Conclusions from a recent survey of avalanche computational models

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ABSTRACT. In this paper we summarise a survey report on computational models for snow avalanche motion that was developed within the frame-work of the EU research project SAME (Snow Avalanche Modelling, Mapping and Warning in Europe).

An examination of existing models shows that: (1) there is not - and probably never will be - a single model that adequately describes all avalanche types; (2) in order to account for the extraordinary variability of avalanche motion in response to initial and boundary conditions, flow-regime transitions and the snow mass balance should be properly described in future models; (3) calibration and validation of these models will require a comprehensive measurement programme; (4) determination of realistic initial conditions is a serious problem. We suggest that using simple models to scan the relevant parameter space with more advanced models for detailed simulations of selected scenarios could improve this situation.

Finally, we discuss the needs for, and benefits of, a co-ordinated programme of avalanche research. The main features of the SAME proposal for an extensive joint experimental programme are described. We suggest that international collaboration could produce high-quality models covering all essential practical needs. Increased interdisciplinary collaboration would be advantageous for model development and facilitate incorporation of other scientific disciplines.

INTRODUCTION: GOALS OF THE SAME PROJECT

SAME (Snow Avalanche Modelling, Mapping and Warning in Europe) is a project within the 4th Framework Programme for Research and Technology Development of the European Union, involving fourteen research institutions in seven European countries. The project is divided into three work packages that cover mapping, warning, and modelling of avalanche motion. The aim of the program is to improve these three aspects by harmonisation and standardisation of avalanche databases and hazard maps; evaluation and comparison of practical methods for mapping and warning; and finally, the concern of this paper: a description of existing computational models for avalanche motion, constituting the basis for a co-ordinated European full-scale avalanche experiment for future model development and validation.

TODAY'S COMPUTATIONAL MODELS

The dynamics of avalanches are complex, involving aspects of fluid, particle and soil mechanics. Also aspects of submarine slide models are applicable. However, no universal avalanche model exists. The limited amount of data available from real events makes it hard to evaluate or calibrate existing models. Thus, the use of several models based on differing descriptions of the flow is a common strategy.

The SAME model survey report (1998) on existing computational models for snow avalanche motion is one of the main products of the SAME program. Various models are presented, both empirical procedures using statistical and comparative models for run-out distance computations, and dynamic models for avalanche motion simulations. The latter describe either the internal dynamics of the material at certain stages of the motion, the dynamics of the moving

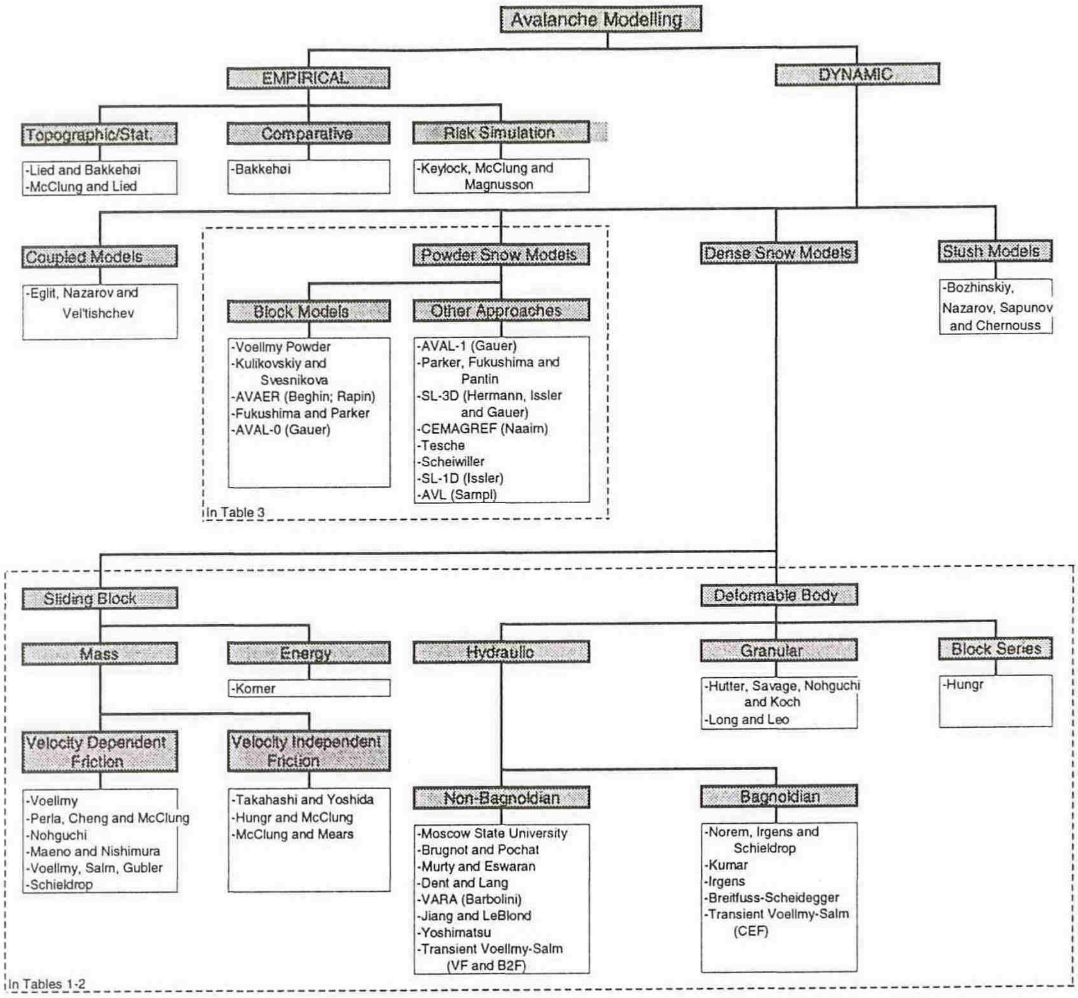

Figure 1: Overview of all models described in the SAME model survey report.

mass as a whole from initiation to rest, or combinations of these. The more advanced dynamic models also provide flow height and velocity information during the event. This information is critical for calculating impact pressures and improving our understanding of avalanche dynamics. An overview of all the models is revealed in Fig. 1.

In the report, the dynamic models are presented with regard to both the physical description of the moving material and to the mathematical and numerical modelling. The limitations and practical applications of each model are discussed.

The capability of the most commonly used avalanche models in Europe is to be tested by M. Barbolini, U. Gruber, C. Keylock, and M. Naaim within SAME Work Package 1.

Empirical procedures

Empirical procedures are based on statistical and comparative models for estimation of avalanche run-out distance. In topographical/statistical models the run-out distance relations are normally found by regression analysis. 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 recognised from considerations of subaerial debris flow behaviour.

Empirical procedures are normally applied to dense flows. However, in principle there is no reason why they could not be applied to slush flows, dense and coupled avalanches (and perhaps even powder snow avalanches with data of sufficient quality) if new coefficients were derived. Thus, these procedures are treated separately in Fig. 1.

Dense snow avalanche dynamic models

Depth-averaged models for an avalanche in a three-dimensional terrain exist, but all models in common use are either one-dimensional rigid body models (lumped mass or sliding block on a linear slope or in two-dimensional terrain) or two-dimensional depth-averaged deformable body models (two-dimensional continuum in a two-dimensional terrain).

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 arise in choosing convenient constitutive equations, boundary conditions, initial conditions and in solving the equations.

Most dense snow avalanche dynamic models are rooted in hydraulic theory, although granular flow models utilising various geotechnical methods from soil mechanics have also been developed. Hydraulic deformable body models are distinguished by the use of depth-averaged equations of motion similar to those used for calculating unsteady flood waves (from an analogy with open-channel hydraulics). A more detailed overview of the dense snow avalanche models is presented in Tables 1-2.

The main problems of dense snow avalanche dynamic models are related to the understanding and description of material properties, that differ considerably between flow and deposition.

Powder snow avalanche dynamic models

Upon reaching speeds of approximately 10 m/s, dense-flow avalanches develop an aerosol 'cloud' of significantly lower density, due to the action of aerodynamic shear forces. The fraction of suspended material varies over a very broad range, depending on running distance, mass, velocity, snow granulometry, snow cover erodibility, surface topography, etc.

The term "powder snow avalanche" (PSA) designates flows dominated by a suspension cloud. However, the majority of avalanches are of a mixed type. The pure PSA models describe this airborne turbulent particle flow by density current models or binary (solid-fluid) mixture models. They disregard the interaction with the dense flow and thus are not able to model the early stages of PSA formation.

Density current models are based on local balances of mass and linear momentum, often integrated over the current height. These models are restricted to the steep part of the track, where phase-separation and mass-change effects may be of minor importance under certain conditions.

In a binary description, mass and momentum balances are formulated for each of the phases and their interaction is accounted for by the mutual interaction force. The interaction must be prescribed by a constitutive relation, and the set of equations have to be closed by a turbulence closure model. Layer averaging is often applied in order to obtain a more tractable system of differential equations.

Block and hydraulic models in one dimension have limited validity under real topographical conditions because the PSA trajectory must be determined before the calculation, and lateral spreading is taken into account in empirical ways at best. In the French model AVAER (Rapin, 1995), empirical growth coefficients obtained in laboratory experiments on density currents (Beghin and Olagne, 1991, and references therein) are utilised in a variable-size block model that has extensively been used in expertise work. Dynamic relations taken from studies on stratified fluids or hydraulics are used to specify air entrainment in the variable-size block models by (Kulikovskiy and Sveshnikova, 1977) and by Fukushima and Parker (1990). The latter model also extrapolates empirical particle entrainment relations from fluvial hydraulics to avalanche dynamics; the obtained rates are not unreasonable, but their functional dependence cannot presently be verified. The Swiss model SL-1D (Issler, 1998) describes the PSA in terms of separate saltation and suspension layers (Norem, 1995) in order to analyse entrainment in terms of simple physical processes that are amenable to detailed numerical simulations. Nevertheless, detailed measurements on real PSAs will be extremely useful to verify the model.

Three-dimensional PSA models have been developed by Scheiwiller (1986) and by Tesche (1986), and other three-dimensional PSA models are now being developed into practical tools for avalanche hazard mapping in France (Naaim, 1995), Switzerland (Hermann *et al.*, 1994) and Austria (Brandstätter *et al.*, 1996). The French and Swiss models allow entrainment and deposition of snow along the bed. The current Austrian and French developments aim at coupled dense flow/powder snow avalanche models. Table 3 characterises the PSA models described in the SAME model report with respect to their physical content, implementation and validation.

At the present stage of development, reasonably sound mathematical models and efficient numerical techniques are available for density currents and developed binary mixtures. The remaining key problems are the modelling of snow entrainment and deposition and the choice of the initial and boundary conditions for each application of the models. In particular, the necessary estimates of suspended mass at an early stage of PSA formation remain rather subjective and uncertain. Nevertheless, for practical applications the recent numerical PSA models seem to be able to reasonably simulate run-out zone motion and stagnation pressure distributions.

Coupled dynamic models

Coupled models try to describe both the dense and powder components of the avalanche, as well as the coupling between them. In principle, the complete coupled avalanche could be described by an universal two-phase model for air and snow particles valid over the encountered range of particle volume fractions: from the high values of the dense layer to the very low values of the powder layer. Unfortunately, such two-phase models are very complex and still affected with uncertainties, especially at high particle volume fractions. In practice, separate models for the dense and powder flow components are applied.

If a coupled model is built upon separate sub-models for the dense and the powder layer, the need for an additional sub-model to describe the exchange of mass and momentum between these layers arises. This exchange happens in a "transition layer", across which the particle concentrations decrease from the high values of the dense layer to the low values of the suspension layer. Similar exchanges take place between the suspension layer and the snow cover, when they are in direct contact. Gravitation, air-particle interaction and particle-particle interaction are assumed to govern particle entrainment in the powder layer.

Only a few coupled dynamic models have been formulated up to the present. The SL-1D model (Issler, 1998) describes mass and momentum transfer within the saltation and powder layers and the interaction between these layers and with the resting snow cover. The model can easily be coupled to a model for the dense layer to give a complete coupled model. In the Russian-Coupled-Model (Eglit, 1983; Eglit and Vel'tishchev 1985; Nazarov, 1991, 1992, and 1993) mass transfer between the layers is modelled based on the boundary instability theory. The transition layer is collapsed to an interface between the dense and powder layers. In both models averaging over the height of the considered layers is applied.

Verification and validation are especially important for coupled models, in particular the analysis of the exchange processes.

Slush flow dynamic models

Very few dynamic models describing the motion of a water saturated snow mass exist. Bozhinskiy *et al.* (1996) present a hydraulic model for slush flows in a channel with trapezoidal cross section, while Bozhinskiy and Nazarov (1998), consider a two-layer hydraulic model with a pure water layer under a floating, water-saturated snow layer. Interaction between the two phases, snow entrainment, upper layer density variations, and rear end water feeding are considered in a channel of rectangular cross section.

FUTURE MODEL DEVELOPMENT

The typical questions that arise in practical applications are linked to the maximum runout of extreme events, run-up height, pressure distributions over an area as a function of the return period, etc. Considering the range of information available in practical studies (topographical maps, digital terrain models, avalanche cadastres, meteorological measurements, snow drift information, etc.) there is not—and probably never will be—a single model that is able to answer all such questions, or adequately describes all types of avalanches. The cruder the knowledge of initial and boundary conditions, the more one should favour relatively simple and robust models at the expense of detail in the predictions. Nevertheless, very often great detail is required and thus rather sophisticated models are needed, too.

Determination of realistic initial conditions is a serious problem in practical applications that has not received sufficient attention in the past. Typically, both the initial avalanche mass (fracture area and depth) and the flow behaviour (friction coefficients, snow entrainment and deposition rates, fraction of suspended snow) non-linearly depend on the return period. On the one hand, very simple models do not adequately reflect this non-linearity and may give strongly distorted results; on the other hand, determination of the effect of uncertainties in the initial conditions on the results requires a large number of simulations that are not presently possible with the more demanding advanced models. We suggest that combining simple models allowing rapid scanning of the relevant parameter space with more advanced models for detailed simulations of selected scenarios could help bridge this gap. The simple models will not disappear but acquire new meaning when combined with the more sophisticated ones.

For such combined analyses to yield meaningful results, the simple and advanced models must be properly matched. The following are among the relevant criteria:

- The input and output parameters of the simple model must be among those of the advanced model. This implies, e.g., that simple statistical models predicting extreme runout distances only, should not be combined with advanced dynamic models.
- The physical processes described by the simple model should also be contained in the matching advanced model so that parameter dependencies found with the simple model will also be reflected by the advanced one. E.g., a one-dimensional model with a simple snow entrainment mechanism explores dimensions of the parameter space that are inaccessible to two- or three-dimensional models without snow entrainment.
- Before practical applications are considered, the two models should be compared in situations that can reasonably be described with the simple model. In this way, a set of parameter values for one model can be approximately related to a set of values for the other model (e.g., friction or entrainment coefficients).

In order to account for the extraordinary variability of avalanche motion in response to initial and boundary conditions, flow-regime transitions and snow mass balance should be properly described. The vast majority of models in use today completely neglect these phenomena. In simple models, flow-regime transitions may be captured "manually" by choosing different sets of parameter values in different sections of the path. Indeed, investigations by Gubler (1987) showed that velocity and flow-depth measurements of several avalanches could only be satisfactorily reproduced by the Voellmy-Salm model if turbulent friction in the track was set significantly below the "canonical" values of the Swiss guidelines (Salm et al., 1990) whereas a higher dry friction coefficient had to be used in the run-out. It is obvious that only very few experts will be able to correct for model deficiencies in this way, and a high degree of subjectivity is thereby introduced.

Figure 2: Comparison of maximum pressures in the runout zone of a powder-snow avalanche path in Switzerland. The area shown corresponds to 650x650 m^2. Left: Very large initial mass, but snow entrainment and deposition suppressed. Right: Much smaller initial mass, but snow entrainment and deposition enabled; this avalanche is much more destructive. The isolines correspond to pressures of 0.5, 1.0, 1.5, 2.0 and 2.5 kPa on the left map; on the right, the 4.0, 6.0 and 8.0 kPa isolines are also shown. Underlying pixel map © Swiss Federal Institute of Cartography; reproduced with permission.

So far, these effects have been qualitatively incorporated in only a few models. The Russian models take up a suggestion by Grigoryan (1979) that shear stresses cannot exceed a material-dependent maximum value—an observation that helps explain the abnormally long run-out distances of very large rock and snow avalanches. The Norwegian NIS model (Norem, Irgens and Schieldrop , 1987, 1989) goes a step further by combining visco-elasticity and cohesion; depending on the choice of exponent in the shear dependence of the stresses, the inertial or macro-viscous flow regimes of a granular material (Bagnold, 1954, 1956) can be described.

What appears to be missing at present, however, is a dynamic determination of the effective constitutive law of avalanching snow in response to the local flow parameters. It is the authors' opinion that the molecular-dynamics approach, modelling the flow in terms of a large number of (inelastically) colliding particles of varying size, holds the promise of elucidating the main features of avalanche flow regimes and their transitions. These results could then be used to construct constitutive relations for practically useful models. Systematic laboratory experiments and theoretical investigations have been conducted by several groups (Hutter and Koch, 1991, Hutter *et al.*, 1995; Keller *et al.*, 1998; Koch *et al.*, 1994), but much more work will be required before this approach bears fruit in practical applications.

Fig. 2 illustrates the importance of the snow entrainment by contrasting two maps of maximum stagnation pressures for the run-out zone of a large PSA path in the Swiss Alps, both produced with the code SL-3D (Hermann, Issler and Keller, 1994). In the first run, a large initial mass corresponding to an event with a return period of about 300 years was specified, but snow entrainment and deposition were disabled. In contrast, the second run started with a much smaller initial mass (roughly corresponding to a return period of 30 years), but Gauer's shear-stress dependent entrainment model (Gauer, 1994) was enabled and initial erodible snow depth varied from 0.2 to 0.8 m. depending on altitude and slope angle. Fig. 3 compares the temporal evolution of total avalanche mass, showing that the mass of the PSA may grow enormously if sufficient erodible snow is available in the track. Fig. 3 compares the temporal evolution of total avalanche mass, showing that the mass of the PSA may grow enormously if sufficient erodible snow is available in the track. While the avalanche without entrainment already begins to decelerate in the track, in the presence of entrainment, maximum speed is reached only at the beginning of the run-out zone. On long avalanche paths, initial PSA mass appears to be much less

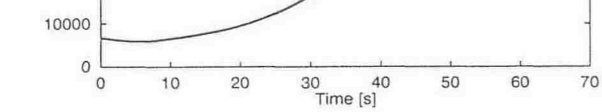

Figure 3: Time evolution of total powder-snow avalanche mass for the two simulations described in Fig. 2. The initial masses correspond to events with estimated return periods of 300 and 30 years, respectively, for the simulations without and with snow entrainment.

important than snow entrainment for a wide range of initial conditions.

CO-ORDINATED EXPERIMENTS

Model development and verification require comprehensive measurements on real avalanches for improved understanding of the underlying physics, validation of the modelling approach, and calibration of the parameters. The remaining key problems—modelling of snow entrainment and deposition, and choice of the initial and boundary conditions for each application of the models—are directly connected to the scarcity of comprehensive, reliable experimental data and the concomitant lack of model validation.

The SAME Work Package 3 meetings have outlined the directions for future experimentation, while the projected costs of comprehensive experimentation again underline the benefits of co-ordination. The objectives of co-ordinated experiments can be divided into practical and modelling objectives summarised in Table 4.

A component of the SAME project is a proposal for future collaborative experimentation, detailing the parameters, measurement techniques, required precision, site requirements, feasibility, and priorities. It was determined that both large (10^{4-5} m^3) and small (10^{3-4} m^3) avalanches need to be studied. The advantages of working at a small site are ease of (safe) observation, rapidity of surveying, cheaper site development and a greater number of observed events. Both a large and small site will be equipped.

Both for small and large sites minimum equipment was determined to comprise three locations heavily instrumented with capacitance probes, load cells, FMCW radar for entrainment and flow depths. In addition, video observation and snow stakes in the starting zone should be provided. Additions for larger sites include Doppler radar for velocity measurements and photogrammetry for starting zone volume estimation. Capacitance probes provide density and velocity information, but are expensive and may be problematic for measurements in wet snow. Consequently, light emitting diodes may need to be substituted in some places (with a consequent loss of density information). Capacitance probes provide unique information for powder-snow avalanche modelling.

Instrumentation and construction costs according to the standards outlined above are estimated to amount to more than one million ECU for a new large site. Reducing the degree of instrumentation would provide significantly less information on the internal dynamics of avalanches and thus make validation of new, advanced models less conclusive.

CONCLUDING REMARKS

Based on an EU Program (SAME) survey report on existing computational models for avalanche motion, the various models for computation of avalanche motion have been surveyed. The models include empirical procedures for run-out distance computations, in addition to dynamic models describing the physics of dense and powder snow avalanches, the coupled combination of these, and slush flows. A few (quasi) three-dimensional models already exist, and effort is now being made to expand more of the one- and two-dimensional models into three dimensions. However, it is the impression of the authors that it is of equal importance to improve the two-dimensional models further.

The model report and the SAME work package 3 meetings suggest that future model development will be in the directions of flow-regime transitions and snow mass balance. Density variations are represented in very few models, and then simply, while the resultant effects on other physical parameter values such as viscosity, are not represented in any of the dynamic models. Other aspects of the moving media (e.g. particle size distributions, cohesion, particle rotation, temperature changes, and energy dissipation) are not adequately described in any of the dynamic models. There is a conspicuous lack of any description of stability and accuracy of the applied numerical methods.

Significant improvements in the quality of avalanche hazard mapping require parallel progress along three complementary paths:

- *Improved knowledge of initial conditions:* Combining an extensive survey of the parameter space with detailed simulations of selected scenarios for each practical problem, as advocated in the section on future model development, should contribute towards a more comprehensive assessment of avalanche hazard, taking into account the uncertainty of our estimates and computations. Beyond this, research into the quasi-stochastic (climate, probability distribution of key weather elements) as well as causal factors (topography) determining release areas and volumes in function of avalanche frequency needs to be intensified.
- *Modelling of the basic physical processes of avalanche dynamics:* Higher accuracy and reliability of the dynamic models can only be achieved if snow entrainment or deposition and changes in the flow regime are correctly captured. Molecular-dynamics models hold promise as a tool for studying the basic processes, interpreting measurements, and for developing practically useful continuum approximations. Detailed analysis of theoretical approaches successful in other gravitational mass movements should stimulate future development in avalanche dynamics.
- *Comprehensive measurements on real avalanches:* For guiding model development and allowing full verification of sophisticated models, a new generation of experiments is required in which the processes in the interior of avalanches are studied in detail. According to the findings from a working group of SAME, these objectives can be reached by combining existing

experimental techniques in one small and one large experimental site, but only at substantial cost. A corresponding proposal is being elaborated.

All points listed above underline the substantial benefits, and even necessity, of international collaboration in the field of avalanche dynamics. The need is felt most urgently for experimentation due to the high costs of the required equipment. But if progress in modelling is to keep pace with experiment, parallel development of nearly identical models should be abandoned in favour of co-ordinated investigations at different levels, from basic studies of granular dynamics to the elaboration of practical procedures for hazard mapping. Within Europe, the SAME project plays the role of catalyst in this integrative process.

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Table 1: Summary of charactersitic features of dense snow avalanche dynamic models described in the SAME model survey report. Dimensions are given as 'flow, terrain' where a flow dimension of 0 represents a block model. Non-integer flow dimensions represent averaging over a dimension, while non-integer terrrain dimensions mean that there is limited inclusion of the additional dimension.

Model Name / Author(s)	*Dimension*	*Friction/material parameterisation*	*Snow entrainment*	*Numerical scheme*	*Validation*
Körner	0, 1	dry friction f_r	No	None	none
Voellmy	0, 1.5	turbulent friction ξ and Coulomb friction μ	No	None	Buser and Frutiger (1980) discuss values of the coefficients.
PCM (Perla, Cheng & McClung)	0, 1.5	Coulomb friction μ. M/D for terms proportional to v^2	Lumped into M/D but not resolvable	None	Bakkehøi et al (1981) discuss the values of the coefficients. Alean (1984) test the model against ice avalanche data
Nohguchi	0, 3	similar to Voellmy model	No	Runge-Kutta	Numerical simulation of real avalanches
Maeno & Nishimura	0, 3	Coulomb friction μ, Viscous term B, Turbulent term C	Related to velocity by an exponential function.	Runge-Kutta	Maseguchi avalanche
Schieldrop	0, 2	similar to PCM model	No	4th order Runge-Kutta	Compared to field observations and Irgens model by Irgens (1997).
VSG (Voellmy, Salm & Gubler)	0, 1.5	Voellmy coefficients with internal friction parameter λ	No	None	Tested by Gubler (1987) and Lied et al (1995)
Transient Voellmy-Salm (Bartelt & Gruber)	1.5, 2.5	Various for the 3 flow laws: Voellmy, Bingham, and modified CEF	None or at a rate equal to airborne powderisation	Galerkin f.e. / upwind f.d (no damping)	Flow laws evaluated against known events (Aulta). Also comparison with experiments (Hutter et al, 1995) and with Voellmy-Salm and McClung-Mears
MSU dense (Grigoryan, Eglit & Yakimov)	1.5, 2.5	Coulomb with an upper limit. Hydraulic turbulent friction k. (v^2 and v dependent)	Ostroumov (1972) extended entrainment to the whole flow.	Not specified	Numerical exploration coupled with calculations for real events
Hungr & McClung	1, 1	Just a Coulomb basal resistance (no turbulent drag)	No	None	Tested by experiment (Chu et al, 1994) and comparisons made to real events
Brugnot & Pochat	1.5, 2.5	dry friction and dynamic drag coefficients	At the leading edge	Not specified	Tested against the Voellmy model and experiments
Murty & Eswaran	1.5, 2.5	dry, laminar and turbulent friction	No	MacCormack method	???
Dent & Lang	1.5, 2	Friction through viscosity terms	No	f.d. scheme	Coefficients evaluated by fitting to experimental results. Successful validation for slow avalanches
VARA (Nettuno & Barbolini)	2, 2.5	Coulomb bed friction and an 'inertial regime' granular resistance.	No	Various types of f.d. scheme	Validation limited by a lack of data. However, comparisons with the transient Voellmy-Salm model
Jiang & LeBlond	1.5, 1	Bingham	No	None	Coparison with the snow flow test of Dent's experiment
Yoshimatsu	1, 1	dynamic and static dry friction coefficients	No	f.d. schemes	The author suggests from experiment that the ratio of the dynamic to the static coefficient = 0.8
NIS (Norem, Irgens & Schieldrop)	1.5, 2	modified CEF	Only theoretically described, not in numerical model	Eulerian f.d. in space and 4th order Runge-Kutta in time.	Widely tested against avalanches, submarine slides and rockslides. Also compared with laboratory experiments
Kumar	1.5, 2.5	Coulomb friction	No	MacCormack method	None specified
Irgens	1.5, 2.5	modified CEF	No	See NIS model	Numerical simulation of real avalanche
Breitfuss-Scheidegger	1, 1	Friction is a result of particulate collision or flow field deformation	No	Not Specified	Suggested parameter values are provided by the authors
Hutter, Savage, Nohguchi & Koch	1.5, 1.5	Coulomb internal friction	No	Lagrangian f.d. scheme with numerical diffusion	Comparisons made with laboratory experiments
Lang &Leo	2.5, 3	granular media with a Coulomb yield criterion. Basal Coulomb friction and boundary drag ($\propto v^2$)	No	Lagrangian f.d. scheme with numerical diffusion	Comparison with the experimental results of Lang *et al* (1989)
Naaim	2, 3	Various rheological models can be selected.	No	Finite Element	None specified
Hungr	1.5, 2.5	Various rheological models can be selected.	Assumed to be a constant % of the cross-sectional area per unit displacement	Lagrangian centred f.d. explicit scheme	Model compared to other models and experiment, as well as flow slides from coal waste dumps by Kent and Hungr (1995). The lateral pressure coefficient is very important

Table 2: Summary of quality, potential and limits of dense snow avalanche dynamic models described in the SAME model survey report.' +' is a point in the model's favour and '–' a weakness. 1) but see McClung and Mears (1995); 2) depends on the rheological model chosen.

Model Name / Author(s)	*Validation successful against real events?*	*All model parameters are physically-based?*	*Parameter values are relatively well constrained*	*The model is readily transferable to other locations?*	*Model is informed by snow mechanics considerations?*	*The approach can be extended to higher flow dimensions?*	*Model results include runout distance (1), pressure distribution (2), and flow height (3)*
Körner	not known	+	+	+	–	–	+ – –
Voellmy	–	+	–	+	–	–	+ – –
PCM (Perla, Cheng & McClung)	–	–	–	+	–	–	+ – –
Nohguchi	not known	+	–	+	–	–	+ – –
Maeno & Nishimura	not known	–	–	–	–	–	+ – –
Schieldrop	+ (small/slow events)	–	–	+	–	–	+ – –
VSG (Voellmy, Salm & Gubler)	Validation results not described	–	–	–	–	–	+ + –
Transient Voellmy-Salm (Bartelt & Gruber)	+–??	+	–	+	+	+	+ – +
MSU dense & hydraulic (Grigoryan, Eglit & Yakimov)	not known	+	–	–	–	+	+ + +
Hungr & McClung	+	+	+	+	–[1]	–	+ – +
Brugnot & Pochat	+	–	–	–	–	+	+ – +
Murty & Eswaran	not known	+	–	+	–	+	+ – +
Dent & Lang	+ (slow events)	+	+	+	–	–	+ – –
VARA (Nettuno & Barbolini)	–	+	–	+	+	+	+ + +
Jiang & LeBlond	+	+	+	+	–	+	+ – +
Yoshimatsu	+	+	+	–	+	–	+ – –
NIS (Norem, Irgens & Schieldrop)	+	–	+	+	+	+	+ – +
Kumar	not known	–	+	–	+	+	+ – +
Irgens	+	–	+	+	+	+	+ – +
Breitfuss-Scheidegger	not known	+	+	+	+	–	+ – –
Hutter, Savage, Nohguchi & Koch	–	+	+	+	+	+	+ + +
Lang &Leo	–	–	–	–	+	+	+ + +
Naaim	not known	+	not known	+	+–[2]	+	+ + +
Hungr	+	+	+ –[2]	+	–	–	+ + +

Table 3: Summary of characteristic features of PSA dynamic models described in the SAME model report. A dimensionality of 0 designates a (variable-size) block model; (0,1,2)+ stands for a model with 0, 1, or 2 explicit dimensions and averaging over height, (0,1)++ for height and width averaging, and 0+++ means that averaging over all avalanche dimensions has been performed (block models only). A mass or momentum balance of 0 indicates no balance in these quantities, 1 means balance for the mixture or only one of the phases, and 2 means separate mass balances for air and snow.

Model name / Author(s)	*Dimension-ality*	*Mass balances*	*Momentum balances*	*Turbulence*	*Transition layer*	*Air entrainment*	*Snow entrainment*	*Numerical scheme*	*Validation*
Voellmy	0+, stationary	0	1	no	no	no	no	none	?
AVAER (Beghin; Rapin)	0+++, non-stationary	2	1	no	no	empirical	user-prescribed	space marching	density current exp.
Kulikovskiy & Sveshnikova	0+++, non-stationary	2	1	no	no	boundary instability	yes	?	Russian experiments
Fukushima & Parker	0++, time-dependent	2	1	1-equation balance	no	empirical (thermal theory)	empirical (hydraulic exp.)	space marching	Maseguchi avalanche
Parker, Fuku-shima & Pantin	1+, mostly stationary	2	1	1-equation balance	no	empirical (hydraulic exp.)	empirical (hydraulic exp.)	space marching	Several hydraulic experiments
AVAL (Gauer)	0++ time-dep. / 1+ stationary	2	1	k-ε model depth-avg.	no	empirical (thermal theory)	empirical (hydraulic exp.)	Runge-Kutta in time / space	Hydraulic exp., Maseguchi aval.
AVL (Brandstät-ter & Sampl)	3, time-dependent	2	1 (2)	k-ε model	no	numerical simulation	no	finite-volume discretization	Beghin exp., observed PSAs
SL-3D (Hermann, Issler & Gauer)	3, time-dependent	2	1 (2)	k-ε model	no	numerical simulation	empirical (hydraulic exp.)	finite-volume discretization	Beghin exp., observed PSAs
CEMAGREF (Naaim)	3, time-dependent	2	1	k-ε model	no	numerical simulation	empirical (hydr. & wind tunnel exp.)	finite-volume discretization	Beghin exp., observed PSAs
Tesche	3, time-dependent	2	2	extended k-ε model	no	numerical, free-surface flow	not specified	?	none
Scheiwiller	2 or 3, time-dep. or stationary	2	2	k-ε model	no	numerical, free-surface flow	no	finite differences / weighted residuals	water tank experiments
SL-1D (Issler)	2×(1+), time-dep.	2+1	2×1	k-ε model depth-avg.	suspension / saltation	computed from turbulence	particle impacts	MacCormack	in progress

Table 4: The objectives of co-ordinated experiments.

Practical Objectives	**Modelling Objectives**
Impact pressure on obstacles: • Dependence of pressure upon avalanche properties and structural configuration. • Spatial and temporal distribution of pressure on an obstacle. • Long-term remnant static pressure after impact. • Shear forces on snow sheds. • Improved design of defence structures. Hazard zoning: • Improved trajectory modelling. • Improved runout distance prediction. • Mapping of pressures. • Effect of obstacles on flow path trajectory and energy. • Dependence of fracture area and depth on topographical and meteorological parameters. Tests of monitoring systems (warning, alarming): • Acoustic and seismic systems; • Radar-based systems; • Mechanical systems.	Validation of existing models through measurements of: • released mass, • trajectory, flow depths and velocities, • run-out distance and deposit distribution, • pressures. Guidance for future model development in addition requires: • Mass balance (global, local, and time-resolved). • Determination of flow regime (velocity fluctuations and profiles, density profiles and fluctuations, and pressure measurements (particle size distributions). • Granulometry of deposits. Seismic and acoustic studies aiming at: • Identification of different sources of seismic and acoustic signals. • Correlation of signal variations to avalanche properties. • Determination of signal variability over different avalanches in the same path. • Estimation of avalanche size and mass from catalogue of seismic signals for different avalanches in different paths.