Collapse of tall granular columns in fluid

Krishna Kumar[1,⋆], *Kenichi* Soga[2,⋆⋆], and *Jean-Yves* Delenne[3,⋆⋆⋆]

[1] *Department of Engineering, University of Cambridge, UK*
[2] *University of California, Berkeley, USA*
[3] *INRA, France*

Abstract. Avalanches, landslides, and debris flows are geophysical hazards, involve rapid mass movement of granular solids, water, and air as a multi-phase system. In order to describe the mechanism of immersed granular flows, it is important to consider both the dynamics of the solid phase and the role of the ambient fluid [1]. In the present study, the collapse of a granular column in fluid is studied using 2D LBM - DEM. The flow kinematics are compared with the dry and buoyant granular collapse to understand the influence of hydrodynamic forces and lubrication on the run-out. In the case of tall columns, the amount of material destabilised above the failure plane is larger than that of short columns. Hence in tall columns, the surface area of the mobilised mass that interacts with the surrounding fluid is significantly higher than the short columns. This increase in the area of soil - fluid interaction results in an increase in the formation of turbulent vortices that alter the deposit morphology during the collapse. It is observed that the vortices result in the formation of heaps that significantly affect the distribution of mass in the flow. In order to understand the behaviour of tall columns, the run-out behaviour of a dense granular column with an initial aspect ratio of 6 is studied. The collapse of a tall granular column on slopes of 0, 2.5, 5 and 7.5 are studied.

1 Collapse of granular columns

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. Experimental investigations have shown that the flow duration, the spreading velocity, the final extent of the deposit, and the energy dissipation can be scaled in a quantitative way independent of substrate properties, grain size, density, and shape of the granular material and released mass [2–5].

Granular collapse on a horizontal plane exhibit two distinct flow regimes: (a) for columns with aspect ratio 'a' < 1.7 a linear relation between the spread and aspect ratio can be observed, and (b) for 'a' > 1.7 a power-law relationship exists. A simple frictional dissipation model is able to capture the flow dynamics for columns with small aspect ratios [6]. However, for tall columns the flow dyanmics of is controlled by the initial collisional regime, resulting in a power-law relationship with the aspect ratios. Simple mathematical models based on conservation of horizontal momentum capture the scaling laws of the final deposit, but fail to describe the initial transition regime [7]. Granular flow is modelled as a frictional dissipation process in continuum mechanics but the lack of influence of inter-particle collision and friction on the energy dissipation and spreading dynamics is surprising.

The amount of material destabilised above the failure plane, in tall columns, is larger than that of short columns. This increase in the mobilised mass results in a signficant increase in the surface area of granular mass that interacts with the surrounding fluid. The increase in the area of soil - fluid interaction results in an increase in the formation of turbulent vortices that alter the deposit morphology during the collapse. It is observed that the vortices result in formation of heaps that significantly affect the distribution of mass in the flow. The distribution of mass in a granular flow plays a crucial role in the flow kinematics [3]. In order to understand the behaviour of tall columns, the run-out behaviour of a dense granular column with an initial aspect ratio of 6 is studied using Lattice Boltzmann - Discrete Element Method coupling.

2 LBM-DEM coupling

The Lattice Boltzmann Method (LBM) is an alternative approach to the classical Navier-Stokes solvers for fluid flow and works on an equidistant grid of cells, called lattice cells, which interact only with their direct neighbours [8]. The fluid domain is divided into a rectangular grid or lattice, with the same spacing 'h' in both the x- and the y-directions. The present study focuses on 2-D problems; hence, the D2Q9 momentum discretization is adopted, where the fluid particles at each node are allowed to move to their eight immediate neighbours with eight different velocities $e_i (i = 1, \dots, 8)$. The primary

⋆e-mail: kks32@cam.ac.uk
⋆⋆e-mail: soga@berkeley.edu
⋆⋆⋆e-mail:

variables in LB formulation are called the *fluid density distribution functions*, f_i, each representing the probable amount of fluid particles moving with the velocity e_i along the direction i at each node. In the present study, Lattice-Boltzmann - Multiple Relaxation Time (LBM-MRT) is used for numerical stability. The nine eigen values of **S** are all between 0 and 2 so as to maintain linear stability and the separation of scales. In this study, the Large Eddy Simulation (LES) is adopted to solve for turbulent flow problems. The separation of scales is achieved by filtering of the Navier-Stokes equations, from which the resolved scales are directly obtained and unresolved scales are modelled by a one-parameter Smagorinski sub-grid methodology [9].

Lattice Boltzmann approach can accommodate large grain sizes and the interaction between the fluid and the moving grains can be modelled through relatively simple fluid – grain interface treatments. Further, employing the Discrete Element Method (DEM) to account for the grain – grain interaction naturally leads to a combined LB – DEM procedure [10]. 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 the simulation of grain – fluid systems. A no-slip boundary condition is used to simulate grain – fluid and grain – grain interactions. The solid grains inside the fluid are represented by lattice nodes. The discrete nature of lattice, results in a stepwise representation of the surfaces, which are circular, hence sufficiently small lattice spacing is adopted. In order to model flow through interconnected pore space, a reduction in radius (The hydrodynamic radius r) is assumed during the LBM computation [6].

3 Numerical set-up

In this study, a 2D poly-disperse system ($d_{max}/d_{min} = 1.8$) of circular discs in fluid was used to understand the behaviour of granular flows on slopes (see fig. 1. The soil column was modelled using 2500 discs of density 2650 $\mathrm{kg\,m^{-3}}$ and a contact friction angle of 26°. The collapse of the column was simulated inside a fluid with a density of 1000 $\mathrm{kg\,m^{-3}}$ and a kinematic viscosity of 1×10^{-6} $\mathrm{m^2\,s^{-1}}$. The fluid was modelled with 5 to 9 million LB nodes. GPU computing was used to simulate the problem. The choice of a 2D geometry has the advantage of cheaper computational effort than a 3D case, makeing it feasible to simulate very large systems. A granular column of aspect ratio 'a' of 6 was used. A hydrodynamic radius of $r = 0.85\ R$ is adopted. Dry analyses were also performed to study the effect of hydrodynamic forces on the run-out distance. The collapse of a tall granular column on slopes of 0°, 2.5°, 5° and 7.5° are studied.

4 Collapse on a horizontal plane

Snapshots of the collapse of an aspect ratio 6 column in fluid on a horizontal surface are shown in fig. 2. The initial stage of collapse is characterised by the free-fall of grains above the failure surface. Unlike the dry condition, as the grains undergo free-fall due to gravity, they interact with the surrounding fluid experiencing drag forces. This results in a significant drop in the kinetic energy available for the flow. As the grains reach the static region, they interact with the neighbouring grains and the kinetic energy gained during the free fall is converted into horizontal acceleration. Uniquely during this stage ($t = 3\tau_c$) the interactions between the soil grains on the surface with the surrounding fluid result in the formation of eddies. The number of eddies formed during the flow is proportional to the surface area of the granular mass interacting with the fluid. Hydroplaning can be observed at the flow front ($t = 3\tau_c$). Two large vortices with almost the same size can be observed at the final stage of collapse. The soil grains on the surface experience suction due to formation of eddies and this results in formation of heaps of granular mass in front of each vortex. The formation of heaps, although in evidence, doesn't significantly affect the distribution of mass in the case of collapse on a horizontal plane.

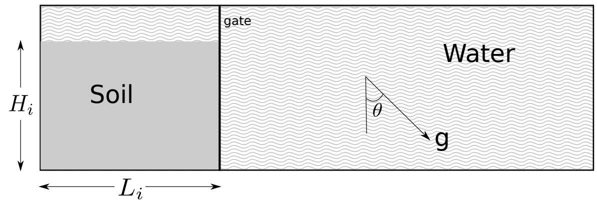
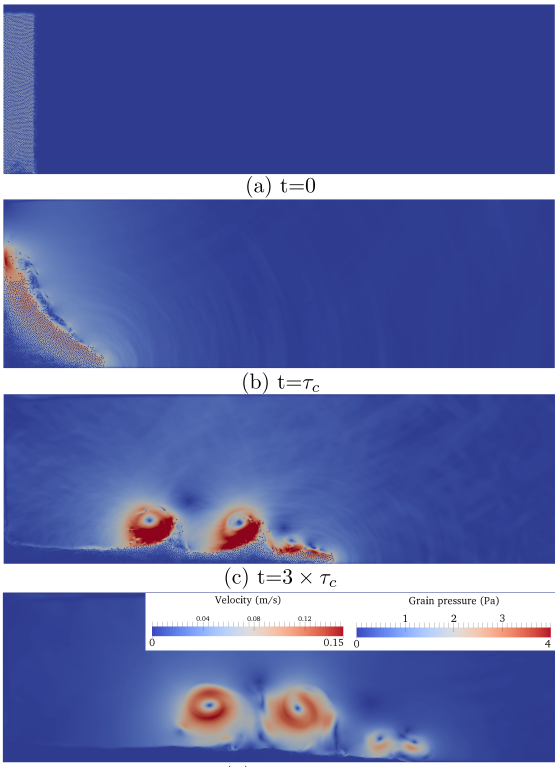


Figure 1: Underwater granular collapse set-up

5 Collapse on slopes

Snapshots of the collapse of a granular column ($a = 6$) on a inclined plane at angle of 5° are shown in fig. 3. The collapse on a slope of 5° show flow evolution behaviour similar to the case of collapse on a horizontal plane. The vortices are formed only during the horizontal spreading stage $t = 3\tau_c$, but the number of vortices formed during the collapse is higher than the collapse on a horizontal plane. However, as the flow progresses a single large vortex engulfs other smaller vortices, thus having a significant influence on the mass distribution. Figure 4 shows the distribution of mass and the packing density at $t = 6\tau_c$ and $t = 8\tau_c$. A heap can be observed in front of the large vortex almost at the middle of the flow. The height of the heap formed in the middle of the granular flow is higher than the collapse height next to the wall. However, when the flow comes to rest and the vortex moves away from the flowing surface, the mass present in the heap gets redistributed (as seen at $t = 8\tau_c$). This behaviour is significantly different from that observed in the case of short columns.

In order to understand the influence of slope angles on the run-out behaviour, the collapse of a granular column with an initial aspect ratio of 6 is performed on slopes of 0°, 2.5°, 5° and 7.5°. The run-out evolution with time for different slope angles are presented in fig. 5a. The run-out distance increases with increase in the slope angle, however the run-out distance in the fluid is significantly shorter



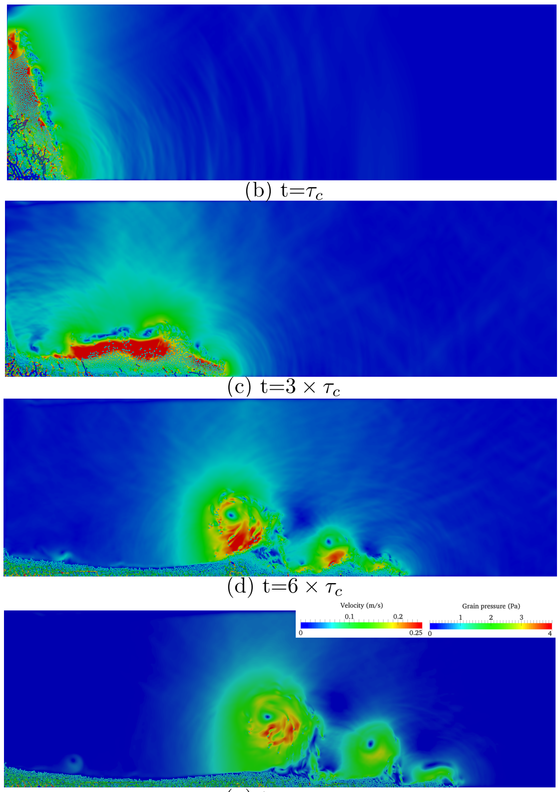
(a) t=0

(b) t=τ_c

(c) t=3 $\times$ τ_c

(d) t=6 $\times$ τ_c

Figure 2: Flow evolution of a granular column collapse in fluid (a = 6) on a horizontal surface.



(b) t=τ_c

(c) t=3 $\times$ τ_c

(d) t=6 $\times$ τ_c

(e) t= 8$\times$ τ_c

Figure 3: Flow evolution of a granular column collapse in fluid (a = 6) on a slope of 5°. Shows the velocity profile of fluid due to interaction with the grains (red - higher velocity).

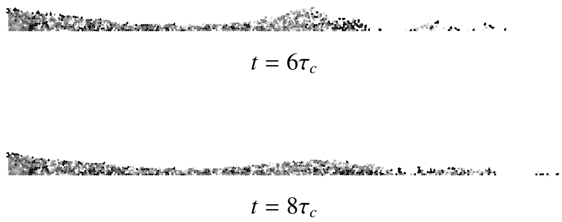


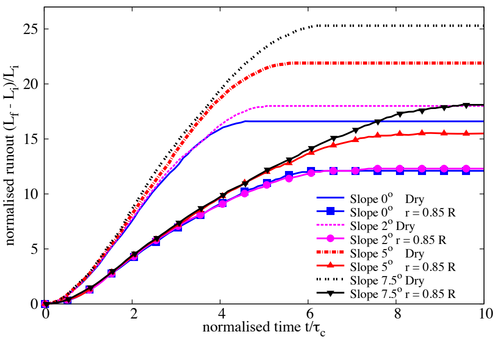
Figure 4: Packing density of a granular column collapse in fluid (a = 6) on a slope of 5°.

than the dry condition. The slow evolution of run-out in the submerged condition is due to the delay in the dissipation of large negative pore-pressures developed during the initial stage of the collapse. The formation of eddies during the flow indicates that most of the potential energy gained during the free-fall is dissipated through viscous drag and turbulence. This effect predominates over the hydroplaning that is observed during the flow resulting in a shorter run-out distance in the case of fluid. The evolution of the normalised height with time (fig. 5b) for collapse on different slope angles indicates that the amount of material destabilised in fluid is less than the dry conditions due to the drag forces experienced by the grains, which retards the quantity and the rate of collapse.

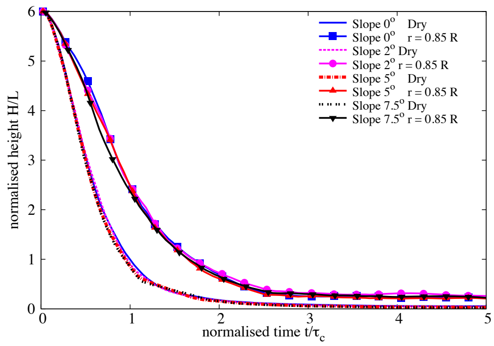
Figure 6a shows the evolution of the normalised kinetic energy for a granular column (a = 6) collapse in fluid on different slope angles. The amount of kinetic energy available for the flow in the submerged condition is almost half that of the dry condition. It can be seen from the figure that the vertical kinetic energy in the fluid condition dissipates a longer duration, in contrast to the free-fall release observed in the dry condition. The slower dissipation is attributed to the viscous drag force experienced by the grains.

6 Summary

The behaviour of tall columns is significantly different from that observed in the case of short columns. The slope angle has a strong influence on the number and size of eddies during the flow. The eddies interact with the surface of the granular flow and forms heaps in front of each vortex. This significantly affects the mass distribution and in turn the run-out evolution. Although tall cliffs are quite rare in submarine condition in comparison to short cliffs or slopes, further research is required to understand the influence of permeability and packing density on the run-out evolution of tall columns.

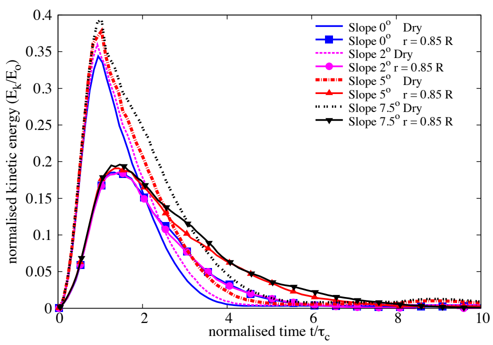


(a) Evolution of run-out for a column collapse in fluid (a = 6).

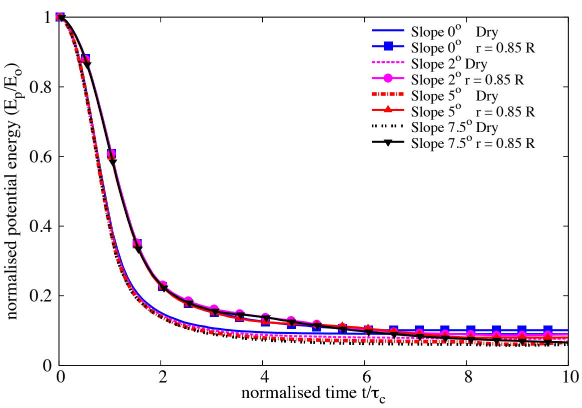


(b) Evolution of height with time for a column collapse in fluid (a = 6).

Figure 5: Evolution of run-out and height for a column collapse in fluid (a = 6).



(a) Evolution of the total kinetic energy.



Acknowledgements

The author would like to thank the Cambridge Commonwealth and Overseas Trust for the financial support to the first author to pursue this research.

References

[1] R. Denlinger, R. Iverson, J. Geophys. Res **106**, 553 (2001)

[2] V. Topin, F. Dubois, Y. Monerie, F. Perales, A. Wachs, Journal of Non-Newtonian Fluid Mechanics **166**, 63 (2011)

[3] L. Staron, E.J. Hinch, Granular Matter **9**, 205 (2007)

[4] E. Lajeunesse, J.B. Monnier, G.M. Homsy, Physics of Fluids **17** (2005)

[5] G. Lube, H.E. Huppert, R.S.J. Sparks, A. Freundt, Physical Review E - Statistical, Nonlinear, and Soft Matter Physics **72**, 1 (2005)

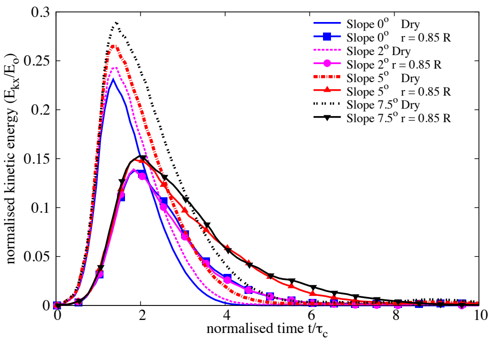
[6] K.K. Soundararajan, Ph.D. thesis, University of Cambridge (2015)

[7] K. Kumar, K. Soga, J.Y. Delenne, *Multi-scale modelling of granular avalanches*, in *AIP Conf. Proc* (2013), Vol. 1542, p. 1250

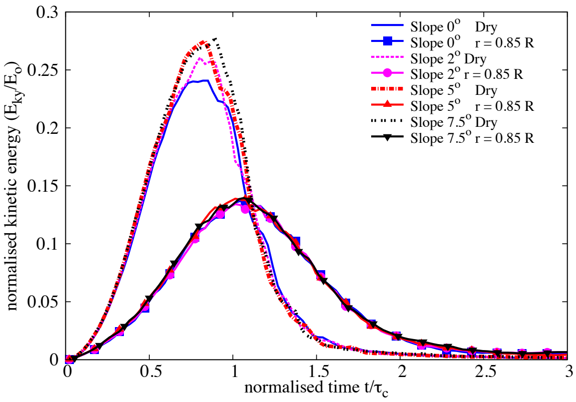
[8] X. He, Q. Zou, L.S. Luo, M. Dembo, Journal of Statistical Physics **87**, 115 (1997)

[9] J. Smagorinsky, Monthly weather review **91**, 99 (1963)

[10] K. Kumar, K. Soga, J.Y. Delenne, *Granular flows in fluid*, in *Discrete Element Modelling of Particulate Media*, edited by C.Y. Wu (Royal Society of Chemistry, Cambridge, 2012), Special Publication, ISBN 978-1-84973-360-1, `http://pubs.rsc.org/en/content/chapter/bk9781849733`



(a) Evolution of the horizontal kinetic energy.



(b) Evolution of the vertical kinetic energy.

Figure 7: Evolution of the kinetic energies with time for a granular column collapse in fluid (a = 6).