

Drag and lift forces when moving in a cohesive granular medium

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Abstract. When a cylinder moves horizontally in a dry granular medium, it experiences both a drag force and a significant lift force, despite the symmetry of the geometry. The lift force arises due to the unique frictional nature of granular material rheology. The drag force is proportional to the pressure exerted by the column of grains above the object, while the lift force is proportional to the pressure gradient controlled by gravity. This study investigates how these forces are affected by the introduction of adhesion between grains and whether measurements of drag and lift can serve as reliable proxies for determining the cohesion of the medium. Experiments were conducted using two types of cohesive granular media: wet grains and grains coated with a sticky polymer. The results indicate that cohesion has a minimal impact on drag, whereas it significantly reduces the lift force.

1 Introduction

Forces experienced by objects moving inside a dry granular medium have been extensively studied [1–6]. This problem is of primary importance in various applications such as stirring, mining, mixing, impact dynamics, and locomotion in sand [7–10]. Additionally, it is of fundamental interest for probing the rheological properties of the medium [11]. Classically, the total force acting on an object in a flow is divided into a drag force, which aligns with the flow direction, and a lift force, which is perpendicular to it. In a dry granular medium, in the quasi-static limit, the drag force on a horizontally moving cylinder is observed to be independent of velocity and proportional to the hydrostatic pressure times the surface area of the object. Conversely, the lift force is related to the pressure gradient and scales with the Archimedean force.

The question of drag and lift in cohesive materials, such as wet sand or powders, remains relatively unexplored. Measuring the force experienced by an object moving in powders is a technique for powder characterization [12], and it would be of great interest to better understand the link between these measurements and the rheological properties of the material. In this study, we investigate through experiments how the drag and lift forces experienced by a horizontally moving cylinder in a granular material are modified when adhesive forces are introduced between the grains. The measurements reveal that the drag is weakly impacted by cohesion, whereas the lift is significantly diminished.

2 Material and methods

To measure the drag and lift forces, we employed a setup similar to that used by F. Guillard et al. [3, 4]. As shown in Fig 1a, the setup consists of a cylinder (linked by a thin rigid rod to the head of a rheometer) rotating inside a granular medium. The drag and lift forces felt by the cylinder can be estimated by measuring the torque and normal force. The cylinder is positioned at a fixed depth, H , and rotates at a slow speed of $\Omega = 2$ rpm, in a quasi-static regime confirmed to be independent of Ω . The cylinder has a length $L = 45$ mm (150d) and a diameter $D = 6$ mm (20d). The granular medium is composed of glass beads with a mean diameter of $d = 300\mu\text{m}$ and a density equals to 2500 kg/m^3 .

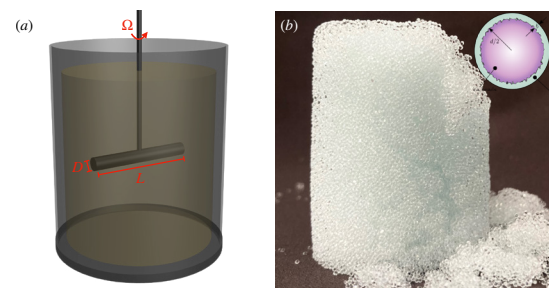


Figure 1. (a) Scheme of the experimental set-up consisting in a cylinder rotating in a bucket filled with grains (b) Picture of a column of CCGM grains.

Experiments were conducted using two types of cohesive granular media: water-wetted grains and polymer-coated sticky glass beads, referred to as CCGM [13]. In

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both cases, the cohesion can be controlled by adjusting the proportion of liquid or PDMS added to the granular assembly. For wet systems in the pendular regime, cohesion increases with the liquid ratio, W , defined as $W = m_{\text{water}}/m_{\text{grains}}$ where m_{water} and m_{grains} are the masses of water and grains, respectively [14]. For CCGM grains, cohesion is directly related to the average thickness of the coating, b [13] (Fig. 1b).

The drag and lift forces were measured after five rotations to ensure a stationary regime and were averaged over three rotations and three independent runs. The drag force in this case is known to be influenced by the previous rotations [3]. However, this method provides a simple and convenient way to prepare the sample in a reproducible state, allowing us to effectively assess the influence of cohesion.

3 Results and discussion

Initially, we validated our experimental setup and protocol by studying the drag and lift forces for dry glass beads. As shown in Figures 2 and 3 (black square symbols), both forces increase with depth H until reaching a saturation point at larger depths. Our measurements align well with the results previously obtained by Guillard et al. (red square symbols) [3, 4].

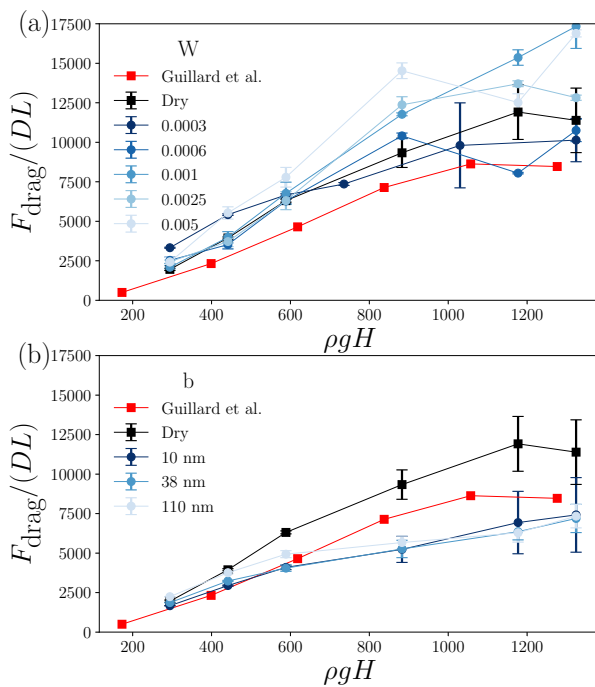


Figure 2. Evolution of the drag force, F_{drag} with the depth for (a) wet grains (b) CCGM grains.

The results for cohesive materials are presented for wet particles (Figs 2a and 3a) and coated particles (Figs.2b and 3b). The first observation is that the drag force (Fig. 2) is not significantly affected by the introduction of adhesion in our systems. Almost no noticeable difference is observed for the wet system, whereas for the polymer-coated parti-

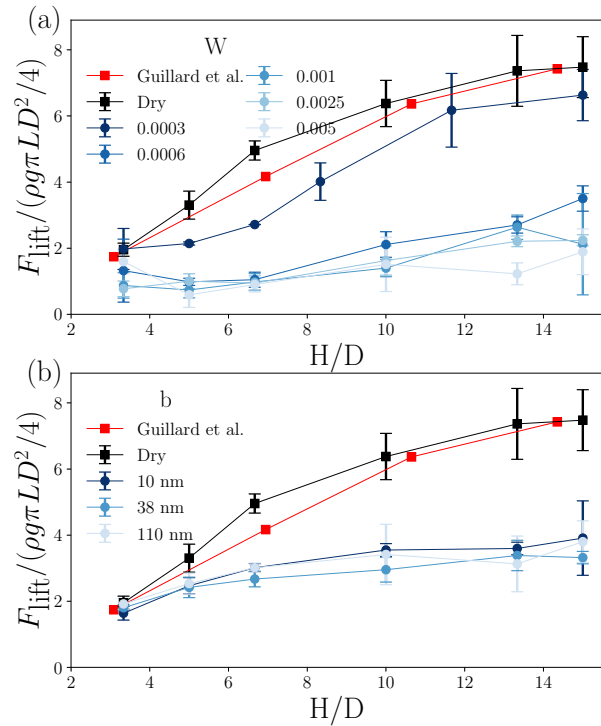


Figure 3. Evolution of the lift force, F_{lift} with the depth for (a) wet grains (b) CCGM grains.

cles, a slight decrease in the force is noted. This is surprising, as cohesion is expected to add resistance to flow. The second major observation is that the lift force is by contrast strongly affected by cohesion. In both wet and coated particles, the lift force is reduced by almost a factor of four, showing that the lift is much more sensitive to cohesion than the drag.

A plausible qualitative explanation can be given by estimating the cohesive stress of our granular material. For our $300\mu\text{m}$ particles, the cohesive stress for both wet and coated particles is on the order of a few hundred Pascals (less than 400Pa for the most adhesive cases). Since the drag force is proportional to the mean hydrostatic stress $\rho g H$, the influence of cohesion is controlled by $\tau_c/\rho g H$, which is less than 0.4 for our glass beads explaining the weak influence of adhesion on the drag.

On the other hand, the lift force is related to the pressure difference above and below the obstacle, with the characteristic pressure difference being $\rho g D$. The influence of cohesion on the lift force is then expected to be related to $\tau_c/\rho g D$, which, in the range of depths investigated, is on the order of 4. This value is ten times larger than the corresponding value for the drag force, which may explain why cohesion primarily affects the lift force rather than the drag force. However, further investigation is necessary to better understand the influence of cohesion on drag and lift. In particular, during the first half rotation of the cylinder where the cylinder does not feel its own wake. Preliminary results show that the preparation protocol plays a crucial role.

4 Conclusion

In this study, we investigated through experiments how the drag and lift forces experienced by a horizontally moving cylinder in a granular medium are modified when cohesion is introduced between the grains. Experiments were conducted using two types of cohesive granular media: wet grains and grains coated with a sticky polymer. For both cases, observations indicate that the drag is weakly impacted by cohesion, whereas the lift is significantly diminished.

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