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On the formulation of entrainment in depth-averaged gravity mass-flow models

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A number of recent studies on the formulation of entrainment terms in depth-averaged gravity mass flow models disagree on several fundamental issues. Perhaps the most practically important among them is whether an "entrainment force" equal to the entrainment rate times the mean flow velocity should be introduced in the momentum balance equations in conservative form or not. In strongly entraining, fast snow avalanches, it is equivalent to an extra retarding shear stress on the order of 1 kPa, similar in magnitude to the Mohr-Coulomb friction force that would be specified for such avalanches in typical avalanche models. We show how an integration of the fundamental conservation equations for mass and momentum, combined with a precise definition of the interface between the flow and the bed allow to find an unequivocal answer. For most dynamical flow models, where the bed is at rest, the entrainment force term is found to be zero. It may be non-zero when fast particles impact on the bed and are absorbed or eject other particles, or at the upper surface of turbulent suspension flows that entrain recirculating ambient air. Similar arguments can be applied to the deposition of flowing material.

Another debated question is whether the force required to break the bonds in the bed material has to be added to the friction term (in many cases the Mohr-Coulomb friction supplemented with some velocity-dependent drag) or is already included therein. We analyze this problem in the case of a quasi-stationary, but entraining flow, distinguishing between the processes of breaking particles loose from the bed (termed erosion) and their acceleration and mixing into the main flow (entrainment). In many materials, erosion requires a threshold shear stress at the interface between the intact bed and the flow (including particles just ripped out of the bed). Entrainment, in contrast, induces

a positive shear stress gradient near the bed. We discuss how the velocity profile is influenced by this and argue that in many situations, the bed shear stress will fluctuate around an equilibrium value that coincides with the threshold stress.