

## Comments on the paper

### Computational snow avalanche simulation in forested terrain

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submitted to: NHESS

Paper # NHESS-2013-294

#### General comments

The authors present a statistical analysis of runout simulations with the avalanche simulation software RAMMS for small- to medium-size avalanches in forested terrain.

Generally, the topic is of high interest for readers of the Journal. The paper is reasonable well written.

However, the paper is not fully self-contained. This makes it hard for the reader to evaluate the physical basis of the model approach for himself. The description in the present paper is insufficient as a stand-alone.

The physical basis of the model approach is described in more detail in the paper

Feistl, T.; Bebi, P.; Teich, M.; Bühler, Y.; Christen, M.; Thuro, K. & Bartelt, P. Observations and modeling of the braking effect of forests on small and medium avalanches Journal of Glaciology, 2014, 60, 124-138

According to this paper the governing equations of the model are the following depth-averaged mass- and momentum-balance equations:

$$\frac{\partial h}{\partial t} + (\mathbf{V} \cdot \nabla) \mathbf{h} = \dot{\mathbf{Q}} \quad (1)$$

and

$$\frac{\partial(h\mathbf{V})}{\partial t} + (\mathbf{V} \cdot \nabla)(h\mathbf{V}) = \mathbf{G} - \mathbf{S} - \frac{1}{2} \nabla(\mathbf{g}_z h^2) \quad (2)$$

where

- $h$  is the flow height
- $\mathbf{V}$  the velocity vector
- $\mathbf{G}$  gravitational acceleration
- $\mathbf{S}$  the flow resistances
- $\dot{\mathbf{Q}} = -\dot{h}_d$  the detrainment rate
- $h_d$  is the mean deposition due to stopped mass in the forest

Using Eqs (1) and (2), one obtains after some rewriting the equation of motion

$$\frac{\partial \mathbf{V}}{\partial t} + (\mathbf{V} \cdot \nabla)(\mathbf{V}) = \frac{\mathbf{G}}{h} - \frac{\mathbf{S}}{h} - \frac{1}{2h} \nabla(g_z h^2) + \dot{h}_d \mathbf{V} \quad (3)$$

The last term on the right side implies that detrainment could contribute to accelerate the avalanche, which is definitely not the case. Compare e.g.

Iverson, R. M. Fernando, H. J. S. (ed.) Handbook of Environmental Fluid Dynamics 43 Mechanics of Debris Flows and Rock Avalanches CRC Press, 2012, 3, 573-587

or discussion

Erlichson, H. A mass-change model for the estimate of debris-flow runout: A discussion: a second discussion: conditions for the application of the rocket equation Journal of Geology, 1990, 99, 633-634.

With respect to the equation of motion, detrainment should only cause a reduction of mass and in this way influence the flow height of the avalanche and not cause directly an acceleration or deceleration. The last term in (3) should actually read  $\dot{h}_d \Delta \mathbf{V} = \dot{h}_d (\mathbf{V} - \mathbf{V}_d)$ .  $\mathbf{V}_d$  is the velocity of the detrainment mass at the boundary. The term  $-\dot{h}_d \mathbf{V}_d$  arise from the application of the Leibniz rule during the dept averaging procedure (see, e.g., above mentioned reference (Iverson, 2012)). In the case of entrainment  $V_d$  might be set to zero and this term disappears. However, this is not the case for detrainment (without out regarding the velocity profile in detail). Conceptually, in a depth averaged model the mass will leave the avalanche at a velocity of  $\mathbf{V}_d \approx \mathbf{V}$  so that the the last term  $\dot{h}_d \Delta \mathbf{V}$ , which should appear in (3), is actually zero. A similar term appears, if one also includes for example entrainment of air, at the top surface.

At this point, I'm not sure if this only an failure in the description or also a failure in the implementation of the model approach. Therefore, I can't evaluate the soundness of the modeling approach, but I've my doubts.

The consideration above are also applicable to the Eqs (1) - (3) in the present paper.

However, I agree that mass loss or as the author name it "detrainment" contributes to the momentum loss. This, however, is a singular/local effect during the "first" impact of the avalanche. The duration of this process (per tree) is approximately

$$t_d \approx \frac{M_d}{\rho_a Q_a} \approx \frac{l_d}{\|\mathbf{V}\|} \quad (4)$$

- $t_d$  time of deposition
- $\|\mathbf{V}\|$  avalanche speed
- $l_d$  length of the deposit
- $M_d$  mass which is deposit per tree (group of trees)
- $Q_a$  volume flux of the avalanche
- $\rho_a$  density of the avalanche

In their approach, the author try to average the effect and to disturb it over the whole area and time during which the avalanche passes a location. In this case detrainment rate needs to be adapted to

$$\dot{h}_d \approx \frac{h_d}{t_a} = \frac{h_d l_a}{\overline{\|\mathbf{V}\|}} \quad (5)$$

- $t_a$  time the avalanche needs to pass the tree ( $t_a \gg t_d$ )
- $\overline{\|\mathbf{V}\|}$  mean avalanche speed
- $l_a$  length of the avalanche

This might be possible for back calculations if one can estimate the time at a location, but makes predictions difficult as the detrainment rate depends in this case on the avalanche length and velocity.

Using eq (6) of the present paper one could get an estimate of the detrainment coefficient

$$K \approx \frac{\rho h_d \overline{\|\mathbf{V}\|}}{t_a} \approx \frac{\rho h_d \overline{\|\mathbf{V}\|}^2}{l_a} \quad (6)$$

This suggest that K should be a function of the expected avalanche length and speed and not solely a function of the forest structure.

On the other side, Netwon's III law implies that as long the avalanche passes a tree, the tree will cause a retarding/reaction force onto the avalanche depending on the avalanche velocity, flow height etc. At present, I'm not convinced that this retarding force is negligible compared to the effect of mass loss, like the authors do.

The contribution due to the force on a single tree may be written

$$F_{tree} = \rho C_D(\mathbf{V}) d_t h \frac{\mathbf{V}^2}{2} \quad (7)$$

where

- $d_t$  is the diameter of tree trunk (or group of trees)
- $C_D(\mathbf{V})$  is the drag factor, which may depend on the flow velocity

To obtain an estimate of the importance of this contribution, one can look at the equation of motion (here for simplicity only written for a simple mass block model using a Voellmy rheology):

$$\frac{dU}{dt} = g \sin \phi - \mu g \cos \phi - \frac{gU^2}{\xi h_0} \left( 1 + \frac{\Delta h}{h_0} \right) - d_t N_A C_D(\mathbf{V}) \frac{U^2}{2} \quad (8)$$

where

- $d_t$  is the diameter of tree trunk (or group of trees)
- $N_A$  is the number of trees per  $m^2$
- $h_0$  is the flow height
- $\Delta h = -\dot{h}_d dt$  is the change in flow height due to detrainment per time step .

Here, Taylor series for the flow height,  $h$ , is used to include the effect of detrainment. To be consistent in mass conservation during detrainment

$$\dot{h}_d \approx \frac{N_A W \bar{U}}{l_a} \quad (9)$$

where

- $W$  is the detrained volume per tree (group of trees).
- $\bar{U}$  is the mean avalanche velocity and
- $l_a$  the length of the avalanche.

To get an estimate of the contribution due to the reaction force due to trees and the detrainment let us some example values (given in (Feistl,2013)). For simplicity let also us  $h_d = 0.02$  m as a upper limit for  $\Delta h$ ,  $h_0 = 1$  m,  $N_D = 0.04$  m<sup>-2</sup> (corresponding to 400 tree per ha),  $C_D = 1$ ,  $\xi = 1500$  m s<sup>-2</sup>, and  $d_t = 1$  m:

$$\frac{N_D C_D d_t}{2} \approx 0.02 \text{ m}^{-1} \quad (10)$$

$$\frac{g}{\xi h_0} \approx 0.002 \text{ m}^{-1} \quad (11)$$

$$\frac{g \Delta h}{\xi h_0^2} \ll 0.0002 \text{ m}^{-1} \quad (12)$$

From this brief estimate one see that the reaction force may have a significant influence and is in no way negligible. The importance of the turbulent friction and the detrainment increases as the flow height decreases.

These are rough estimates but suggest that the proposed modeling approach is not physically sound.

**Therefore, I propose a major revision, in which the authors at least justify why they neglect the reaction forces. Furthermore, that they check the implementation of the model and improve the description of the actual model.**

The second part of the paper describes modeling study which may give reasonable empirical values for the regarded cause, but are based on a doubtable numerical model approach.

#### Specfic comments:

- line 9 page 5567:  $g_n$  is the surface normal component of the vector of gravitational acceleration  $g = (0, 0, g_z)$ . *Your vector  $(g_x, g_y)$  should only be slope parallel.*
- line 10 page 5567:  $\|\mathbf{U}\|$  is the magnitude and direction of the mean flow.  $\|\mathbf{U}\|$  *does not have a direction.*
- line 2 page 5568: “The extracted mass stops promptly and, thus, is instantly subtracted from the flow...” *This is what happens, but it is not how you try to model it. Your approach needs a better description in this paper that the paper is self-contained.*
- line 7 page 5568: The use of Pa as unit for  $K$  is deceive even formally is correct.  $K$  describes the mass loss / detrainment and not a stress, I propose to use kg m<sup>-1</sup> s<sup>-2</sup>.
- line 12 page 5568: As mentioned  $K$  accounts for the detrainment and not for the braking power.
- “This relationship indicates that the higher the velocity the less snow is removed from the flow.” *No, amount of snow removed from the flow is independent of the velocity. The relationship indicates at which rate you have to extract snow in your model to have extracted the right amount of snow at the end in your model. With that your rate should be depended on the avalanche length and its mean velocity.*
- line 4 page 5571:  $\mu$  is dimensionless.

- line 5 page 5575: ... difference  $\Delta runout_{ref}$  (Eq. 11) revealed overestimations by RAMMS up to 700% for the chosen parameters  $K = 0$ ,  $\mu = 0.29$ , and  $\xi = 1500 \text{ ms}^{-2}$ .
- line 25 page 5579: still overestimated when applying the smallest chosen  $\xi$  value of  $100 \text{ ms}^2$  ... *This is no surprise. As long as  $\tan \phi > \mu$ , a Voellmy model will not stop.*
- line 25 page 5579: still overestimated when applying the smallest chosen  $\xi$  value of  $100 \text{ ms}^2$  ... *This is no surprise. As long as  $\tan \phi > \mu$ , a Voellmy model will not stop.*
- line 6 page 5580: forests influence ( $K = 0$ ) highlight the importance of modeling local braking effects of forests on avalanche flow. *as I understand your approach you are not modeling a braking rather than mass loss. That this could lead enhanced braking is a secondary effect in your case due to a possible reduction in flow height.*
- fig 7: Figure 7 is meaningless without an indication of the topography. Furthermore, to me it looks like there is quite a discrepancy between the observations and the simulation in the figure on the right.