that the avalanche dated January 30th 1999 must have been a 30 year avalanche, because the 300 year simulation results are much too high. The 30 year results for the obstacles and the bunker are in good agreement with the measurements. Fig. 8 shows measured and simulated velocities along the avalanche path. At the start of the track the simulated velocities are higher than measured, further on they fit well.

Table 1 Simulated and measured (mean) velocities, v(m/s) at three points; couloir, obstacles and bunker. T(s) indicates the time elapsed since release.

Velocities	300 year		30 year		Measured	
(m/s)	v (m/s)	t (s)	v (m/s)	t (s)	v (m/s)	t (s)
Couloir	66.0	27	49.2	30	58.0	37
Obstacles	83.5	45	50.8	55	50.0	52
Bunker	88.5	55	48.1	71		72

On February 25th 1999 the largest powder snow avalanche of the test series was triggered in Vallée de la Sionne. Studying velocities, suspension heights and runout distance, this avalanche clearly was a 300 year avalanche. At the obstacles, velocities of up to 80 m/s were obtained which corresponds very well with the 300 year simulation results (see Table 1, 300 year simulation).
In general, good agreement in velocity was obtained with AVAL-1D. Further validations with pressure forces and suspension heights must be performed.

CONCLUSIONS

AVAL-1D represents the first attempt to introduce numerical avalanche dynamics models to the general practice. We envision that the program will be applied to solve problems where existing calculation procedures are clearly inadequate; for example, the calculation of powder snow avalanches. Our goal is to provide snow avalanche professionals with a simple, stable and well calibrated tool. The software is user-friendly and not expensive. Avalanche track profiles can be easily generated from maps and a wide range of output results can be visualized graphically. Not only computer experts can handle the program, but also users with little computer knowledge are able to operate AVAL-1D. However, although the program is easy to use, the demands on the user are still high: Considerable snow avalanche know-how is required to correctly select the avalanche track, starting conditions and the correct flow parameters.

In the future, improved avalanche dynamics models will be implemented in the program. Presently, work is underway to combine the dense flow and powder snow avalanche models as well as to implement snow entrainment into the dense flow part.

REFERENCES

Bartelt, P., B. Salm and U. Gruber. (1999) Calculating dense-snow avalanche runout using a Voellmy-fluid model with active/passive longitudinal straining. *Journal of Glaciology*, **45**, No. 150, 242-254.

Förster, M. (2000) Ausführliche Dokumentation ausgewählter Staublawinenereignisse und Bestimmung ihrer Eingangsparameter für die Verifikation von Staublawinenmodellen. *Interner Bericht des Eidgenössischen Institutes für Schnee und Lawinenforschung*, No. 730, Davos, Switzerland.

Gruber, U., P. Bartelt and H. Haefner. (1998) Avalanche hazard mapping using numerical Voellmy-fluid models. In Hestnes, E., ed. *Proceedings of the Anniversary Conference 25 Years of Snow*

Avalanche Research, Voss, 12-16 May 1998. Oslo, Norwegian Geotechnical Institute, 117-121. (Publication 203).

Issler, D. (1998) Modelling of snow entrainment and deposition in powder-snow avalanches. *Annals of Glaciology*, **26**, 253-258.

Issler, D., P. Gauer and M. Barbolini. (1998) Continuum models of particle entrainment and deposition in snow drift and avalanche dynamics, In Balean, R., editor. Models of Continuum Mechanics in Analysis and Engineering. *Proceedings of a conference held at the Technische Universität Darmstadt, September 30 to October 2, 1998*. Achen - Maastricht, Technische Universität Darmstadt, Shaker Verlag.

Norem, H. (1995) Shear stresses and boundary layers in snow avalanches. *Technical Report 581240-3*. Oslo, Norway, Norges Geotekniske Institutt.

Salm, B. (1966) Contribution to avalanche dynamics. *International Association of Scientific Hydrology Publication* **69** (Symposium at Davos 1965 - Scientific Aspects of Snow and Ice Avalanches), 199-214.

Salm, B. (1968) On nonuniform, steady flow of avalanching snow. *International Association of Scientific Hydrology Publication* **79** (General Assembly of Bern 1967 - Snow and Ice), 19-29.

Salm, B., A. Burkard and H. Gubler. (1990) Berechnung von Fliesslawinen, eine Anleitung für Praktiker mit Beispielen. *Mitteilungen des Eidgenössischen Institutes für Schnee und Lawinenforschung*, No. **47**, Davos, Switzerland.

Sartoris, G. and P. Bartelt. (2000) Upwinded Finite Difference Schemes for Dense Snow Avalanche Modeling. *International Journal for Numerical Methods in Fluids*, **32**, 799-821

SLF. (1951) Winterbericht 1951. *Winterberichte des Eidg. Institut für Schnee- und Lawinenforschung*, Nr. **15**, Davos.

SLF. (2000) Der Lawinenwinter 1999. *Ereignisanalyse*. Eidg. Institut für Schnee- und Lawinenforschung, Davos.

Voellmy, A. (1955) Über die Zerstörungskraft von Lawinen. *Schweizerische Bauzeitung*, Jahrg. 73. Heft **12**, 159 - 162, 15, 212 - 217, 17, 246 - 249, 19, 280-285.