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GRANULAR SLUMPING IN A FLUID : FOCUS ON RUNOUT DISTANCES

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Abstract. We investigate the effect of an ambient fluid on the dynamics of collapse and spread of a granular column simulated by means of a recently developed model which takes into account both fluid forces that act on each grain and contacts between grains. The model couples the contact dynamics method for discrete element modeling of the grains and their interactions with the finite element method for the integration of Navier-Stokes equations in 2D. The coupling is based on the fictitious domain approach in which the fluid domain is extended to that of grains, and the rigid-body motion of the grains is imposed by means of distributed Lagrange multipliers. As in similar numerical and experimental works with dry grains, we focus here on the run-out distances and avalanche durations for different column aspect ratios (height vs width). We consider three options for the surrounding fluid: 1) no fluid, 2) water and 3) a viscous fluid that allows us to perform our simulations in the grain-inertial, fluid-inertial and viscous regimes, respectively. The run-out distance is found to increase as a power law with the aspect ratio of the column, and surprisingly, for a given aspect ratio and packing fraction, it may be similar in the grain-inertial regime and fluid inertial regimes but with considerably longer duration in the latter case. We show that the effect of the fluid in viscous and fluid-inertial regimes is both to reduce the kinetic energy during the collapse and enhance the flow by lubrication during the spread. Hence, the run-out distance in a fluid may be below or equal to that in the absence of fluid due to compensation between those effects.

1 INTRODUCTION

Most natural destructive events (slurries, submarine avalanches and debris flows) involve the destabilization and flow of dense granular materials (sand, gravels or rocks) saturated by or immersed in water [1–4]. The prediction of the runout distance and duration of such flows according to their initial composition and geometry is crucial for risk assessment. Likewise, the dispersion of fuel fragments in the coolant water during a hypothetic nuclear accident is another example of the intricate grain/fluid mixing process in extreme conditions, which remains a real unknown for the design of modern pressurized water reactors [5]. The presence of a fluid phase in a granular medium has profound effects on its mechanical behavior. In dry granular media the rheology is governed by grain inertia and static stresses sustained by the contact network. As the fluid inertia and viscosity come into play, complications arise as a result of competing effects. The fluid may delay the onset of granular flow or prevent the dispersion of the grains by developing negative pore pressures [3, 6, 7]. The fluid also lubricates the contacts between grains, enhancing in this way the granular flow, and it has a retarding effect at the same time by inducing drag forces on the grains [8]. In this paper, we rely on extensive numerical simulations to analyze the relative importance of grain inertia, fluid inertia and viscous effects on the dynamics of a granular column allowed to collapse and spread on a horizontal plane under its own weight. This choice was motivated by well-documented experimental and numerical data for similar tests with dry granular materials, showing that the runout distance grows in a nontrivial manner with the initial aspect ratio [9–12]. Our simulations reveal a nearly similar behavior in the presence of a suspending fluid but with a complex dependence on the fluid inertia and viscosity.

2 NUMERICAL METHOD

The simulations were performed by means of a recently developed model coupling the contact dynamics method [13–15] for discrete-element modeling of grain dynamics with the finite-element method for the integration of Navier-Stokes equations in 2D. The grains are treated as no-slip boundary conditions for the fluid and the fluid forces are applied at the boundaries of the grains for the calculation of their motions. This coupling was implemented by means of the fictitious domain approach in which the fluid domain is extended to that of grains, and the rigid-body motion of the grains is imposed by means of distributed Lagrange multipliers [16]. This approach has been tested and applied previously with the molecular dynamics method [17] and recently extended to the contact dynamics method [7]. A technical problem requiring special treatment is the zero permeability of a 2D granular system when the grains are in contact. This problem was fixed by allowing the grains to move during a short lag of time within the time step with no feedback from the fluid. The Lagrange multipliers are applied only after the grains have moved to their new positions so that the fluid physically never penetrates the grains. Note that, due to a broad fluid domain with frictional contact interactions and long spreading dynamics, these simulations are cpu-intensive and take several days with a parallelized version of the software running on several tens of processors. Sample movies of the simulations are available at www.cgp-gateway.org/ref013.

3 SYSTEM PARAMETERS

The granular samples are composed of disks of mean diameter $d = 10^{-3}m$ with a weak size polydispersity $\Delta d/d = 0.8$. The disks are assembled in a rectangular domain of width R_0 and height H_0. The fluid domain is rectangular with dimensions varying between $150d \times 60d$ and $300d \times 150d$. The grains are assumed to be perfectly rigid with normal and tangential restitution coefficients set to zero. The Coulomb friction coefficient is fixed to 0.3 between grains and with the walls. The fluid density ρ_f is that of water ρ_{H_2O} and we set the density of grains $\rho_s = 2.6\rho_f$, roughly corresponding to rock debris in water. For each aspect ratio $a = H_0/R_0$, three simulations were performed: one without fluid and two with fluid for two values of the viscosity $\eta = \eta_{H_2O}$ and $10^3\eta_{H_2O}$. These simulations correspond to grain-inertial, fluid-inertial and viscous regimes, respectively [18, 19]. The largest values of the Reynolds number Re vary in the range $0.12 < Re < 1.26$ in the viscous regime and in the range $560 < Re < 2340$ in the inertial regime. The width of the column is fixed to $R_0 = 11.5d$ and a varies in the range $]0; 10]$. The largest number of grains is 1360 for $a = 10$. Since we focus here on the influence of the column aspect ratio and grain/fluid regimes on the runout, the packing fraction is set to $\phi = 0.8$ in all simulations. Note that only d, the grain mass m and the gravity g keep the same values in all regimes, and for this reason we normalize the lengths by d, the times by $\sqrt{d/g}$, the velocities by $\sqrt{gd}$, the energies by mgd and the viscosities by $m\sqrt{g/d}$.

4 COLLAPSE DYNAMICS

Figure 1 displays successive snapshots of the collapse and flow of grains for $a = 8$ in the three grain/fluid regimes. The grains collapse vertically and jam in a heap that spreads along the plane and finally stops. Convective rolls are induced in fluid by granular flow. The three phases (collapse, heap and spread) can clearly be distinguished in the simulations, as shown in Fig. 2 where grain trajectories are shown together with the mean kinetic energy per grain $E_{cx} = \langle mv_x^2/2\rangle$ and $E_{cy} = \langle mv_y^2/2\rangle$ carried by the horizontal and vertical grain velocity components, respectively, as a function of time. The vertical collapse is characterized by the fast growth of E_{cy} and negligible E_{cx}. The latter begins to increase only at the peak value of E_{cy}, and in a short time interval extending from this point to the peak value of E_{cx}, most of the kinetic energy is transformed from vertical direction to horizontal direction. This short interval defines unambiguously the heap phase. Finally, the spread phase is reflected in the long tail of E_{cx} falling off from its maximum to zero. For small aspect ratios ($a < 4$), we observe no distinct collapse phase and only two steps are observed: the flow is first initiated by the failure of the right flank along a fracture surface above which material slides down and below which grains remain

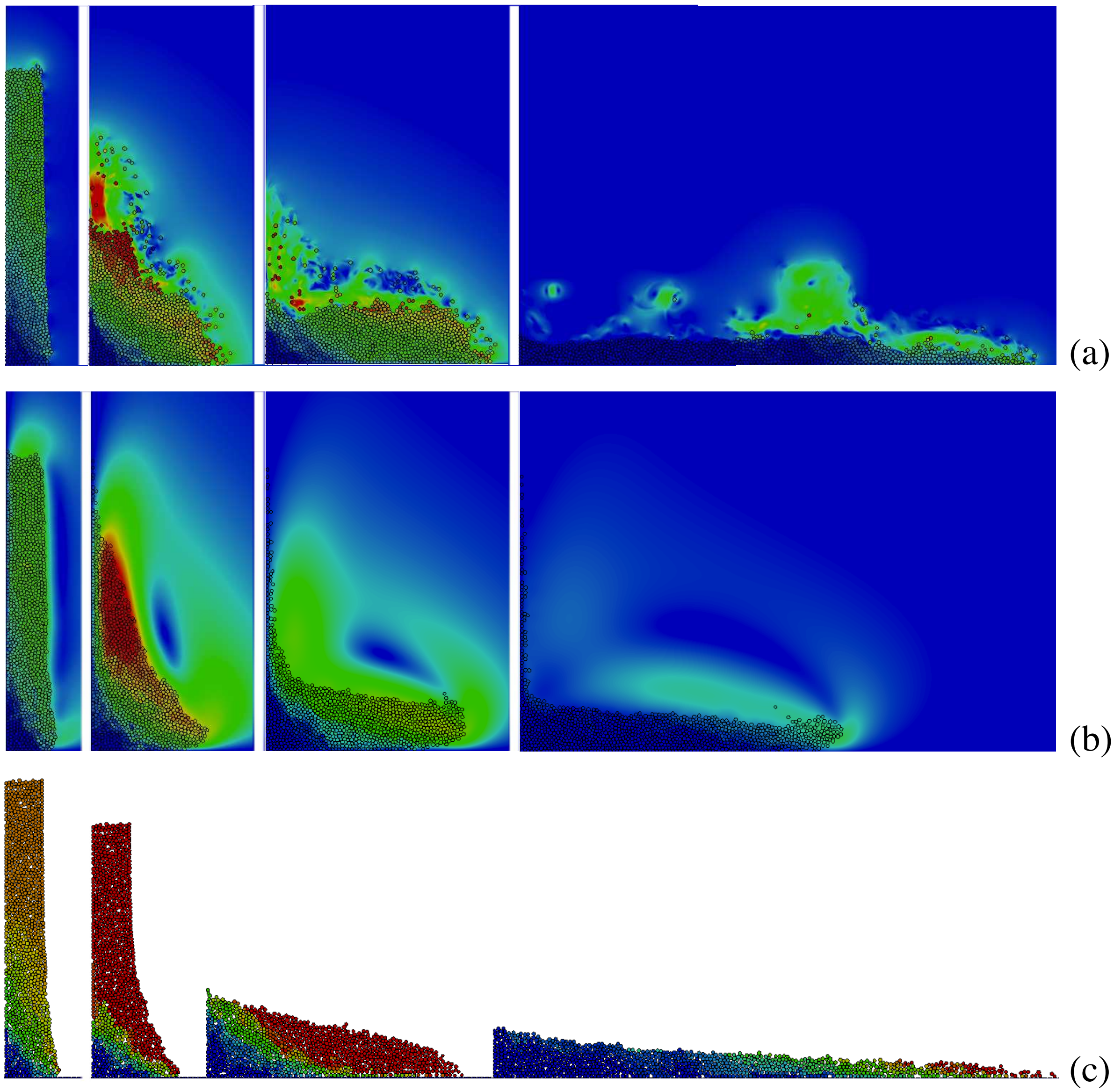

Figure 1: Successive instants of the collapse of a column of aspect ratio $a = 8$ in (a) fluid-inertial, (b) viscous and (c) grain-inertial regimes. The grains and fluid are colored according to the amplitude of their velocities.

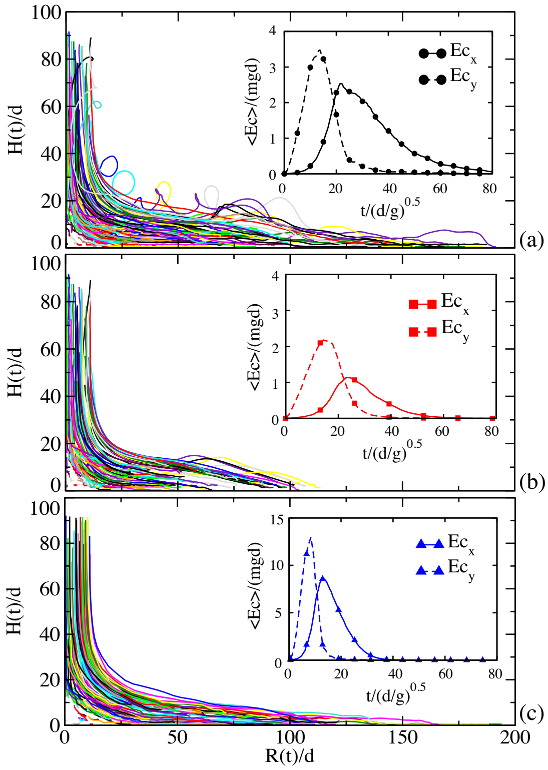

Figure 2: Grain trajectories (main plots) in the fluid-inertial (a), viscous (b) and grain-inertial (c) regimes for $a = 8$. Only 10 % of trajectories are plotted. The insets show the evolution of the mean kinetic energy per grain carried by the horizontal (x) and vertical (y) components of grain velocities.

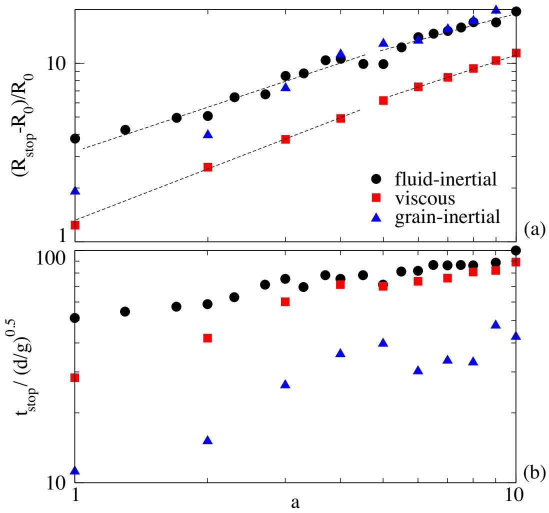

Figure 3: Normalized runout distance (a) and duration (b) as a function of the aspect ratio in different grain/fluid regimes.

static.

The evolution of E_{cy} indicates that the grains do not reach their Stokes velocity in the fluid. Following the mean vertical velocity of the ten highest grains we find that, regardless of the grain/fluid regime, the collapse obeys a power law $\langle V_y \rangle_{10} \propto t^{\beta}$ over nearly one decade with $\beta \simeq 1$ in the grain-inertial regime, corresponding to a ballistic fall, $\beta \simeq 0.95$ in the fluid-inertial regime and $\beta \simeq 0.75$ in the viscous regime.

Figure 3 shows the total normalized runout distance $(R_{stop} - R_0)/R_0$ and runout duration t_{stop} as a function of a. The behavior is similar in all regimes: for small aspect ratios ($a < 4$) the runout distance increases linearly: $(R_{stop} - R_0)/R_0 = \lambda_1 a$ with $\lambda_1 \simeq 2.45$ for the grain-inertial and fluid-inertial regimes and $\simeq 1.21$ in the viscous regime. For larger aspect ratios, the runout distance follows a power law $R_{stop} \propto \lambda_2 a^{\alpha}$ with $\alpha \simeq 0.6 \pm 0.1$ and $\lambda_2 \simeq 4.3$ in the grain-inertial and fluid-inertial regimes and $\alpha \simeq 0.87 \pm 0.1$ and $\lambda_2 \simeq 1.5$ in the viscous regime. It is remarkable that the values of λ_1, λ_2 and α in the grain-inertial and fluid-inertial regimes are identical to those reported in the dry case for narrow or 2D flows [9–12]. The equality of the runout distance between grain-inertial and fluid-inertial regimes contradicts at first sight the fact that underwater avalanches have a longer runout distance [4]. The change of behavior between small and large aspect ratios also appears in t_{stop}, which seems to increase linearly but with two different slopes as a function of a. However, unlike the runout distance, the duration is significantly shorter in the grain-inertial regime than in the fluid-inertial regime for all values of a. Moreover, unexpectedly, the runout duration is shorter in the viscous regime than in the fluid-inertial regime.

5 VISCOUS DISSIPATION VS. LUBRICATION

The spatio-temporal evolution of the grains and their kinetic energy, evidenced in Fig. 2, suggests that the runout results from the transformation of (part of) the initial potential energy into the peak kinetic energy E_{cx}^{max} that controls in turn the subsequent runout along the plane. This process can thus be split by analyzing separately the dependence of E_{cx}^{max} with respect to a, on one hand, and R_{stop} as a function of $E_{cx}^{m}ax$, on the other hand.

These functions are plotted from all simulation data in Fig. 4. We see that, irrespective of the grain/fluid regime, E_{cx}^{max} is a growing function of a with a transition around $a \simeq 4$. This is consistent with the fact that the grains do not reach their Stokes velocity in the fluid since otherwise the kinetic energy per grain would not depend on a unless probably at low a. E_{cx}^{max} is considerably higher in the grain-inertial regime, indicating that part of the potential energy in the presence of the fluid is dissipated during vertical collapse due to viscous friction and contact interactions. Figure 4(b) reveals a very simple dependence of the runout distance with respect to the maximum kinetic energy at large aspect ratios. In all regimes, in exception to low energies in the grain-inertial regime, the runout distance increases as a power law $R_{stop} \propto (E_{cx}^{max})^{\gamma}$ with $\gamma = 0.50 \pm 0.05$. When the runout distance is compared among the three regimes not for the same initial aspect ratio as in Fig.3, but rather at the same level of E_{cx}^{max}, it has its lowest value in the grain-inertial regime, largest value in the fluid-inertial regime and intermediate values in the viscous regime. This result is plausible as the fluid has a lubricating effect at the contacts and fluidizes the grain/fluid mixture. These effects are more pronounced in the fluid-inertial regime where the viscosity is lower. For this reason, R_{stop} is larger in the fluid-inertial regime than in the viscous regime. In this way, the paradox observed in Fig. 3 can be understood in the light of the collapse and runout data of Fig. 4. For a given aspect ratio, the grains acquire the highest kinetic energy in the grain-inertial regime due to the lack of fluid dissipation during vertical collapse. This energy is high enough to propel the heap, in spite of a high frictional dissipation, over a distance that can be longer than the runout distance in the fluid-inertial regime. In the latter case, the grains begin to spread with a lower kinetic energy but dissipate much less energy due to contact lubrication. In the viscous regime, for the same aspect ratio, the kinetic energy available for spreading is still lower and the dissipation due to viscous drag is higher, leading thus to a much shorter runout distance. The scaling of R_{stop} with E_{cx}^{max} at large aspect ratios is consistent with a simple physical picture in which each grain in the spread phase is on average subject to an effective viscous drag force [20].

6 CONCLUSION

In this paper, we used the dam-break configuration to simulate and analyze the collapse dynamics of a granular column immersed in a fluid. The effect of fluid in both viscous and fluid-inertial regimes is to reduce the kinetic energy during collapse and to enhance the flow by lubrication (in the generic sense of forces exerted by the fluid on the grains

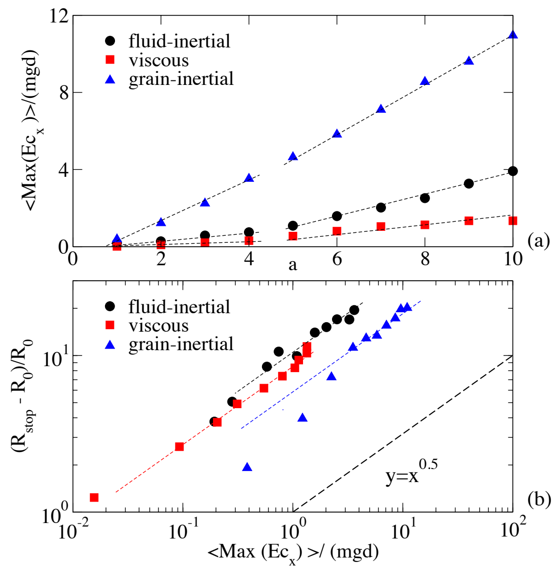

Figure 4: (a) Peak value of the mean horizontal kinetic energy per grain in different grain/fluid regimes as a function of aspect ratio. (b) Normalized runout distance as a function of the peak value of the horizontal kinetic energy per grain.

in proportion to their relative velocities) during spread. Hence, the runout distance in a fluid for a given geometry of the column may be below or equal to that in the absence of fluid due to compensation between those effects.

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