Geophysical Research Abstracts
Vol. 16, EGU2014-10971, 2014
EGU General Assembly 2014

Influence of bed surface changes on snow avalanche simulation

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Gravitational flows, such as snow avalanches, are often modeled employing the shallowness assumption. The driving gravitational force has a first order effect on the dynamics of the flow, especially in complex terrain. Under suitable conditions, erosion and deposition during passage of the flow may change the bed surface by a similar amount as the flow depth itself. The accompanying changes of local slope angle and curvature are particularly significant at the side margins of the flow, where they may induce self-channeling and levée formation. Generally, one ought to expect visible effects wherever the flow depth and velocity are small, e.g., in deposition zones.

Most current numerical models in practical use neglect this effect. In order to study the importance of these effects in typical applications, we modified the quasi-3D (depth-averaged) code MoT-Voellmy, which implements the well-known Voellmy friction law that is traditionally used in hazard mapping: The bed shear stress is given by

$$\tau_{iz}(h,\mathbf{u}) = -\frac{u_i}{||\mathbf{u}||}(\mu g h \cos\theta + k\mathbf{u}^2), \tag{1}$$

with $\mu = \mathcal{O}(0.1\ldots0.5)$ and $k = \mathcal{O}(10^{-3}\ldots10^{-2})$ the dimensionless friction and drag coefficients, respectively. The leading curvature effects, i.e., extra friction due to centrifugal normal forces, are taken into account. The mass and momentum balances are solved by the (simplified) method of transport on a grid whose cells are squares when projected onto the horizontal plane. The direction of depth-averaging is everywhere perpendicular to the topographic surface.

A simple erosion model is used. The erosion formula is based on the assumption that the snow cover behaves as a perfectly brittle solid with shear strength τ_c, above which it instantaneously fails. The erosion rate is derived from the balance of momentum across the interface between bed and flow, where there is a discontinuity of the shear stress, which is given by equation 1 just above the interface and by τ_c just below it according to the assumptions. This immediately leads to the formula

$$q_e = \frac{\mu g h \cos\theta + k\mathbf{u}^2 - \tau_c/\rho_f}{||\mathbf{u}||}\Theta(\mu g h \cos\theta + k\mathbf{u}^2 - \tau_c/\rho_f). \tag{2}$$

We present numerical simulations with static and dynamic beds in two different cases. First, an avalanche simulation on an inclined plane allows to study the occurring effects in their most immediate form. This allows to study the influence of spatial resolution of the computational grid. Second, we back-calculate a typical mid-size avalanche that was measured and documented in 1993 at the Norwegian test site Ryggfonn. This case study serves to test the relevance of including bed surface changes under conditions typical of real-world applications.