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Revisiting the role of friction in transient granular flows through non-smooth simulations and experiments

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(a) Experimental setup of the granular collapses onto inclined erodible beds.

(b) 3-D simulation of a granular column collapse on a 15°-tilted bed.

Figure 1. Inclined granular column collapses: experiments and simulations [1].

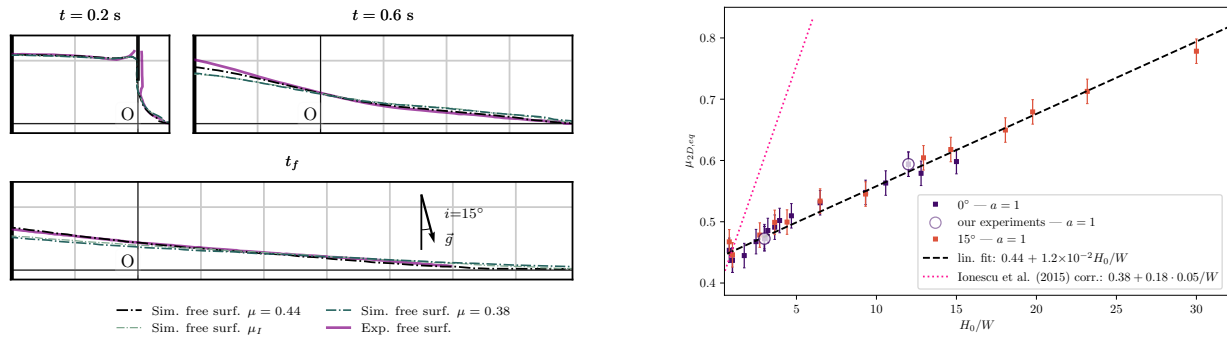
The large-scale continuum simulation of granular matter is a long-standing challenge, mainly stemming from the large diversity of effects at play. Even in the simplest mono-disperse systems, the macroscopic rheology features intricate state transitions, pressure-dependent yield stress, kinetic – viscous – dissipation and hysteresis. The Drucker-Prager model [2] proposes a first-order plastic rheology, with a pressure-dependent yield-stress, close to the Mohr-Coulomb law for brittle materials. While it accurately captures the transition from rest to flow of granular matter, it does not account for the rate-dependent viscosity responsible for the existence of steady flow profiles over a range of imposed shear-rates. The celebrated $\mu(I)$ rheology [3] extends the plastic Drucker-Prager model to account for inter-grain shock dissipation by introducing an increasing dependence of the friction coefficient on the inertial number $I = \dot{\epsilon}d\sqrt{\rho/p}$, which characterises the ratio between the inertial and deformation time-scales. As such, it effectively incorporates viscous dissipation into the model, crucial in granular flows with large strain rates or low pressure. While this visco-plastic rheology is able to accurately describe steady inertial flows, its actual role in the low I regime, in particular for transient flows subject to rest-to-flow transitions, remains unclear, all the more as these transitions display a hysteretic behaviour, characterised by the existence of a static friction coefficient larger than the dynamic one (see e.g. [4] and references therein).

In this work, we perform experiments of granular column collapses over erodible beds, along with the corresponding 3-D continuum-based numerical simulations. We carry out the collapses with different bed slopes, ranging from 0° to 20°, different channel widths, and different materials, in order to carefully investigate the role of friction – within the material or with its enclosing walls – in transient flows with low inertial numbers.

Our simulation method leverages the non-smooth MPM-based continuum framework introduced in [5] to accurately resolve the plastic Drucker-Prager threshold without regularisation, and carefully accounts for all the experimental setup (c.f. fig. 1), including friction with the lateral walls and the lifting gate. We notably compare simulations obtained with the fully plastic Drucker-Prager and the viscoplastic $\mu(I)$ rheologies, and compare both the resulting transient and final states with experimental measurements of the free-surface profiles and material velocities measured at the side wall.

While our results (e.g. fig. 2a) confirm the weak impact of the viscous effects introduced by the $\mu(I)$ rheology in this regime, as previously suggested in [6, 7], they also stress the importance of

setting the – constant – plastic bulk friction coefficient to the value extracted from the avalanche angle in order to accurately predict collapse rest states, instead of the stop angle measured from the steady flow experimental protocols [8], as is usually done.



(a) 15° -tilted collapse: comparison between experiment and 3-D simulations with Drucker-Prager laws ($\mu = \mu_a = 0.44$ or $\mu = \mu_s = 0.38$), or the $\mu(I)$ law.

(b) Friction with lateral walls: scaling law of an “equivalent” 2-D friction coefficient, compared with the corresponding model extended from the steady case.

Figure 2. Investigating the role of friction by comparing experiments and simulations.

We also carefully investigate the role of friction with the enclosing walls (c.f. fig. 2b), and find it remarkably less impactful than assumed in previous studies extending the steady analysis to the transient case.

Finally, we show that a simple hysteresis model, inspired by the non-monotonous friction laws proposed in [9] can improve the simple Drucker-Prager law in the early dynamics of the collapse, thereby suggesting the high sensitivity of the actual solid-liquid transition to mechanical noise and paving the way to further analysis.

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