Multi-scale multiphase modelling of granular flows

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Geophysical hazards usually involve flow of dense granular solids and water as a single-phase system. The dynamics of a homogeneous granular flow involve three distinct scales: the *microscopic scale*, the *meso-scale*, and the *macroscopic scale*. Although soil flows are conventionally modelled as a continuum, recent studies have shown the limitations of continuum models to capture the in-homogeneities at the grain-scale level. On a grain scale, the granular materials exhibit complex solid-like and/or fluid-like behaviour depending on how the grains interact with each other. In the present study, a multi-scale approach is adopted to understand the rheology of granular flows and the limitation of continuum models.

The Generalised Interpolation Material Point Method (GI-MPM), a hybrid Eulerian – Lagrangian approach is implemented in the present study to describe the continuum behaviour of granular flows. The Discrete Element Method (DEM) is used to model the micro-mechanics of granular flows. The two-dimensional plane-strain collapse of a granular column on a horizontal surface is analysed both at the continuum scale and at the grain scale.

The run-out distance of a granular column collapse exhibits a power law dependency with the aspect ratio of the column. For columns with small aspect ratios (‘h/l’ ≤ 2), both MPM and DEM approaches predict similar run-out behaviour. However, MPM predicts longer run-out distances for columns with larger aspect ratios (‘h/l’ > 2). Analysis the energy evolution during the collapse reveals higher collisional dissipation in the initial free-fall regime for tall columns. The lack of collisional energy dissipation mechanism in MPM simulations results in longer run-out distances. The dimensionless inertial number I is used to identify different flow regimes during a column collapse. The classical Mohr-Coloumb model has the ability to capture the rheology of granular flows in dense-granular and critical state flow regimes (for example, run-out evolution of slopes subjected to impact loading, where the Inertial number I < 0.1). Voronoi tesselation is used to study the meso-scale behaviour such as the evolution of local packing density for different initial volume fraction.

Certain macroscopic models are able to capture simple mechanical behaviours, however the complex physical mechanisms that occur at the grain scale, such as hydrodynamic instabilities, the formation of clusters, collapse, and transport, have largely been ignored. In order to describe the mechanism of saturated and/or immersed granular flows, it is important to consider both the dynamics of the solid phase and the role of the ambient fluid. In particular, when the solid phase reaches a high volume fraction, it is important to consider the strong heterogeneity arising from the contact forces between the grains, the drag interactions which counteract the movement of the grains, and the hydrodynamic forces that reduce the weight of the solids inducing a transition from dense compacted to a dense suspended flow. Hence, it is important to understand the mechanism of underwater granular flows at the granular scale. A pending research issue is the parameterisation of interactions between the water phase and the sediment phase. Owing to the number of flow variables involved and measurement imprecision, estimating such parameters from laboratory experiments remains difficult.

In this study, two-dimensional sub-grain scale numerical simulations are performed to understand the local rheology of a dense granular flows in a fluid. The Discrete Element Method (DEM) is coupled with the Lattice Boltzmann Method (LBM) for fluid-grain interactions, to understand the evolution of immersed granular flows. The fluid phase is simulated using Multiple-Relaxation-Time LBM method for better numerical stabilities. The Eulerian nature of the LBM formulation, together with the common explicit time step scheme of both LBM and DEM makes this coupling strategy an efficient numerical procedure for systems dominated by both grain–fluid and grain–grain interactions. The D2Q9 Model in LBM is used to simulate the fluid phase. In order to simulate interconnected pore space in 2D, a reduction in radius of the grains is assumed during LBM computations. Granular materials of different permeabilities are simulated by varying the reduction in radius of the grains. A parametric analysis is performed to assess the influence of the grain sample characteristics (initial configuration, permeability, slope of inclined plane) on the evolution of flow and run-out distances. The effect of hydrodynamic forces and hydroplaning on the run-out evolution is analysed by comparing the mechanism of energy dissipation and flow evolution in dry and immersed granular flows. Voronoi tesselation was used to study the evolution of local density and water entrainment at the flow front. A parameteric analysis is performed to assess the influence of the grain sample characteristics (initial configuration) and the fluid properties (e.g., viscosity) on the evolution of flow and run-out distances. The effect of hydrodynamic forces on the run-out evolution is analysed by comparing the mechanism of energy dissipation and flow evolution in dry and immersed granular flows.