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Wake effects of large particles in a dry granular flow

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Introduction

- Flows of polydisperse dry granular materials relevant in many natural and industrial environments.
- Here: **dynamics of 2 large particles** (diameter d_t) free to move in a flow of small particles (diameter d) down a rough incline.
 - Same density for all particles.
 - High size ratios $d_t/d \Rightarrow$ reverse segregation [1] i.e. large particles near the bottom of the flow (in contrast with the segregation at small size ratios for which large particles locate at the free surface).
- **Experimental and numerical study of the interaction between the large particles.**
- Analysis of the **wake effect** of one tracer on the other combined to the **vertical shear** in the flow.

1 Interaction between two large particles (tracers) in a dry granular flow down an incline

Experiments

Flow of small glass beads, $d = 350 \mu\text{m}$
 Tracers : 2 large colored glass beads, $d_t = 2.0$ or 3.5 mm

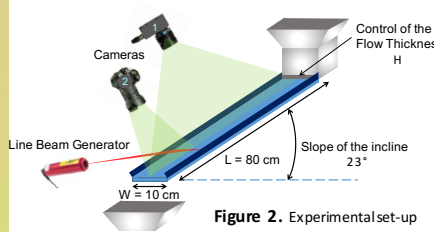


Figure 2. Experimental set-up

Results

- The tracers align with the flow
- The longitudinal distance between the tracers tends to a defined value function of H
 - > at small H, the tracers end up in contact,
 - > at intermediate H, the tracers locate at a distance that increases with H,
 - > at large H, the tracers stand as far as possible.

DEM simulations

Periodic Boundary conditions in x and y
 Domain size : $L_x = 80d$ or $160d$, $L_y = 40d$ or $80d$
 Slope of the rough incline : 24°

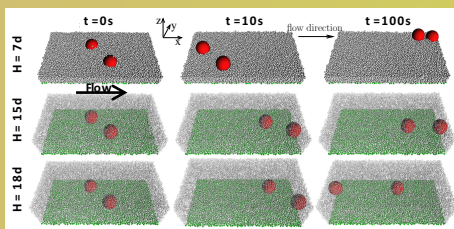


Figure 1. Size ratio $d_t/d = 10$

Successive positions of the tracers for 3 flow thicknesses. Small particles (in grey) are drawn partly transparent when the tracers are embedded in the granular flow to make them visible. The green color stands for the rough incline.

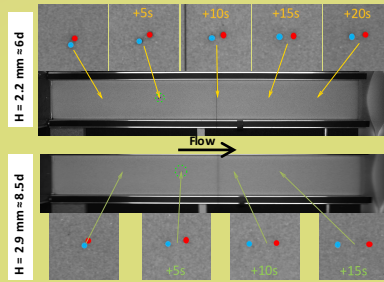


Figure 3. Size ratio $d_t/d = 6$ ($d_t = 2.0$ mm)

View from above the incline and successive positions of the tracers for 2 flow thicknesses. The front (resp. back) tracer is highlighted by a red (resp. blue) circle of same diameter as the tracer.

2 Transition between an attractive and a repulsive regime of interaction at increasing flow thickness H

Study of the steady state:

- Mean transverse distance $\langle \Delta y \rangle$
- Mean longitudinal distance $\langle \Delta x \rangle$

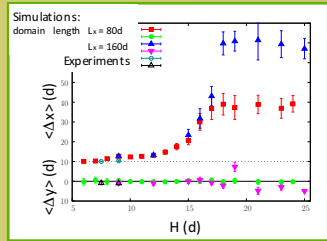


Figure 4. Size ratio $d_t/d = 10$

3 Characterization of the attractive – repulsive transition for various size ratios

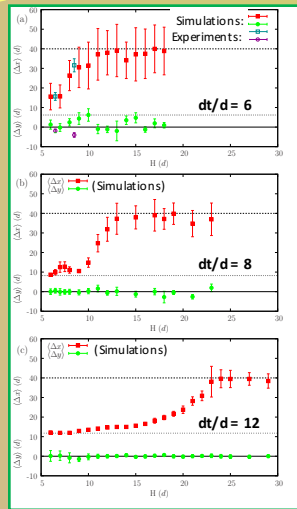


Figure 5. Mean longitudinal and transverse distances between the tracers, $\langle \Delta x \rangle$ and $\langle \Delta y \rangle$, vs flow thickness H for various size ratios.

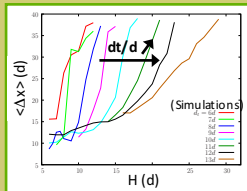


Figure 6. \Rightarrow Shift of the transition toward larger flow thickness H at increasing tracer size

Vertical location of the tracers $\langle \Delta z \rangle$ and mean height difference $\langle \Delta z \rangle$ between the tracers (DEM simulations)

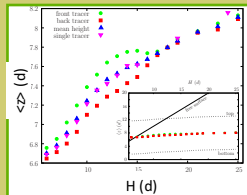


Figure 7. Size ratio $d_t/d = 10$. Mean height of the front (●) and back (■) tracers vs flow thickness H. Their center of mass (▲) remains at the same height as a single tracer in a similar flow (◆). Insert: Vertical positions of the top and bottom of the tracers (dotted lines) compared to the free surface of the flow (solid line).

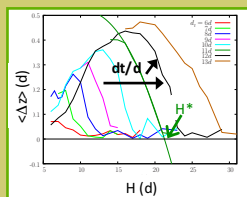


Figure 8. Bell-shaped curves of $\langle \Delta z \rangle$ vs H for size ratios ranging from 6 to 13.

\Rightarrow Definition of the transition thickness H^* from the intersection of a 2nd order polynomial fit of the right part of the curves with the horizontal axis.

- The transition is NOT concomitant to the emergence of the tracers from the granular flow.
- The emergence of the tracers results in an extra buoyancy term that counterbalances the interaction between the tracers \Rightarrow Decrease of $\langle \Delta z \rangle$ at small H.

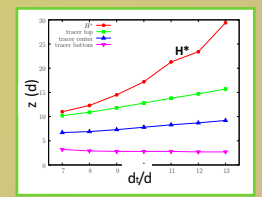


Figure 9. Transition thickness H^* vs size ratio.

4 Link between $\langle \Delta x \rangle$ and $\langle \Delta z \rangle$

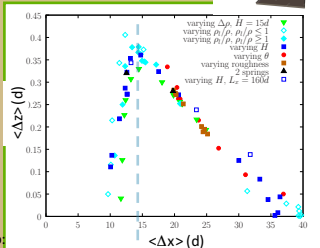
Several configurations explored:

- ▲ A density difference $\Delta \rho$ between the two tracers
- ▲ A density ρ_t of both tracers slightly smaller or larger than the small-particles density ρ
- ▲ Variation in the flow thickness H
- ▲ Variation in the slope of the incline
- ▲ Variation in roughness of the incline
- ▲ Addition of two horizontal springs between the tracers (necessary to compute velocity maps)

\Rightarrow All points on a Master curve

Figure 10. Size ratio $d_t/d = 10$.

- Left part of the curve
- A decrease in $\langle \Delta z \rangle$ may be due to:
 - ▲ Emergence of tracers from a thin flow
 - ▲ Emergence of tracers less dense than the small particles
 - ▲ Strong interaction with the rough incline for tracers heavier than the small particles
 - ▲ A front tracer heavier than the back tracer
- A simultaneous decrease is observed in $\langle \Delta x \rangle$.
- Right part of the curve: The decrease in $\langle \Delta z \rangle$ and the increase in $\langle \Delta x \rangle$ are associated to a weaker and weaker interaction between the tracers.



5 Combination of wake effects and shear

($d_t/d = 10$, $H = 15d < H^*$)

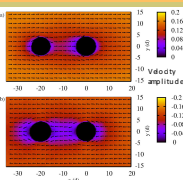


Figure 11. Velocity maps in the horizontal plane at a distance $2.5d$ above (a) and below (b) the center of the front tracer in the reference frame of this tracer (right tracer).

Alignment of the tracers.

The small particles on the sides of the tracers move faster than those in the wake regions and push the two tracers in line in the direction of the flow.

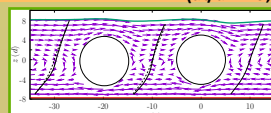


Figure 12. Velocity map in the vertical plane in the reference frame of the front tracer (right tracer). Thin black lines: velocity profile behind (left), between (center) and ahead (right) of the tracers. Dashed lines: velocity profile ahead of the tracers shifted horizontally for comparison.

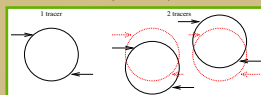


Figure 13. Sketch of the tracer interactions with the small particles of the granular flow. The length of the arrows is indicative of intensity of the shocks.



What determines the steady state value of $\langle \Delta x \rangle$?

- Velocity gradient in between the tracers reduced compared to that ahead of the tracers
- Lower (resp. upper) half of the back (resp. front) tracer in the wake of the lower (resp. upper) half of the front (resp. back) tracer \Rightarrow the back tracer accelerates and the front tracer decelerates $\Rightarrow \langle \Delta x \rangle$ decreases.
- Front (resp. back) tracer higher (resp. lower) in a shear flow \Rightarrow the tracers move away $\Rightarrow \langle \Delta x \rangle$ increases.
- These two mechanisms lead to the equilibrium longitudinal distance $\langle \Delta x \rangle$.

Why a difference in height $\langle \Delta z \rangle$ between the tracers?

- For a single tracer in a granular flow, the vertical location at equilibrium results from the tracer weight, the buoyancy and the collisions with the small particles.
- The wake effects cause an asymmetry of the shocks with the small particles on two tracers at the same height (red dotted circles on Fig.13) \Rightarrow the front tracer moves upwards and the back tracer moves downwards \Rightarrow new vertical equilibrium positions (black circles on Fig.13) $\Rightarrow \langle \Delta z \rangle$.

Prospects • Explore the similarities and differences with the sedimentation of particles in fluids.

- More than 2 large particles: formation of patterns or flow organizations (e.g. trains of tracers, bands in polydisperse flows) with major interest for natural granular flows (e.g. debris flows) or industrial processes.

References

- [1] N. Thomas, Phys. Rev. E **62**, 961 (2000)
- [2] N. Fraysse, U. d'Ortona, N. Thomas. Preprint ([hal-03571280v2](https://arxiv.org/abs/1803.07128v2)) (scan QR code for article)

