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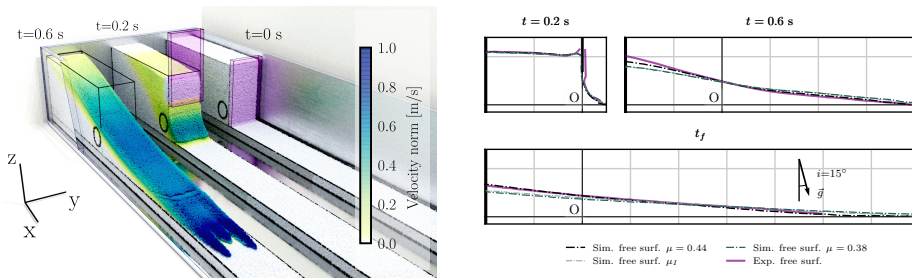
Granular material as a continuum: confronting non-smooth simulations with experiments

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

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

Figure 1: Inclined granular column collapses: simulations and experiments [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 $I = \varepsilon d \sqrt{\rho/p}$, 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

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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 leverage the non-smooth MPM-based continuum framework introduced in [5] to simulate 3D granular collapses, thereby accurately resolving the plastic Drucker-Prager threshold without regularisation. Our numerical framework notably allows to account for fully realistic setups (c.f. fig. 1a), including friction with the lateral walls and the lifting gate. The absence of numerical artifacts close to the rest-to-flow transition offered by our framework allows us to carefully investigate the role of friction in transient granular flows.

To this end, we perform experiments of granular column collapses over erodible beds, along with the corresponding numerical simulations. We carry out the collapses with different bed slopes, ranging from 0° to 20° , different channel widths, and different materials, and compare the resulting transient and final states to discriminate between different friction models.

While our results (e.g. fig. 1b) 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.

We also carefully investigate the role of friction with the enclosing walls, 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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