Chapter 7

Conclusions and recommendations for future research

7.1 Introduction

This PhD has made advances in several aspects of multi-scale modelling of granular flows and understanding the complex rheology of dry and submerged granular flows. The significant contributions of this PhD are summarised in this chapter.

7.1.1 Multi-scale modelling of dry granular flows

A mult-scale approach is adopted to study the granular flow behaviour. The material point method, a continuum approach, is used to model the macro-scale response, while the grain-scale behaviour is captured using discrete element technique. In the present study, a two-dimensional DEM code is developed in C++ to study the micro-scale rheology of dry granular flows. A Verlet-list algorithm is implemented for neighbourhood detection to improve the computational efficiency. A linear-elastic model with a frictional contact behaviour is used to model dense rapid granular flows. A sweep-line Voronoi tesselation algorithm is implemented, in the present study, to extract continuum properties such as packing density from the local grain-scale simulations.

In order to capture the macro-scale response, a template-based three-dimensional C++ Material Point Method code, an Eulerian-Lagrangian approach, developed at the University of Cambridge is modified and extended to study granular flows as a continuum. In the present study, the Generalised Interpolation Material Point GIMP method is implemented to reduce the cell-crossing noise and oscillations observed during large-deformation problems, when using the standard MPM. The three-dimensional MPM code is parallelised to run on multi-core systems, thus improving the computational efficiency. The algorithm of the MPM code is improved to handle multi-body dynamics and interactions. Advanced constitutive models such as NorSand and modified Bingham fluid are also implemented. This dissertation includes only those results from two-dimensional plane-strain granular flow problems.

Granular column collapse

Multi-scale simulation of dry granular flows are performed to capture the local rheology, and to understand the capability and limitations of continuum models in realistic simulation of granular flow dynamics. For short columns, the run-out distance is found to be proportional to the granular mass destabilised above the failure surface. The spreading results from a Coulomb-like failure of the edges. The continuum approach, using a simple frictional dissipation model, is able to capture the flow dynamics of short columns. Unlike short columns, the collapse of tall columns is characterised by an initial collisional regime and a power-law dependence between the run-out and the initial aspect ratio of the granular column is observed. The energy evolution study reveals that the lack of collisional dissipation mechanism in the MPM simulations results in a substantially longer run-out distance for large aspect ratio columns. This shows that continuum approach using frictional laws are able to capture the flow kinematics at small aspect ratios, which is characterised by an inertial number I less than 0.2 indicating a dense granular regime. However, a continuum approach like MPM is unable to precisely describe the flow dynamics of tall columns, which is characterised by an initial collisional regime ($I > 0.2$). DEM studies on the role of initial material properties reveal that the initial packing fraction and the distribution of the kinetic energy in the system have a significant influence on the flow kinematics and the run-out behaviour. For the same material, a dense granular packing results in a longer run-out distance in comparison to the initially loose granular column. Hence, it is important to consider macroscopic parameters like packing fraction, which are due to meso-scale grain arrangements, when modelling the granular system as a continuum.

Granular slopes subjected to impact loading

The ability of MPM in modelling transient flows that does not involve collision is further investigated. The distribution of kinetic energy in the granular mass is found to have a significant effect on the flow kinematics. In the present study, a multi-scale analyses of a granular slope subjected to impact velocities reveals a power-law dependence of the run-out distance and time as a function of the input energy with non-trivial exponents. The power-law behaviour is found to be a generic feature of granular dynamics. Two different regimes are observed depending on the input energy. The low energy regime reflects mainly the destabilisation of the pile, with a run-out time independent of the input energy. Whereas, the high energy regime involves spreading dynamics, which is characterised by a decay time that is defined as the time required for the input energy to decline by a factor $1/2$. MPM is successfully able to simulate the transient evolution with a single input parameter, the macroscopic friction angle. This study exemplifies the suitability of MPM, as a continuum approach, in modelling large-deformation granular flow dynamics and opens the possibility of realistic simulations of geological-scale flows on complex topographies.

The distribution of the kinetic energy in the system is found to have a significant influence in the low energy regime, where a large fraction of the input energy is consumed in the destabilisation process. However at higher input energy, where most of the energy is dissipated during the spreading phase, the run-out distance has a weak dependence on the distribution of velocity in the granular mass. The material characteristics of the granular slope affect the constant of proportionality and not the exponent in the power-law relation between the run-out and the input energy.

7.1.2 Granular flows in fluid

A two-dimensional coupled lattice Boltzmann - DEM technique is developed in C++ to understand the local rheology of granular flows in fluid. A multi-relaxation time LBM approach is implemented in the present study to ensure numerical stability. The coupled LBM–DEM technique offers the possibility to capture the intricate micro-scale effects such as the hydrodynamic instabilities. Coupled LBM-DEM involves modelling interactions of a few thousand soil grains with a few million fluid nodes. Hence, in the present study the LBM-DEM approach is implemented in the General Purpose Graphics Processing Units. The GPGPU implementation of the coupled LBM – DEM technique offers the capability to model large scale fluid – grain systems, which are otherwise impossible to simulate using conventional computational techniques. In the present study, simulations involving up to 5000 soil grains interacting with 9 million LBM fluid nodes are modelled. Efficient data transfer mechanisms that achieves coalesced global memory ensures that the GPGPU implementation scales linearly with the domain size. Granular flows in fluid involves soil grains interacting with fluid resulting in formation of turbulent vortices. In order to model the turbulent nature of granular flows, the LBM-MRT technique is coupled with the Smagorinsky turbulent model. The LBM-DEM code offers the possibility to simulate large-scale turbulent systems and probe micro-scale properties, which are otherwise impossible to capture in complex fluid - grain systems.

Granular collapse in fluid

Two-dimensional LB-DEM simulations pose a problem of non-interconnected pore-space between the soil grains, which are in contact with each other. In the present study, a hydrodynamic radius, a reduction in the radius of the grains, is adopted during the LBM computation stage to ensure continuous pore-space for the fluid flow. A relation between the hydrodynamic radius and the permeability of the granular media is obtained.

In order to understand the difference in the mechanism of granular flows in the dry and submarine conditions, LBM-DEM simulations of granular column collapse are performed and are compared with the dry case. Unlike the dry granular collapse, the run-out behaviour in fluid is found to be dictated by the initial volume fraction. For dense granular columns, the run-out distance in fluid is much shorter than its dry counterpart. Dense granular columns experience significantly high drag force and develop large negative pore-pressures during the initial stage of collapse resulting in a shorter run-out distance. On the contrary, granular columns with loose packing and low permeability tend to flow further in comparison to dry granular columns. This is due to entrainment of water at the flow front leading to hydroplaning.

In both dense and loose initial packing conditions, the run-out distance is found to increase with decrease in the permeability. With decrease in permeability, the duration required for the flow to initiate takes longer due to the development of large negative pore-pressures. However, the low permeability of the granular mass results in entrainment of water at the flow front causing hydroplaning. For the same thickness and velocity of the flow, the potential of hydroplaning is influenced by the density of the flowing mass. Loose columns are more likely to hydroplane than the dense granular masses resulting in a longer run-out distance. This is in contrast to the behaviour observed in the dry collapse, where dense granular columns flow longer in comparison to loose columns.

Similar to the dry condition, a power-law relation is observed between the initial aspect ratio and the run-out distance in fluid. For a given aspect ratio and initial packing density, the run-out distance in the dry case is usually longer than the submerged condition. However, for the same kinetic energy, the run-out distance in fluid is found to be significantly higher than the dry conditions. The run-out distance in the granular collapse has a power-law relation with the peak kinetic energy. For the same peak kinetic energy, the run-out distance is found to increase with decrease in the permeability. The permeability, a material property, affects the constant of proportionality and not the exponent of the power-law relation between the run-out and the peak kinetic energy.

Granular collapse down inclined planes

The influence of slope angle on the effect of permeability and the initial packing density on the run-out behaviour are studied. For increase in slope angle, the viscous drag on the dense column tends to predominate over the influence of hydroplaning on the run-out behaviour. The difference in the run-out between the dry and the submerged conditions, for a dense granular assembly, increases with increase in the slope angle above an inclination of 5°. In contrast to the dense granular columns, the loose granular columns show a longer run-out distance in immersed conditions. The run-out distance increases with increase in the slope angle in comparison to the dry cases. The low permeable loose granular column retains the water entrained at the base of the flow front resulting in sustained lubrication effect. In contrast to the dry granular collapse, for all slope inclinations, the loose granular column in fluid flows further than the dense column.

For granular collapse on inclined planes, the run-out distance is unaffected by the initial packing density at high permeability conditions. For collapse down inclined planes at high permeabilities, the viscous drag forces predominate resulting in almost the same run-out distance for both dense and loose initial conditions. However, at low permeability the entrainment of water at the flow front and the reduction in the effective stress of the flowing mass result in a longer run-out distance in the loose condition than the dense case with increase in the slope angle.

In tall columns, the run-out behaviour is found to be influenced by the formation of vortices during the collapse. The interaction of the surface grains with the surround fluid results in formation of vortices uniquely during the horizontal acceleration stage. The vortices result in redistribution of granular mass and thus affecting the run-out behaviour. This effect is predominant with increases in the slope angle.

7.2 Recommendations for future research

Further research can be pursued along two directions: *a*. improvement of the numerical tools and constitutive models to realistically simulate large-deformation problems and *b*. investigation of the rheology of granular flows using experimental and numerical tools.

7.2.1 Development of numerical tools

Discrete element method

The two-dimensional discrete element method, developed in the present study, can be extended to three-dimensions to model realistic soil flow problems. Although, linear-elastic contact model is found to be sufficient to describe rapid granular flows, further research using Hertz-Mindlin or other advanced contact model shall be performed. DEM is limited by the number of grains that can be simulated. Hence, it is important to be able to run DEM simulations on multi-core systems or on GPUs to model large-scale geometries. The initial gain properties are found to have a significant influence on the run-out behaviour, hence, it is vital to model grains of different shapes to understand their influence on the run-out distance. Agglomerates can also be used to study the effect of grain-crushing as the flow progresses down slope.

Material point method

The present MPM code is capable of solving both 2D and 3D granular flow problems. Further research should focus on modelling three-dimensional granular flow problems and validate the suitability of MPM in modelling geological scale run-out behaviours. As the scale of the domain increases, the computational time increases especially when using GIMP method. To improve the computational efficiency, the material point method developed in the present study shall be modified to run on large clusters. The dynamic re-meshing technique (Shin, 2010) shall be implemented to efficiently solve large deformation problems. The dynamic meshing approach is useful for problems involving motion of a finite size body in unbounded domains, in which the extent of material run-out and the deformation is unknown a *priori*. The approach involves searching for cells that only contain material points, thereby avoiding unnecessary storage and computation.

The current MPM code is capable of handling fluid-solid interactions in two-dimensions. Further research shall be pursued to implement fully coupled 3D material point method. The MPM code can also be extended to include the phase-transition behaviour in a continuum domain for partially fluidized granular flows (Aranson and Tsimring, 2001, 2002; Volfson et al., 2003). Fluid - solid interactions result in pressure oscillations. Further research is essential to explore advanced stabilisation methods that can be used to avoid the oscillations that occur due to incompressibility.

Lattice Boltzmann - DEM coupling

The GPGPU parallelised 2D LBM-DEM coupled code, developed in the present study, shall be extended to three-dimensions. This would require a very high computational cost and hence it is important to parallelise the LBM-DEM code across multiple GPUs through a Message Passing Interface (MPI) similar to a large cluser parallelisation. A three-phase system of granular solids, water and air can be developed to realistically capture debris flow behaviour. The LB code can be extended to include a free surface, which can be used to investigate the influence of submarine mass movements on the free surface, such as tsunami generation.

Constitutive models

DEM simulations of granular flow problems reveal that the initial material properties play a crucial role on the run-out evolution. The granular materials experience change in the packing fraction as the flow progresses. Hence, it is important to consider advanced models such as NorSand, a critical state based model, and $\mu(I)$ to model the dense granular flows. The behaviour of the soil under large deformations can be better expressed with a critical state model. Modified Nor-Sand constitutive model (Robert, 2010) implemented in the present study can be used in large-deformation flow problems. The $\mu(I)$ rheology, which is capable of capturing the complex rheology of dense granular flow, can be extended to include the effect of fluid viscosity (Pouliquen et al., 2005) to model granular flows in fluids.

7.2.2 Understanding the rheology of granular flows

Granular column collapse

Although, two-dimensional simulations provide a good understanding of the physics of granular flows, it is important to perform three-dimensional analysis to understand the realistic granular flow behaviour. Multi-scale simulations of three dimensional granular collapse experiments can be performed in dry and submerged conditions to understand the flow kinematics. Further research is essential to quantify the influence of initial packing density, shape and size of grains on the run-out behaviour for different initial aspect ratios. This would provide a basis for macro-scale parameters that are required to model the granular flow behaviour in a continuum scale.

Slopes subjected to impact

This work may be pursued along two directions: *a*. experimental realization of a similar setup with different modes of energy injection and *b*. investigating the effect of various particle shapes or the presence of an ambient fluid. Although numerical simulations are generally reliable with realistic results found in the past studies of steady flows, the transient phases are more sensitive than steady flows and hence experimental investigation are necessary for validation. This configuration is also interesting for the investigation of the behaviour of a submerged slope subjected to an earthquake loading.

Granular flow down inclined planes

Multi-scale analyses of large deformation flow problems such as the flow of dry granular materials down an inclined flume can be performed. This analysis will provide an insight on the limits of the continuum approach in modelling large deformation problems, which involve high shear-rates. The influence of parameters, such as particle size, density, packing and dilation, on the flow dynamics can be explored. These studies will be useful in describing the granular flow behaviour using the $\mu(I)$ rheology.

Granular flows in fluid

Three dimensional LBM-DEM simulations of granular collapse in fluid can be carried out with varying shape, friction angle and size of particles to understand the influence of initial material properties on the run-out behaviour. Parametric analyses on the initial properties can be used to develop a non-dimensional number that is capable of delineating different flow regimes observed in granular flows in a fluid. Further research can be carried out on the collapse of tall columns and the influence of vortices on the run-out behaviour and re-distribution of the granular mass during the flow.

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