NUMERICAL MODELING OF A SLUSHFLOW EVENT

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ABSTRACT: Slushflows—flowing mixtures of snow and water—constitute a natural hazard especially in higher latitudes, i.e., Norway, Iceland, or Alaska. The combination of high densities and high mobility can make them to a highly destructive force.

A slushflow model is presented that regards the slushflow and the ambient air as a two-phase flow with air as continues gas-phase and slush as dispersed multi-component "fluid" consisting of snow clods and water. The rheological model of a non-Newtonian fluid is used to describe the behavior of the slush including visco-plastic and granular effects. The yield strength is assumed to depend on the snow density and the water content. The viscosity of the water and air component is estimate using the Krieger and Doughert expression for a suspension of snow in water and snow in air, respectively. For the turbulent closure the Smagorinsky LES model is used.

As case study, the model is run for the slushflow event in Patreksfjörður, Iceland, on January 22nd, 1983. Comparison between field observations and simulations are in reasonable good agreement.

Keywords: slushflow, numerical modeling, field observation

1. INTRODUCTION

Slushflows—flowing mixtures of snow and water—constitute a natural hazard especially in higher latitudes, i.e., Norway, Iceland, or Alaska. However, they can occur in all regions having a seasonal snowcover. According to (McClung & Schaerer, 1993), characteristics for slushflows are: starting zone slope angels are in the range from 5º to 40º, but rarely exceeding 25º to 30º; the snowpack is partially or totally saturated with water; the release is associated with layers, for example the ground surface, that are nearly impermeable to water flow; depth hoar is often present at the base of the snow cover; release is usually associated with sudden intense snowmelt or heavy rainfall.

The release of slushflows is most likely caused by a reduction of the snow cohesion due to the presence of water accompanied by reduced effective strength due to the hydrostatic pressure. In water-saturated snow (slush), particles are usually entirely separated from each other by water. This occurs at a water volume fraction larger than approximately 15 %.

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The flow behavior varies from laminar to fully turbulent, depending on topography and water content. On top of the dense layer one may find a saltation layer, and large slushflows may even have an airborne part (Lied, 1998). That means a change in the flow regime might occur.

The combination of snow and water—i.e. high densities (in the range from 300 to 1000 kg m^{-3}) companied with a high mobility (velocities up to 30 m s^{-1})—can make slushflows to a highly destructive force. Those, the demand for a numerical model as a tool for landuse-planning is not surprising. However, due to the inherent complexity of the flow only few attempts have been made to model slushflows, e.g. (Bozhinskiy & Nazarov, 1998)

2. SLUSHFLOW MODEL DESCRIPITION

This section gives a brief and basic outline of a proposed slushflow model. As the model is still in development and some coefficients may change during validation absolute values are omitted here.

2.1 Governing Equations

The slushflow and the ambient air are modeled by a two-phase model approach with air as a continuous gas-phase and the slush as dispersed multi-component "fluid" consisting of snow clods and water. For both phases, the continuity equation is solved in order to determine the individual volume fraction. The mass balance for ambient air (marked with the subscript a) and those for the slush (marked with the subscript s) can be written in the from

$$\frac{\partial v_a \rho_a}{\partial t} + \nabla \cdot (v_a \rho_a \mathbf{U_a}) = 0 \,, \tag{1}$$

$$\frac{\partial v_s \rho_s}{\partial t} + \nabla \cdot (v_s \rho_s \mathbf{U_s}) = 0 \,, \tag{2}$$

where **U** is the velocity, ρ the intrinsic density of the respective phase, and v_a and v_s are the volume fractions of the air and slush (v_a = 1-v_s). ∂/∂t indicates the local differentiation in time and ∇ is the gradient operator.

In addition to the continuity equation (2), a scalar transport equation for the mass fraction, θ_m, of the liquid water content is solved:

$$\frac{\partial v_s \rho_s \theta_m}{\partial t} + \nabla \cdot \left(v_s \rho_s \theta_m \left(\mathbf{U}_s + \mathbf{U}_{slip} \right) \right) = 0 \,. \tag{3}$$

The slush density,

$$\rho_s = \left(\frac{(1-\theta_m)}{\rho_p} + \frac{\theta_m}{\rho_{wtr}} \right)^{-1} , \tag{4}$$

where ρ_p is the density of the snow clods and ρ_{wtr} the density of water. At present, the slip velocity, $\mathbf{U}_{slip}$, which describes the additional percolation of water through the snow, is set to zero.

The momentum equation for the ambient air reads

$$\frac{\partial v_a \rho_a \mathbf{U}_a}{\partial t} + \nabla \cdot (v_a \rho_a \mathbf{U}_a \otimes \mathbf{U}_a) = \\ -v_a \nabla p + \nabla \cdot \left[v_a \mu_{aeff} \left(\nabla \mathbf{U}_a + (\nabla \mathbf{U}_a)^T \right) \right] + v_a \rho_a \mathbf{g} - \mathbf{F_D}, \tag{5}$$

here ⊗ indicates the tensor product, p is the pressure common in both phases, **g** the gravitational acceleration.

$$\mu_{aeff} = \mu_a \, \mathrm{M}_0 + \mu_{SGSa} + \mu_T \,, \tag{6}$$

where μ_a is the viscosity of air, M_0 is the Krieger and Dougherty factor, which accounts for the effect of particles on the ambient fluid (Siginer, 1999). μ_{SGSa} is the Smagorinsky sub-grid scale viscosity (Ferziger, J. H. and M. Perić, 1999), which is used for the turbulent closure and μ_T is an extra particle induced turbulence term. For this, the model from (Sato & Sekoguchi, 1975) is used, which gives

$$\mu_T = c_{\mu b} \rho_a v_s d_p \left| \mathbf{U_s} - \mathbf{U_a} \right| , \tag{7}$$

where d_p is the particle diameter and $c_{\mu b}$ a coefficient.

The momentum equation for the slush reads as follows

$$\frac{\partial v_s \rho_s \mathbf{U}_s}{\partial t} + \nabla \cdot (v_s \rho_s \mathbf{U}_s \otimes \mathbf{U}_s) = \\ -v_s \nabla p + \nabla \cdot \left[v_s \mu_{seff} \left(\nabla \mathbf{U}_s + (\nabla \mathbf{U}_s)^T \right) \right] + v_s \rho_s \mathbf{g} + \mathbf{F_D}. \tag{8}$$

The effective viscosity of the slide μ_{seff} will be given in the following section. The coupling term, $\mathbf{F}_D$, in (5) and (8) accounts for the drag between the air and the slush clods, i.e.,

$$\mathbf{F_D} = C_D (\mathbf{U}_a - \mathbf{U}_s) . \tag{9}$$

C^*_D is a drag coefficient, which depends on volume fractions and on the flow regime.

2.2 Rheological model for the slush

The rheology to describe the dense slush is based on those of a non-Newtonian fluid with visco-plastic and granular behavior. Further, to fit the model into the framework of the used flow solver, the stress-strain relationship is written in following form

$$\mathbf{T} = -p\mathbf{I} + w \mu_{wtr} \mathbf{D}_s \\ + c_1 \left(\frac{Y_e}{2\sqrt{-\mathbf{II_D}}} \mathbf{D}_s - p_c \mathbf{I} + \mu_c \mathbf{D}_s \right) , \tag{10}$$

where **T** is the stress tensor, $\mathbf{D_s}$ the rate of strain (deformation) tensor of the slush phase, and **I** the unit tensor. $\mathbf{II}_D$ (= -½tr($\mathbf{D}_s^2$)) is its second invariant, which is a measure of the effective shear rate. The water content, w (= $\rho_s \theta_m / \rho_{wtr}$), is given by volume fraction of the slush phase and c_1 is a blending factor to describe the transition from a more snow (granular) to a more water dominated flow regime. The effective viscosity of the water is given by

$$\mu_{wfr} = \mu_w \, \mathrm{M}_0 + \mu_{SGSw} \,. \tag{11}$$

The third term on the right-hand side in (10) gives the contribution of the snow to the rheology. Here, the first term describes a visco-plastic behavior, where the effective yield strength, Y_e, is assumed to be a function of the density of the dry snowpack and its water content. p_c is the collisional pressure and μ_c the collisional viscosity. Both are set to be functions of $\mathbf{II}_D$ and of the diameter and volume fraction of the snow clods.

All terms in (10) involving $\mathbf{D_s}$ are combined to the effective viscosity, μ_{seff} (see (8)). The collisional pressure is added to common pressure.

At the bed surface, in addition to the commonly used no slip conditions the momentum loss due to particle impacts is regarded (Gauer & Issler, in press).

The model is implemented in the commercial flow solver CFX4.4 from ANSYS (CFX4.3, 1999), which uses a finite volume approach to solve the Navier-Stokes equations.

3. CASE STUDY

A slushflow fell from Geirseyrargil in Patreksfjörđur/northwest Iceland, at 15:40 on January 22, 1983. Three people were killed. The flow damaged 13 houses and several other buildings and killed some sheep and other animals. A detailed description of the meteorological conditions is given in (Tómasson & Hestnes, 2000).

Figure 1 Overview map of Geirseyrargil gully / Patreksfjörđur showing the approximate location of the release area and the observed outline of the slush-flow

The release area of the slush flow was located approximately between 85 and 100 m a.s.l. in the mouth of the gully. The total volume, which was involved in the flow, is stated as "somewhat more than 30 000 m^3". According to the field report only a small part of the total volume of the slushflow can have originated from the release area in the mouth of the gully. The averaged snowdepth of the surrounding area was approximately 1 m. It is estimate that the origin of the involved snow was distributed as follows:

	m a.s.l.	m^3
Release area	85-100	2000-2500
Track	30-85	17 000
Run-out area	0-30	12 000

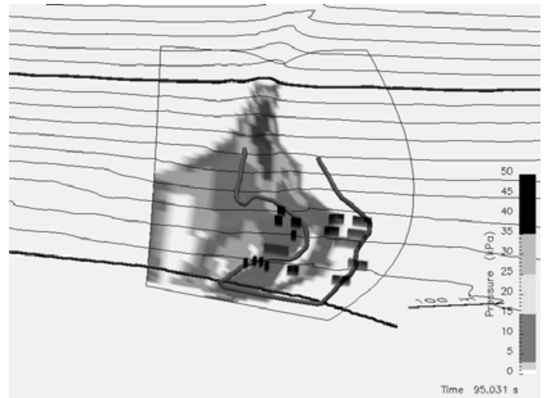

Figure 3 Simulated maximum pressure distribution for case 1 —without surrounding snowpack. (10 m contour lines)

3.1 Numerical simulation

In the following section, preliminary results of slushflow simulations are presented for Geirseyrargil case. Two approaches are presented: 1) disregarding the surrounding snowpack, i.e. no erosion—only a small fraction of the involved mass is regarded; 2) including the surrounding snowpack as part of the simulation. In both case the assumed initial mass of the slushflow is approximately 1.5 Gg of which 1.0 Gg is assumed to be water. This corresponds to the estimated volume in the release area.

Figure 3 shows a map of the simulated maximum pressure for case 1. In this case, the slushflow partly leaved the creek bed and followed the alluvial fan. This behavior is properly correct, if one disregards the surrounding snowpack and its erosion. However, it is in discrepancy with the observation.

The maximum pressure distribution for case 2 is shown in Figure 2. Figure 4 presents a time series of this simulation. The interaction

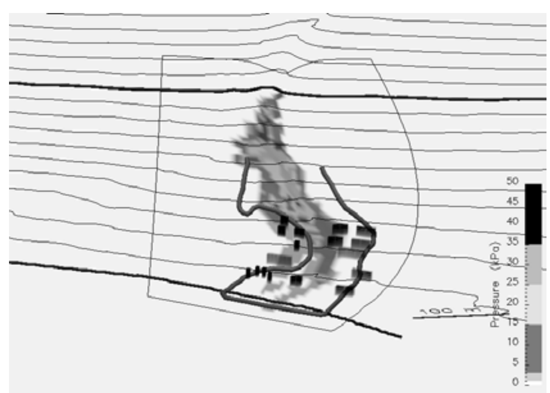

Figure 2 Simulated maximum pressure distribution for case 2 —including surrounding snowpack. (10 m contour lines)

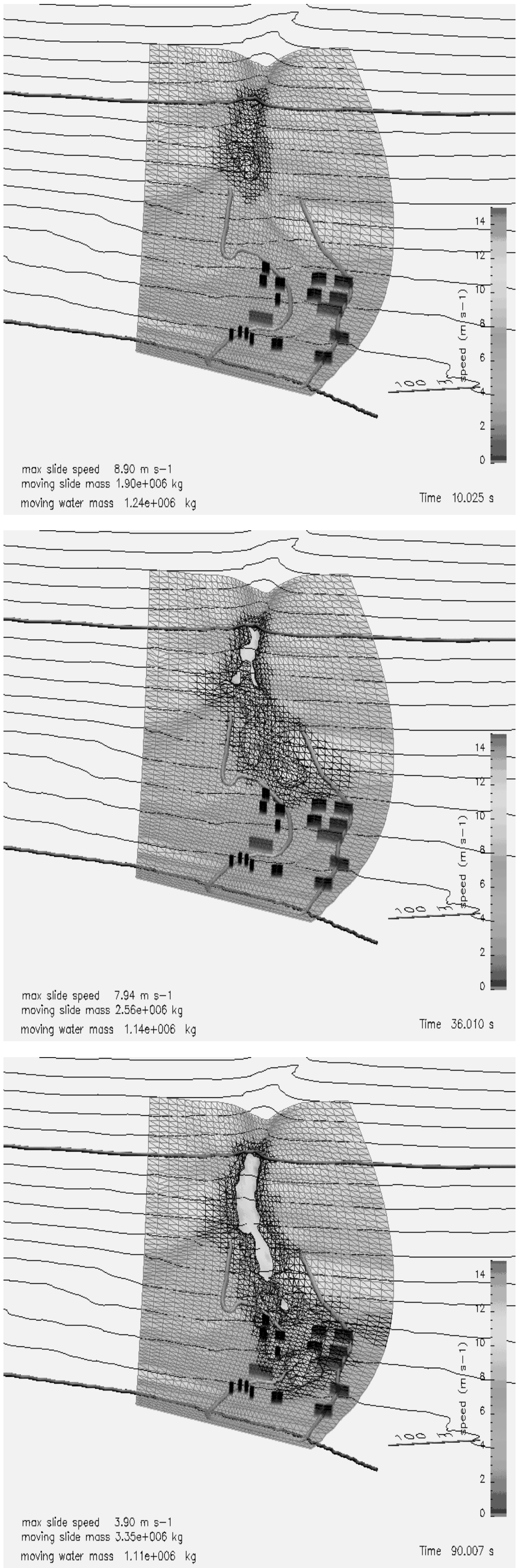

Figure 4 Time series of the slushflow simulation including the surrounding snow pack. Shown are the 100 kg m^{-3} density isosurface (and speed).

between the flowing part and the snowpack at rest and the erosion of the snowpack causes the slush-flow to stay more closely to the creek bed. The flow pattern shows a reasonable good agreement with the field observation. The comparison between the simulated pressures with respect to the vulnerability of the involved building types (e.g. Valentine, 1998) and the reported damage is also in satisfying. Note, sheltering effects due to houses were not included in the simulations yet.

4. CONCLUSIONS

The paper presents ideas and expressions in an attempt to model slushflows. The presented model is a fully 3-dimensional approach. It includes the interaction with the snowpack in a direct way, i.e., the surrounding snowpack is part of the resolved flow domain. Simple expressions are used to express the strength and disintegration of the snowpack.

One problem by almost all geo/natural hazard related flows is their shallowness, i.e., length scale >> vertical scale. This leads to a problem to grid the flow domain with a reasonable resolution. A compromise between desirable resolution and computational effort has to be found.

A problem is the necessity in using a full two-phase approach for the momentum equation combined with the requirement of a fine grid resolution. Both requirements result in an increase in computational time and costs. However, on long-term perspectives this may change with more powerful computer.

Also, the subject of multi-phase turbulence modeling is not as well developed as single-phase turbulence modeling. There is no ‘industrial standard' model, like the single-phase k-ε model, which is known to perform reasonably well to engineering accuracy in a wide range of applications. Regarding the relevant range of Reynolds numbers in slushflows, Large Eddy Simulations (LES) might be a candidate for the turbulent closure. However, LES treatment in multi-phase flow is also an open question.

A comparison between simulations with and without surrounding snowpack shows that disregarding the snowpack gives a totally different result. It can be concluded that it is necessary also to consider the interaction with and the erosion of the snowpack. This is especially important in a fully 3-dimensional approach. However, that makes the matter even more complicated. The solid-like behavior of the snowpack has to be modeled within the flow-solver. To include the disintegration process, the resolution of the grid has to be sufficiently high. Little is know about the disintegration process itself.

Recommendations and requirements for further developments are (not necessarily in the same order and not necessarily complete):

- improved modeling of the disintegration process of the snowpack (erosion);
- improvement of the rheological model;
- verification of the blending factors used for transition between flow regimes;
- turbulent closure for multi-phase flows;
- improvement of wall function/treatment, depending on improved turbulence criteria;

However, a major problem is there are basically no direct measurements available, like speed or pressures measurements, to validate the model.

ACKNOWLEDGEMENT

This work was partly funded through NGI's SIP-programs “Avalanche research” and “Offshore Geohazards”. I gratefully acknowledge T. Jóhannesson from Icelandic Meteorological Office for his support. I also wish to thank my colleagues of the avalanche group at NGI for their keen interest and stimulating discussions. Simulations were performed using the CFX4.4 flow-solver from ANSYS. This is publication number 62 of the International Center for Geohazards (ICG).

REFERENCES

Bozhinskiy, A.N. and N.N. Nazarov, 1998. Dynamics of two-layer slushflows. In Hestens, E., editor, 25 Years of Snow Avalanche Research, Volume 203 of NGI-Publication. Oslo, Norwegian Geotechnical Institute, pp. 74--78.

CFX-4.3 Flow Solver User Guide (1999): ANSYS

Ferziger, J. H. and M. Perić, 1999. Computational Methodes for Fluid Dynamics 2nd rev. ed. Heidelberg, Springer.

Gauer, P. and D. Issler, in press. Possible Erosion Mechanisms in Snow Avalanches. Annals of Glaciology 38.

Lied, K., 1998. Snow avalanche experience through 25 years at NGI. In Hestens, E., editor, 25 Years of Snow Avalanche Research, Volume 203 of NGI-Publication. Oslo, Norwegian Geotechnical Institute, pp. 7--14.

McClung, D. and P. Schaerer, 1993. The Avalanche Handbook 1011 SW Klickitat Way, Seattle, Washington 98134, The Mountaineers.

Sato, Y. and K. Sekoguchi, (1975). Liquid velocity distribution in two-phase bubble flow, Int. J. Multiphase Flow, **2** p79.

Siginer, D. A., D. De Kee, and R. P. Chhabra, 1999. Rheology properties of concentrated suspensions. In Balmforth, N.J. and A. Provenzale, editors, Advances in the Flow and Rheology of Non-Newtonian fluids, Part B Rheology Series 8, Elsevier, pages 1299--1346.

Tómasson, G. G. and Erik Hestnes, 2000. Slushflow hazard and mitigation in Vesturbyggd, Northwest Iceland. Nordic Hydrology, 31(4/5), pp. 399--410.

Valentine, G., (1998). Damage to structures by pyroclastic flows and surges, inferred from nuclear weapons effects. Journal of Volcanology and Geothermal Research 87, pp. 117-140.