Results 2014 from SP 4 FoU Snøskred: Work Package 1 — Ryggfonn and Avalanche Dynamics

**Project nr:** 20140053-200  
**Title:** Ryggfonn and avalanche dynamics

<table>
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<th>Total budget (kNOK)</th>
<th>From Dept. Of Oil and Energy (kNOK)</th>
<th>Costs per 2014-12-31 (kNOK)</th>
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**Task 1: Avalanche experiments at the Ryggfonn test site**

The objective is providing experimental data from full scale avalanche experiments to:

- improve the understanding of the behavior of the avalanches with a focus on flow regime changes,
- obtain data of sufficient quality for model calibration,
- gain in-depth understanding of the interaction of snow avalanches with catching dams.

**Task 2: Avalanche Dynamics**

The objective is to provide improved tools for avalanche hazard mapping (with a focus on flow regime changes).

**Har prosjektet oppnådd de oppsatte mål:** Ja: [X]  Nei: [X]

**Begrunnelse for eventuelle avvik og beskrivelse av korrigerende tiltak:**

Task 1: No artificial avalanche release during the winter 2013/14 due to unfavorable weather conditions. The resources saved in this way were partially reallocated to maintenance of the Ryggfonn test-site and re-evaluation of old data from Ryggfonn (Gauer and Kristensen, 2014), and reporting of observations from an artificial avalanche release on Stjernøya (Frauenfelder et al., 2014).

Task 2: Due to other work packages of SP4 using more than their allocated resources, only a small part of the planned work in this task could be carried out. The main deliverables (recommendations for choosing the parameters of the PCM block model and for using the new quasi-3D code MoT-Voellmy) could be finished, however.

The main results are published or are going to be published in refereed journals and conference proceedings.

**Dato**  **Prosjektleder**  **Dato**  **Fagleder**

2014-12-17  Peter Gauer  2015-01-28  Christian Jaedicke
TASK 1: AVALANCHE EXPERIMENTS AT THE RYGGFONN TEST SITE

Subtask 1.1: Maintenance of Ryggfonn

Under this task, necessary repairs and updating of the data acquisition system at the Ryggfonn avalanche test site were carried out so that the site is ready for the winter season 2014/15.

A wet-snow avalanche released on or around May 22 and caused considerable damage on one load cell at the concrete wedge. This led to unforeseen maintenance work and costs besides the usual maintenance and the planned replacement of load cells at the pylon.

![Figure 1. Damaged load cell (LC2) due to impact of a rock at the concrete wedge.](image)

Task 2: Avalanche Dynamics

In the course of 2014, emphasis was put on the following points:

1. Recommendation for parameter choices for PCM/Coulomb type block model (Deliverable D1.2)
2. Recommendations for the use of the quasi-3D code MoT-Voellmy (Deliverable D1.3)
3. Further investigation of the consistency constraints imposed on erosion formulae by the flow rheology
PUBLICATIONS IN 2014


PRESENTATIONS IN 2014


Issler, D. How can snow avalanches attain a run-out angle of 14°? Colloquium at NIED Snow and Ice Research Center, Nagaoka, Japan, 2014-08-22.

Issler, D. Snow avalanches in a nutshell – a brief phenomenology for non-specialists and some advanced topics. Colloquium at Nagoya National University, Graduate School of Environmental Studies, Nagoya, Japan, 2014-12-03.

DELIVERABLE D1.1
DATA REPORTING AND DATA ANALYSIS FROM MEASUREMENTS AT RYGGFONN

A natural dry-snow avalanche was registered on 13 March 2014 at 23:50 after a period with about 30 to 40 cm new snow (HNS3d). The estimated front velocity between the pylon and the concrete wedge was around 25 m/s, and between the concrete wedge and the mast M2 at the foot of the dam it was around 20 m/s. Figure 2 shows pressure measurements at the pylon, the concrete wedge and at the mast M2.

Figure 2. Load cell measurements: pressure vs. time 20140316 23:50: a) LC45 and LC123, b) M2 G29 raw data and filtered.
On 22 May 2014, two wet-snow avalanches reached the upper sensor area, the first released around 16:45, the second around 23:45. Figure 3 shows photos of the deposits taken automatically from the instrumentation hut at Ryggfonna. The front velocities of these two events between LC45 (Pylon) and LC123 (concrete wedge) were probably around 20 m/s and 25 m/s, respectively.

Figure 3. Avalanche events on 22 May 2014 a) 16:47 and b) 23:46.

Figure 4 shows the pressure measured at the load cell on the pylon and on the concrete wedge. Within the measurements of 20140522 23:46 one can observe a single pressure peak, which probably originated from the rock impact that damaged LC2. The pressure peak corresponds to an impact force of around 1.5 MN.
Figure 4. Load cell measurements: pressure vs time. a) 20140522 16:47 and b) 20140522 23:46.

Data analysis
In addition to the data reporting from 2013/2014, the re-evaluation of old data from the test site has been continued. In this re-evaluation, we attempted to correlate avalanche observations and obtained measurements from the Ryggfonn path with snow and weather conditions at the time of the avalanche events. In this way, we hope to obtain an improved data set useful for model calibration and to obtain information on avalanche release probability. Figure 5, for example, shows the influence of the air temperature on the measured velocity between the pylon (LC45) and the concrete wedge (LC123). Results of this re-evaluation have been presented at the International Snow Science Workshop 2014 in Banff, Canada (Gauer & Kristensen, 2014).
Figure 5. Influence of the air temperature on the front velocity between the pylon (LC45) and the concrete wedge (LC123).

References

DELIVERABLE D1.2

RECOMMENDATION FOR PARAMETER CHOICES FOR COULOMB/PCM-TYPE BLOCK MODEL

The core of the Coulomb/PCM-type model is the momentum balance, which can be written for a simple mass block with constant mass as

\[ \frac{dU}{dt} = g \sin \phi - a_{\text{ret}}, \]

where

\[ a_{\text{ret}} = a_0 g \cos \phi + a_2 U^2 \]

is the retarding acceleration. Here, \( a_0 \) corresponds to the commonly used Coulomb-friction coefficient \( \mu \) and \( a_2^{-1} \) to the mass to drag ratio \( M/D \). \( U \) is the velocity of the mass block. Based on the analysis of observed runout distance (Gauer et al. 2010) and (front) velocity measurements (Gauer, 2013, 2014) the most appropriate choice of Coulomb-friction coefficient \( \mu \) is given by

\[ \mu \approx c_1 \tan \beta + \frac{c_0 - c_m g}{g \cos \beta}, \]

where \( \beta \) is the so-called beta angle (Lied and Bakkehøi, 1980), which might be regarded as the mean slope angle of the avalanche track, and \( g \) is the gravitational acceleration. Furthermore, \( c_0, c_1, c_a \) and \( c_m \) are parameters, where \( c_0 = 0.51 \text{ m s}^{-2}, c_1 = 0.82, c_a = 0.49 \pm 0.15 \) and

\[ c_m \approx c_a (0.6)^2 a_2 Hsc \leq 0.1. \]

Figure 6 shows a plot of \( \mu \) versus \( g \sin \beta \) for \( c_m = 0 \) and \( c_m = 0.1 \). The figure implies that \( \mu \) is a function of the mean slope angle \( \beta \).

![Figure 6](image)

*Figure 6. The Coulomb coefficient \( \mu \) versus the mean acceleration \( g \sin \beta \) for \( c_m = 0 \), which corresponds to a pure Coulomb-type friction model, and \( c_m = 0.1 \). The gray shaded area indicates the most appropriate range.*
From measured maximum velocities one can obtain estimates for the choice of $a_2^{-1} (= M/D)$ in the PCM model. The choice depends on the total fall height, $H_{sc}$, of the track, the chosen coefficient $\mu$ (see above) and the approximate slope angle at the point where the maximum velocity is expected ($\phi_m \approx 25^\circ$):

$$U_{\text{max}} \approx \sqrt{\frac{1}{a_2 H_{sc}}} \sqrt{\sin \phi_m - \mu \cos \phi_m} \approx (0.5 - 0.75)$$

Figure 7 shows the relation between $H_{sc} a_2$, $\mu$, and the slope angle $\phi_m$ for $U_{\text{max}} = 0.6$.

![Figure 7](image)

**Figure 7.** $a_2 H_{sc}$ versus the slope angle at the point where the maximum velocity is reached for varying values of $\mu$ and the normalized maximum velocity $U_{\text{max}} = 0.6$.

**References**


Gauer, P.; Kronholm, K.; Lied, K.; Kristensen, K. & Bakkehøi, S. 2010. Can we learn more from the data underlying the statistical $\alpha$-$\beta$ model with respect to the dynamical behavior of avalanches? *Cold Regions Science and Technology* 62, 42–54.


DELIVERABLE D1.3

RECOMMENDATIONS FOR THE USE OF THE QUASI-3D CODE MOT-VOELLMY

Summary of the features of MoT-Voellmy and of its areas of application

MoT-Voellmy, developed at NGI, shares many features with the well-known code RAMMS:::AVALANCHE from SLF (Christen et al., 2010), which is also in use at NGI. It was developed in order to have a platform for developing models that are more advanced and to achieve tight integration with the hazard-mapping workflow based on ArcGIS. The main features of MoT-Voellmy are the following:

- The earth pressure term is assumed hydrostatic, i.e., no distinction is made between active and passive deformation states. It is as of yet not established that the formulation originally introduced by Salm (1993) and Savage & Hutter (1989) is closer to reality than the simpler and numerically more benign assumption of hydrostatic earth pressure (Gray et al., 1999).

- MoT-Voellmy offers a choice of erosion laws. One of these is equivalent to the one available in some versions of RAMMS and given by \( w_e = c |u| \), with \( c \) a free parameter for which SLF recommends \( 0.2 < c < 1 \). Another option is a formula that can be rigorously derived for a plug flow with slip velocity equal to the flow velocity and a perfectly brittle snow cover, characterized by its shear strength \( \tau_c \).

- In the calculation of the speed \( |u| = (\dot{u}u)^{1/2} \), which is important for determining the drag term, MoT-Voellmy properly takes into account that the co-ordinate system is non-orthogonal and that the covariant \( (\dot{u}) \) and contravariant \( (\dot{u}) \) components of the velocity vector are different. This difference is important where the path is inclined and the direction of steepest descent is not parallel to one of the co-ordinate directions. The difference between the expressions for \( u^2 \) used in RAMMS and MoT-Voellmy can be as large as 10–30%.

- MoT-Voellmy is a finite-difference Eulerian code like RAMMS, i.e., the computational grid is fixed in space and the avalanche moves through the grid. RAMMS uses an essentially second-order spatial discretization with flux limiters so that the code has the TVD property (total-variation diminishing). This is an essential property for higher-order shock-capturing codes. MoT-Voellmy implements the simplest version of the Method of Transport (Fey, 1995), which moves the field components from one cell to its neighbors according the local propagation velocity. The fields are decomposed into a number of «waves» with their individual propagation velocities. MoT-Voellmy limits itself to just one «wave» and is therefore not fully shock capturing. In addition, using the velocities at the cell centers and forward differencing in time, only first-order accuracy in space and time is achieved (Noelle, 2000). Future versions of the code, however, will implement the highly accurate and efficient second-order interface-centered scheme proposed by Noelle (2000).

- MoT-Voellmy reduces the computational load considerably by limiting the computation at each time step to the smallest co-ordinate-parallel rectangle that fully encompasses the flowing mass and optionally writing output in a simple and efficient binary format.
Numerical considerations

Binary or ASCII output?

MoT-Voellmy offers both ASCII and binary output formats. The ASCII format is ESRI ASCII Grid, which is the usual data interchange format for ArcGIS. Its advantage is that it is a de facto standard and human readable. However, it is somewhat less compact than a binary format and takes much more time to read and write. The implemented binary format is BT 1.3 (Binary Terrain), which can be read by ArcGIS with the GDAL libraries installed and is described in detail at http://vtterrain.org/Implementation/Formats/BT.html. It is one to two orders of magnitude faster to write data in this format than in ESRI ASCII Grid format. Some extra information on the projection method can be stored in the file header.

We recommend using the BT binary format for output rather than the ESRI ASCII Grid format. In simulations with frequent output, the computation time drops drastically (by as much as 80%) if one uses the binary format. Reading the binary files in ArcGIS also seems to be somewhat faster than with ASCII format. Note, however, that the input raster files (DEM, release area, snow depth, shear strength, variable friction parameters) are always in ESRI ASCII Grid format. This makes it easier to find errors in the input data files.

Which grid spacing is optimal?

We are not aware of systematic studies to determine the optimum grid spacing in snow avalanche simulations—the answer to this question depends on the numerical scheme, the topography, the avalanche size and the physical processes taken into account. In models based on the SPH (Smoothed Particle Hydrodynamics) technique or other meshless methods, the question turns into the problem of determining the optimum number of "particles" to represent the flow. Some Eulerian models (e.g., those based on the CLAWPACK/GeoCLAW library) may have adaptive grid refinement implemented so that the question becomes essentially obsolete. This is, however, not the case for RAMMS::AVALANCHE and MoT-Voellmy. Both models have a default grid spacing of 5 m, but the user may select another value.

In order to obtain information on the influence of the grid spacing on the quantities of interest—run-out distance, maximum flow depth and maximum velocity—we carried out simulations on a simple artificial topography. It consists of a parabolic open slope with a horizontal length of 1000 m and a fall height of 500 m, which then continues as a horizontal plane for 300 m. The release area is the rectangle [60 m, 200 m] × [140 m, 260 m] in the projected horizontal X-Y plane, and the release depth is 1.0 m, measured perpendicular to the surface. The dry-friction and drag parameters were set to $\mu = 0.3$ and $k = 0.001$ ($\xi = 9810$ m/s²), respectively. Centrifugal effects and entrainment were disregarded.

The right-hand side panel of Figure 8 shows that the run-out distance varies by roughly one grid cell length, as is to be expected. This implies that the grid spacing should not be chosen larger than 5 m (or 10 m at most) in consulting projects, so as not to introduce substantial uncertainty due to discretization errors. Surprisingly, the maximum flow depth shows a much more pronounced dependence on the grid spacing, but only in the area where the maximum flow speed begins to diminish (Figure 9). It is not presently clear what causes this effect. Even with a 5 m grid, the peak is about 10% lower than with a 1 m grid. On the other hand, the simulation converges sufficiently well for all practical purposes with a 2 m grid.

The results from the 2 m grid are also practically identical with the ones from a 1 m grid with regard to the maximum flow speed (Figure 9). The initial acceleration increases with the grid spacing. The reason is that the time step grows linearly with the grid spacing and the explicit numerical scheme uses the drag force at the beginning of a time step throughout the entire time step. This underestimates the flow resistance during the acceleration phase.
Figure 8. Comparison of the maximum flow depth along the centerline for different grid spacings from 1 m to 20 m. The left panel shows that finer grid resolution gives a much more pronounced compression peak near the bottom of the flow, yet the run-out distance varies only moderately and within the range expected in view of the finite grid resolution (right panel).

Figure 9. Comparison of maximum flow speed along the centerline of the path (black line) for grid spacings from 1 m to 20 m.

How to set the simulation duration, dump interval, maximum and minimum time step?

Ideally, one would choose a very long duration for the simulation, which would terminate automatically as soon as the avalanche has come to a stop. However, in the present version of MoT-Voellmy, instabilities arising in areas with small flow depth but large flow-depth gradient that can lead to unphysical localized peaks of flow depth and/or velocity. They typically arise when the flow velocity is low, i.e., when the avalanche front has stopped, but some snow in the steeper reaches of the path is still flowing. Except for minor modifications in the deposit distribution, the simulation result will not change any more. Therefore, we recommend to run a first simulation with a sufficiently long duration (60–120 s, depending on avalanche path size) and to note the time when instabilities develop. If the front has already come to a stop, one may repeat the simulation with a simulation time slightly smaller than the beginning of the instabilities.

The dump interval can be set according to the visualization needs. Note that the maximum flow depth and velocity are updated at each internal time step and therefore are completely inde-
dependent of the choice of dump interval. For the sake of good control of the simulation, an interval of 1–2 s is often adequate. A reasonable animation can be produced with a dump interval of 1 s, without producing inordinately large data sets. If a smooth video is desirable, one should choose the dump interval in the range 0.1–1 s.

MoT-Voellmy chooses the length of the computational time step automatically in accordance with the so-called CFL (Courant–Friedrichs–Levy) condition. If strong source terms in hindsight lead to a violation of the CFL condition, MoT-Voellmy repeats the time step. It is useful, however, to impose an upper limit on the time step in order to maintain precision, in particular in steep terrain or with substantial erosion. The default value of 0.2 s should be adequate in most cases, but can be lowered to, e.g., 0.1 s if the terminal output of the code indicates that time steps often have to be repeated. The minimum time step helps to save time when a simulation has diverged. When this occurs, non-physical high velocities typically arise and the time step becomes very small. Setting the minimum time step length will lead to the code aborting in such a situation. For real-size avalanches and a cell size of 5 m, the minimum time step could be chosen somewhat smaller than 0.05 s, but the default value of 0.001 s is also acceptable.

How does one use the stopping criteria?

The stopping criteria will be implemented in a different way in the next version of the code, hence these parameters will not be discussed further in this document. It is recommended to use the default values for the time being.

Recommended parameters when using MoT-Voellmy as a replacement for RAMMS::AVALANCHE

SLF has elaborated a detailed calibration of RAMMS against a number of observed avalanche events from Switzerland, including some from the Vallée de la Sionne test site. The main parameter-fitting criterion is the observed run-out distance. In most of these cases, the extent of the release area and the release depth are not known and were presumably estimated following the methods exposed in the Swiss guidelines (Salm et al., 1990).

Key elements of this calibration are the following:

- The tabulated values are valid for simulations without entrainment. When using entrainment in the simulation, one ought to use a substantially different calibration, but no general guidelines seem to be available at this point.

- Avalanches are categorized into tiny (< 5000 m$^3$), small (5000–25,000 m$^3$), medium-size (25,000–60,000 m$^3$) and large (> 60,000 m$^3$). This is somewhat problematic because there are significant differences between these categories, with abrupt changes of the friction parameters. $\mu$ for a tiny avalanche is typically 50% larger than for a large avalanche while $\xi$ increases by 15–100%. The volume categories do not take into account the shape of the release area: A short, but very wide avalanche may easily fall into the category “large”, but will likely behave as “small”.

- The friction parameters $\mu$ and $\xi = g/k$ are considered spatially variable. In particular, they depend on the altitude zone (below 1000 m a.s.l., 1000–1500 m a.s.l., > 1500 m a.s.l.). As in the case of avalanche size, the transitions are abrupt and the differences between the categories considerable. $\mu$ increases 10–20% from high altitude to low altitude, $k$ by 30–50%. Note that these altitude categories were designed for the Swiss Alps and need to be adapted for use in Norway.

- The friction parameter $\mu$ (but not $\xi$) depends also on the return period of the event, with four categories ($T = 10$ y, $30$ y, $100$ y, $300$ y) indicated in a table. The difference between
$T = 10$ y and $T = 300$ y amounts to 15–20%. Note that the longest return period considered in Switzerland is 300 y whereas return periods of 100, 1000 and 5000 y are relevant for applications to hazard mapping in Norway.

- Terrain curvature also influences the choice of local friction parameters. Four categories are considered: flat, unchanneled, channeled, gully. In a gully, $\mu$ is 70–90% larger than on a flat slope, $k$ increases 70–150% from flat slope to gully.

- The release depth is determined according to the Swiss guidelines (Salm et al., 1990), taking into account the reference three-day-sum of snow depth increase for the considered return period (at an altitude of 2000 m a.s.l.), the precipitation gradient, the slope angle, and the wind exposure. Note that it is assumed that the initial flow depth is equal to the release depth, even though the density of the avalanche is assumed to be 300 kg/m$^3$, while new snow has a typical density of 100 kg/m$^3$ and measurements in release zones typically yield values around 200 kg/m$^3$. If the collapse of the avalanching snow were taken into account, $k$ should be rescaled by a factor $(200 \text{ kg/m}^3) / (300 \text{ kg/m}^3) = 0.67$ (the retardation due to the Coulomb friction term is independent of the flow depth).

- In forested areas, SLF recommends to increase $\mu$ by 0.02 and to set $k = 0.025$ independent of avalanche size, return period, altitude, terrain curvature, etc. The recommendations do not stipulate dependence on the forest density either.

Extensive use of RAMMS in consulting projects in Norway indicates that one obtains plausible run-out distances in most cases with these parameters if the altitude categories are adapted to the Norwegian climate. In most applications at NGI, the three categories I (0–500 m a.s.l.), II (500–1000 m a.s.l.) and III (> 1000 m a.s.l.) have been used. Using timberline as a proxy for climate and recalling that timberline varies between 1800 and 2300 m a.s.l. in the Alps, one might consider applying only categories II and III in Norway, with the boundary between them ranging from 700 m a.s.l. (southern Norway) to sea level (Finmark and Svalbard).

One can use MoT-Voellmy in the same way as RAMMS::AVALANCHE if the parameters are locally variable and are determined according to the tables published for RAMMS. Presently, there is no automated calculation of the friction parameters available as in RAMMS, but using ArcGIS functions one easily evaluates the curvature and can use raster algebra to reproduce the algorithms of RAMMS for calculating the friction parameters.

Figures 10 and 11 show the results of simulations of an avalanche at the Ryggfonn test site with both MoT-Voellmy and RAMMS, using the same terrain model, initial conditions and friction parameters in both cases. The initial conditions correspond to the estimated release area and depth of the 1993-03-27 avalanche event. The friction parameters were chosen in accordance with SLF’s recommendations, with the altitude intervals lowered by 500 m to account for the lower altitudes at which sub-alpine and alpine conditions occur in Norway (see the discussion above). Snow entrainment was neglected in both cases. Comparing the maximum flow depth (Figure 10), one sees that the two models give quite similar results, although MoT-Voellmy appears to be somewhat more diffusive. This manifests itself primarily in the somewhat lower maximum flow depths. The width of the area touched by the avalanche is not a reliable indicator in itself for this because RAMMS appears to do some “sharpening” of the boundary during post-processing by suppressing areas where there is a very thin deposit. The run-out distances agree to about 15 m, with RAMMS stopping farther on the right-hand (eastern) side and MoT-Voellmy stopping farther on the left-hand (western) side. The overflow patterns at the catching dam are also quite similar.
Somewhat larger differences occur with regard to the velocities (Figure 11). MoT-Voellmy shows a fringe of low-velocity flow on either side of the main gully and in the more open stretch between the concrete wedge and the catching dam as well. In a small ravine east of the main gully, RAMMS predicts a very narrow flow (less than 10 m) at velocities below 5 m/s, whereas

Figure 11: Comparison of maximum flow depth between MoT-Voellmy (left-hand panel) and RAMMS (right-hand panel) for identical initial conditions and friction parameters.

Figure 10: Comparison of maximum flow speed between MoT-Voellmy (left-hand panel) and RAMMS (right-hand panel) for identical initial conditions and friction parameters.

Somewhat larger differences occur with regard to the velocities (Figure 11). MoT-Voellmy shows a fringe of low-velocity flow on either side of the main gully and in the more open stretch between the concrete wedge and the catching dam as well. In a small ravine east of the main gully, RAMMS predicts a very narrow flow (less than 10 m) at velocities below 5 m/s, whereas
MoT-Voellmy indicates a wider flow (20–30 m) and velocities of 5–10 m/s in the middle. According to RAMMS, the avalanche attains a maximum velocity around 40 m/s, whereas the smaller flow depth in MoT-Voellmy reduces this to about 35 m/s.

An undesirable feature of the current version of MoT-Voellmy are the spurious high velocities in the compression zone just upstream of the dam. This phenomenon appears to arise due to so-called checkerboard oscillations, which are a consequence of the simple numerical scheme: The highest wavenumber components of the earth pressure gradient do not couple properly to the velocity field and thus can grow rapidly. Work is in progress on the numerical aspects of the code, with a focus on this issue: We have introduced a staggered grid, which defines the flow depth at the cell centers as before, but localizes the velocity components in the middle of the cell boundaries.

**Recommended parameters when using MoT-Voellmy as an extension of the PCM-type block models in accordance with the \( \alpha - \beta \) model**

It is not possible at this point to use MoT-Voellmy as a quasi-3D version of the PCM model (but such an option could easily be implemented in 2015). The difference between the Voellmy and PCM models lies in the flow-depth dependence of the drag term:

\[
\sigma_{drag}^V = \frac{u^I}{|u|} \left( \frac{D}{M} \frac{\rho u^2}{k u^2} \right), \quad \text{PCM}
\]
\[
\sigma_{drag}^V = \frac{u^I}{|u|} \left( \frac{D}{M} \frac{\rho u^2}{k u^2} \right), \quad \text{Voellmy}
\]

While the parameter \( k \) in the Voellmy model is dimensionless, the mass-over-drag ratio \( M/D \) in the PCM model has the dimension of a length and the drag at the bed is proportional to the flow depth. This makes the acceleration in the PCM model independent of the flow depth (except for the earth-pressure term), while the drag force per unit mass diminishes with increasing flow depth in the Voellmy model.

However, if the flow depth is roughly constant along the path, the differences between the Voellmy and PCM models are not very large and the recommendations given in Deliverable D1.2 apply in a similar way in the quasi-3D model. The following considerations are important, however:

- The length of the release area—and to some degree, its width— influences the run-out distance. In the PCM-type block models, a similar dependence arises on the release length (but not on the release width) only if the option of finite slab length is chosen.

- The earth-pressure term in MoT-Voellmy leads to considerable spreading of the flow. On the one hand, this will tend to increase the run-out distance somewhat because the front is pressed forward, but on the other hand, it also increases the drag because the flow depth diminishes. Which effect dominates depends on the terrain properties.

- In both the block models and MoT-Voellmy, one may either include centrifugal forces or neglect them. Their effect is to increase dry friction in concave bends and to decrease the run-out distance typically by some tens of meters. The recommended parameters refer to simulations without centrifugal effects; if they are accounted for, the friction parameters \( \mu \) and/or \( k \) should be reduced somewhat. No general rule can be given as of now, but for a given avalanche path, one may obtain an indication of the required change of parameters by first running a simulation without centrifugal effects and then adjusting the parameters \( \mu \) and \( k \) such that the same run-out distance is obtained with the centrifugal effects included.
How should one include entrainment of the snow cover?

Note that one needs to recalibrate the model if entrainment is included. Generally, one expects the range of the friction parameters to become narrower if an important physical process like mass growth is included. However, the erosion models used in practice today introduce yet another parameter that cannot be fixed from physical consideration, but must be calibrated (Eglit & Demidov, 2005). MoT-Voellmy implements the (dynamically inconsistent) formula present in some versions of RAMMS,

\[ q_e = \rho_p |u|, \]

which is independent of the snow-cover properties and has a coefficient \( c \) that needs to be set by the user. In addition, MoT-Voellmy offers a formula that is consistent with the Voellmy friction law, does not have user-selectable coefficients, but requires specifying the shear strength, \( \tau_c \), of the erodible snow cover:

\[
q_e = \begin{cases} 
0 & \text{if } |u| \leq \frac{\tau_c - \mu g h \cos \theta}{k \rho}, \\
\frac{k u^2 + \mu g h \cos \theta - \tau_c}{\rho u} & \text{else}. 
\end{cases}
\]

Figure 12. Comparison of two simulations with MoT-Voellmy using the same initial conditions and friction coefficients. Left panel: RAMMS entrainment formula with \( c = 0.2 \). Right panel: Consistent entrainment formula, snow shear strength varying with altitude.
Figure 13. Depth of the remaining snow cover for the two simulations shown in Figure 12. The erodible snow depth was assumed to be 1 m. Left panel: The RAMMS erosion formula is independent of the flow depth and thus sensitive to the numerical diffusion of the model. Complete erosion of the snow cover occurred far to the sides of the release areas. Right panel: The consistent erosion formula is insensitive to such spurious effects. The erosion depth is smaller or 0 at the edge of the flow, where the shear stress not always exceeded the erosion threshold.

From laboratory tests of natural snow and field observations, one may deduce that typical values of $\tau_c$ are in the range 0.5–2 kPa.

This formula is dynamically consistent with the postulated Voellmy friction law and the assumed uniform velocity profile (implying slip at the base), but it is not consistent with more physically meaningful rheologies, like the proposal by Jop et al. (2006) or the frictional-collisional model by Issler (2014). Figures 12 and 13 show a comparison of the two erosion models under the same initial conditions. It is clearly advisable to use the consistent formula instead of the RAMMS formula with the parameter $c$ in the range suggested by SLF. One obtains results that are more reasonable if $c$ is set equal to $k$, i.e. two or three orders of magnitude smaller. Then the RAMMS formula will asymptotically (for $u$ tending to infinity) agree with the consistent formula.

Direct comparison with field observations is not presently possible because the shear strength of the snow cover at an avalanche site has not been measured hitherto, but values in the range expected from measurements in other situations gives plausible simulation results.
Summary of the recommendations

A number of preliminary conclusions follow from the discussions and the numerical experiments presented above, even though we could run and analyze only a restricted number of simulations in this work:

- MoT-Voellmy may serve as a replacement for RAMMS::AVALANCHE unless 100% compatibility with the results produced by RAMMS is required. The differences due to the different numerical methods of the models are typically much smaller than the uncertainty in the initial conditions and the well-known general shortcomings of the Voellmy ansatz.

- MoT-Voellmy is somewhat more diffusive than RAMMS, and this may result in smaller flow depths and lower velocities, but the run-out distances are very similar.

- When detailed information becomes available from SLF on the algorithm used to determine the locally varying friction parameters, the same algorithm can be implemented in NGI’s GIS-based workflow. However, it is questionable whether this complicated calibration of a too simplistic model is useful in the long term. As discussed in Deliverable D1.2, the calibration is based on run-out distances and underestimates the velocities critically in some cases.

- Deliverable D1.2 summarizes a strategy for choosing the friction parameters in the PCM block model so that they are consistent both with the run-out predictions of the $\alpha$-$\beta$ model and velocity measurements at different sites. With MoT-Voellmy one can take essentially the same approach, but the drag friction coefficient $k$ should be chosen somewhat smaller than $(M/D)/h_0$ in order to compensate for the diminishing flow depth due to lateral and longitudinal spreading of the flow. It remains to establish, however, whether one should choose different $\mu$ and $k$ values for different return periods or whether the dependence of the run-out of an avalanche on its return period is solely due to the variation of the release depth $h_0$ with the return period.

- In contrast to the PCM model, the release depth has a definite influence on the run-out distance and speed of avalanches as predicted by RAMMS and MoT-Voellmy. The general approach stipulated by the Swiss guidelines (Salm et al., 1990) appears applicable to Norwegian conditions as well, but there is presently much uncertainty as to the altitude dependence of three-day snowfall sums and the wind effect. In many cases, estimates of the conditional release probabilities given various snow-depth increases are essential for obtaining realistic run-out estimates.

- The user needs to estimate the extent of the release area for different return periods. If the simulation includes snow entrainment, the release area of an actual avalanche typically is only a fraction of the potential release area (i.e., the area of sufficient steepness). If entrainment is not simulated directly, the release area should be chosen larger than the likely area of primary fracture and include some of the secondary release areas or the area where much snow is entrained. However, experience shows that unrealistic run-out distances often result if the entire potential release area is included, particularly with large avalanches. The Austrian practice of limiting the release area to at most 300 vertical meters appears plausible.

- We cannot presently give firm recommendations as to the choice of the friction parameters when including snow entrainment. Work on this problem is ongoing at several institutes.
References


