Fingering instabilities and levee formation in shallow granular free-surface flows

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Geophysical granular flows, such as landslides, pyroclastic flows and snow avalanches, consist of particles with different sizes that have a tendency to segregate during flow. This can feedback on the bulk flow to spontaneously form coarse-grained lateral levees and 'finger-like' features. As a polydisperse mixture flows downslope large particles rise to the surface. Here the velocity is greatest and consequently they are sheared towards the front, where they are overrun and recirculated by segregation to form a coarse-rich flow head. This may become unstable and break up into a series of lobate structures, with each finger being bounded by large-particle-rich levees, lined with low friction material. These channelise the finer grained interior, enhancing the overall runout distance of the flow. A depth-averaged model for such feedback effects in geophysical granular flows is presented, along with numerical solutions of the resulting system of equations. The feedback arises via a basal friction law that is composition dependent, implying greater friction where there are more large particles. The model qualitatively captures the development of fingering instabilities in bidisperse flows and the formation of coarse- grained lateral levees. It extends previous attempts, which were shown to be ill-posed and grid dependent, by including extra dissipative terms in the momentum equation. These are a two-dimensional generalisation of the depth-averaged $\mu(I)$-rheology for shallow dense granular flows. The resulting linear stability analysis shows that the additional viscous terms remove the unbounded growth rates of the previous model, making it mathematically well-posed. Numerical simulations are grid convergent with the finger wavelength being controlled by the magnitude of the effective viscosity.