Multi-scale multiphase modelling of granular flows

Krishna Kumar Soundararajan

Department of Engineering

University of Cambridge

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Geophysical hazards usually involve flow of dense granular solids and water as a single-phase system. Understanding the mechanics of granular flow is of particular importance in predicting the run-out distances of debris flows. The dynamics of a homogeneous granular flow involve at least three distinct scales: the *microscopic scale*, which is characterised by contact between grains, *the meso-scale* that represents micro-structural effects such as grain rearrangement, and the *macroscopic scale*, where geometric correlations can be observed.

Conventionally, granular materials such as soils are modelled as a continuum. On a macroscopic scale, granular materials exhibit many collective phenomena and the use of continuum mechanics to describe the macroscopic behaviour can be justified. However, 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. Recent works on granular materials suggest that a continuum law may be incapable of revealing inhomogeneities at the grain scale level, such as orientation of force chains, which are purely due to micro-structural effects. Discrete element method (DEM) is capable of simulating the granular material as a discontinuous system allowing one to probe into local variables such as position, velocities, contact forces, etc. In the present study, a multi-scale approach is adopted to better understand the rheology of granular flows and the limitations of continuum models.

The collapse of a granular column on a horizontal surface is a simple case of granular flow, however a proper model that describes the flow dynamics is still lacking. Granular flow is modelled as a frictional dissipation process in continuum mechanics but studies showing the lack of influence of inter-particle friction on the energy dissipation and spreading dynamics is surprising. In the present study, the generalised interpolation material point method (GIMPM), a hybrid Eulerian – Lagrangian approach, is implemented with Mohr-Coloumb failure criterion to describe the continuum behaviour of granular flows. While, the micro-mechanics of granular flows is modelled using discrete element method (DEM).

The run-out distance of a granular column collapse exhibits a power law dependency with the aspect ratio of the column. The difference between the continuum and discrete approaches in modelling the collapse and spreading dynamics is studied by inspecting the energy dissipation mechanisms. The lack of collisional dissipation in MPM is found to be the primary reason for the discrepancy in modelling collapse of tall granular columns. The classical Mohr-Coloumb model has the ability to capture the rheology of granular flows in dense-granular and critical state flow regimes, such as run-out evolution of slopes subjected to impact loading, where the inertial number $I < 0.1$.

The initiation and propagation of submarine granular flows depend mainly on the slope, density, and quantity of the material destabilised. The complex physical mechanisms that occur at the grain scale, such as the hydrodynamic instabilities and formation of clusters, have largely been ignored. A GPU paralellised two-dimensional Lattice Boltzmann LBM – DEM coupled technique is developed to understand the local rheology of dense granular flows in fluid. Granular materials of different permeabilities are simulated by varying the hydrodynamic radius of the grains. Parametric analyses are performed to assess the influence of the initial configuration, permeability, and the slope of the 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 the flow evolution in dry and immersed granular flows. Voronoi tesselation is used to capture the meso-scale behaviour such as the evolution of local density and water entrainment at the flow front.

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.