Swiss Avalanche-Dynamics Procedures for Dense Flow Avalanches

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Introduction

In Switzerland the Voellmy-Salm model is used for estimating avalanche flow speeds, flow heights and runout distances. The model has been calibrated against observed runout distances of large avalanches. SFISAR has published guidelines for practitioners including examples. The guidelines are available in German and French from SFISAR. A PC-code with menus and helps in German, French, Italian, Spanish and English is also available from AlpuG. This paper summarizes the most important assumptions and features of the method. For more details and examples please refer to the guidelines.

Model assumptions

- Constant flow rate along the track (continuity),
- Incompressibility of the flow,
- Steady flow in the track,
- Non-steady quasi-rigid-body movement of the avalanche in the runout,
- Variations of flow height along the track are small.

Model parameters

- Flow rate at the beginning of the track or fracture depth, release area and slope angle,
- turbulent friction coefficient,
- kinetic friction coefficient,
- cross section and slope angles in track and runout.

Determination of parameters

The most critical parameter is the flow rate. Flow rate depends on topography and fracture depth. Statistical values depending on mean return period and slope angle are used to obtain fracture depth. They have been evaluated from extreme-value statistics of new snow accumulation during 3 days for every climate region in the Swiss Alps. The software supports the estimation of initial flow rate in complex terrain. The kinetic friction

parameter is tabulated in function of avalanche size (flow height) and snow type (dry, wet). The turbulent friction parameter is tabulated in function of ground roughness and cross section of the flow (channelled, open slope).
There are special rules for selecting the beginning of the runout which is basically determined by the kinetic friction angle. Flow speed and flow depth calculations depend critically on the length of the track segment selected. If cross section of the flow and steepness of the track vary along the track above the point of interest, mean slope angle and typical cross section for the track segment depend on segment length. The segment length is determined by the distance necessary for the flow to reach approximately "normal" flow again (length of segment of transition flow). Therefore the length of the track segment determining flow speed and flow depth at the beginning of the runout or at any other point in the track has to be chosen according to strict rules.

Standard calculation

- Selection of the friction parameters based on characteristics of avalanche and track.
- Estimation of discharge rate. Most critical!
- Determination of beginning of runout.
- Determination of speed and flow height at selected points in the track, at least at the end of the track.
- Determination of runout distance, deposition height. If necessary, segmentation of the runout. Calculation of speed at selected positions.
- Determination of the 30kPa boundary for zoning.
- Estimation of dynamic pressure and forces on deflection walls, small obstacles, gallery roofs, pylons etc. at selected locations.

Limitations

- All calculations depend on the estimation of the discharge rate!
- Method and parameters are calibrated against runout distances of extreme avalanches!
- Overestimation of deposition heights.
- Underestimation of speeds of large dry avalanches in steep tracks.

The Swiss avalanche-dynamics analysis subdivides the avalanche path into starting-zone, track, and runout-zone sections of constant slope, that are analyzed separately according to strict rules. In the starting zone, released slab thickness, d_o, is determined from statistical analysis of precipitation data from several Swiss mountain areas. Starting-zone area, A, is determined from 1:10,000 or 1:25,000-scale topographic map study and terrain analysis, and the volume, K, is calculated from

$$K = A\, d_o. \qquad \text{(Eq. 1)}$$

Discharge, Q [m^3/s] of snow flowing through the bottom of the starting zone is computed as

$$Q = W_o d_o v_o, \qquad \text{(Eq. 2)}$$

for rectangular starting zones where W_o is average width. Velocity, v_o, at the end of the starting zone, is computed according to

$$v_o = [d_o\, \xi\, (\sin \Psi - \mu \cos \Psi)]^{1/2}. \qquad \text{(Eq.3)}$$

The parameters (μ and ξ) have not been directly measured but have been calibrated by fitting observed run-outs with the model, see tables. The turbulence coefficient, ξ, is varied from 400 to 1000m/s^2 (larger values may be appropriate for very large dry avalanches in cold climate), and the dynamic friction coefficient μ is varied from 0.155 to 0.30. ξ depends on track shape (laterally confined or unconfined) and bed roughness, μ depends on avalanche volume and type (wet or dry). Ψ is the mean slope angle of the starting zone.

Discharge, Q, from an irregular or bowl-shaped starting zone is calculated as

$$Q = K/\Delta t\,, \qquad \text{(Eq. 4)}$$

where Δt is the time required to discharge snow from the starting zone. The discharge time, Δt is calculated as $\Delta t = l/v_m$ where v_m is average velocity (Eq.3) over the starting zone length l, the latter being a representative distance from the top to the bottom of the starting zone.

The velocity at the bottom of the avalanche *track,* v_p, is computed at the lower end of a "control section" of track, a reach of typically a few hundred meter in length, at the end of which flow is assumed to reach constant velocity (segment of flow transition). The control section length, x_u, is approximately equal to

$$x_u = 0.7\ (\frac{\xi}{g})d_p \qquad \text{(Eq.5)}$$

where

$$d_p = \frac{Q}{W_p v_p}. \qquad \text{(Eq.6)}$$

The velocity, v_p, at the bottom of the control section of track in unconfined avalanches is computed

$$v_p = [(\frac{Q}{W_p})\ \xi\ (\sin\ \Psi_p\ -\ my\ \cos\ \Psi_p)]^{1/3} \qquad \text{(Eq.7)}$$

Typical values for μ and ξ

ξ [m/s^2]	Conditions (independent of avalanche size!)
> 1000	- very cold dry snow - only moderately channelled avalanches - very low bed roughness.
1000	- low bed roughness - unconfined or only moderately channelled (flow width to flow depth > 10:1)
500 - 600	- large bed roughness (order of m) - channelled flow (flow width to flow depth 1:1 to 1:2)
400	- avalanche flowing through a forest

μ	Conditions
0.155	- extreme avalanches (rare avalanches with very large volumes > 10^6m^3) - higher altitudes, dry cold snow - flow depth > 1 to 2m
0.20	- as above but for dry snow at higher temperatures, lower altitudes
0.25 - 0.30	- smaller avalanches with lower mean return periods and volumes < 10^4m^3. - flow heights 1 to 2m. - independent of snow type.
0.30	- wet snow avalanches of any size.

where W_p is average avalanche width within the control section, Ψ_p is track inclination in the control section, and Q has been determined in the starting zone calculations. Average track width W_p in the control section will be different from starting-zone width or upper track width in many paths; width affects the computed flow depth and velocity. In the track of laterally confined or channelized avalanches

$$v_p = [R\xi(\sin \Psi_p - \mu\cos \Psi_p)]^{1/2}, \qquad \text{(Eq.8)}$$

where the hydraulic radius $R= A/L$, A is the channel cross-sectional area and L is the channel "wetted perimeter". The friction parameters may have to be modified for the calculations in the track compared to those chosen for the starting zone. This part of the calculation has to be iterated to fulfill the condition $Av_p = Q$.

The length of the control section, corresponding mean slope angle and lateral confinement are determined on the map and have to be varied to approximately match the theoretical length of the control section (Eq.5).

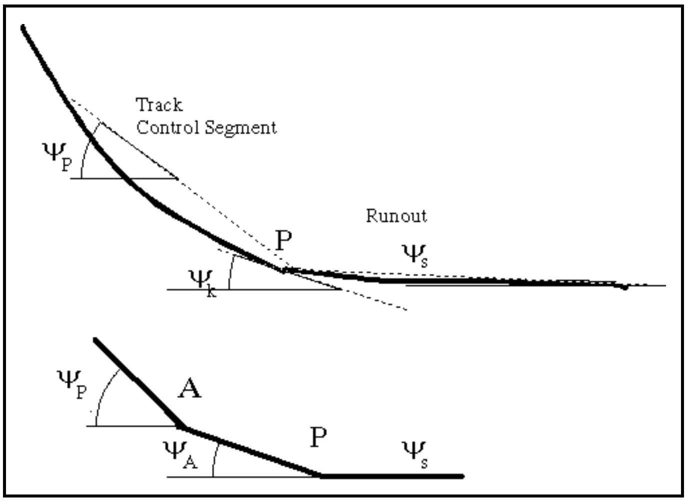

Fig.1 How to select the control section, points P and A . Ψ_p , Ψ_A , Ψ_S are mean slope angles for respective sections, Ψ_K the critical angle.

The *runout zone* is assumed to begin at *P*. The slope steepness at *P* is determined by the value of the friction coefficient μ, therefore the slope angle at *P*, Ψ_K is equal to $\tan^{-1}$ (μ), and the average angle below this point must be less than $\tan^{-1}$ (μ), see Fig. 1. Note that Ψ_p is not the slope angle at P but the average slope angle in the control section. Therefore the runout calculations begin on more gentle slopes when larger avalanches are calculated because the assumed μ values will be smaller. If the slope angle changes only gradually at *P*, then the control section ends above *P* at A (Fig. 1), at a point where the local angle approximately equals $\tan^{-1}\mu+3.5°$. Although the control section now ends above *P*, runout calculations begin at the original point *P*, it being assumed that velocity and flow depth will not change significantly between the bottom of the control section (point A) and *P.*

The equations follow from time dependent modelling of the movement of the front element of the avalanche. The model assumes a linear decrease of the speed squared, v^2, in the runout zone. In some cases the μ and ξ values have to be modified in the runout to consider conditions different from those in track and release zone.

Runout distance, s, below the point *P* is computed according to

$$s = \left(\frac{d_s}{2g}\right) \ln\left[1 + \left(\frac{v_p^2}{V^2}\right)\right] \qquad \text{(Eq.9)}$$

where *g* is the gravitational acceleration. Avalanche width in the runout zone may be assumed to be different from the width at the point *P* and must be based on local terrain analysis. An increase in width will decrease flow depth and runout distance while a decrease will increase flow depth and runout. Deposit height, d_s, and a velocity parameter, *V*, used in (Eq.9) are defined by:

$$d_s = d_p + \frac{v_p^2}{4\lambda g} \qquad \text{(Eq.10)}$$

$$V^2 = d_s\, \xi(my \cos \Psi - \sin \Psi). \qquad \text{(Eq.11)}$$

The parameter λ accounts for the efficiency of transfer of kinetic energy (particle speed) to potential energy (flow height). Part of the kinetic energy is dissipated as heat by internal friction. λ is chosen to be equal 2.5.

When significant slope changes occur within the runout zone below *P*, the velocity may be interpolated by the relationship

$$v_{p2}^2 = v_{p1}^2 \left(1 - \frac{x}{s}\right) \qquad \text{(Eq.12)}$$

where v_{p1} is the calculated velocity at the point *P*, *s* is the runout distance given the initial slope, velocity, and flow height at *P* and *x* is the interpolation distance. This interpolation procedure can be repeated as many times as necessary if the runout-zone slope is irregular. In addition to velocity interpolation in the runout zone, the remaining mass of the avalanche can also be reduced with distance in the runout zone. This is done by reducing discharge, *Q*, flowing into additional runout segments. A reduction of *Q* reduces the flow depth and runout distance.

In the software an improved model for the runout calculations has been included (Salm, 1993). Avalanche motion is modeled as a flexible, sliding sheet (very high internal friction, λ' =20). Speed declines faster in function of runout distance compared to the standard model and deposition height is reduced to more realistic values. With respect to the traditional model it can be concluded that the runout distance is only slightly changed, therefore Eqs. 9 to 11 can be maintained, eq. 12 overestimates speeds and can be applied safely.

The Swiss avalanche-dynamics calculating procedure requires a careful estimation of its input parameters as fracture height and/or flow rate. The friction parameters should be chosen along the rules stated above or have to be carefully recalibrated with local data of extreme avalanches. As with every model, critical assessment of the results is very important and depends on the experience of the consultant.

Although the Swiss method does require the user to determine one more input parameter (turbulence coefficient dependent on track cross section and roughness) than e.g. the PCM or topographical model, more detail is produced for use in engineering applications. If the user has excellent topographic maps and detailed, long-term weather and snow pack records, the Swiss method can provide estimates of velocity, flow depth, discharge, and runout distance.

Furthermore, release volume and track cross-sectional shape can be considered in the Swiss model but not in the PCM or topographical models which consider only avalanche path profile. Other factors being equal, runout distance will be substantially longer below a channelized (V-shaped) track than below an unconfined track because discharge, *Q*, is assumed constant in the track from stauchwall to point *P*, the beginning of the runout zone, and flow depths tend to increase in channels.

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