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# EXPERIMENTAL INVESTIGATION SIZE PARTICLES SEGREGATION BY LAMINAR SHEARING FLOWS

Jaime Gonzalez Maya <sup>a,b</sup>

Fernando David Cúñez Benalcázar <sup>a</sup>

Erick de Moraes Franklin <sup>a</sup>

<sup>a</sup> UNICAMP-University of Campinas, School of Mechanical Engineering, Rua Mendeleev, 200, Campinas, 13083-860, Brazil

<sup>b</sup> Escuela Politécnica Nacional, Petroleum Department, Quito, Ecuador

jaime.gonzalez@epn.edu.ec, fernandodcb@fem.unicamp.br, franklin@fem.unicamp.br

**Abstract.** In this work, annular flume experiments are carried out to study a granular bed sheared by a viscous flow. The aim is to investigate the mechanism of segregation of coarse grains within a bi-dispersed granular bed sheared by a Couette flow. The annular flume mimics an infinitely-long river, enabling us to observe the evolution of the motion of the particles from the inception of the motion until the transport of the particles as bedload. In some cases, the bed material consists of a wide range of particles that has different grain sizes, densities, and shapes. Usually, those particles segregate by the presence of a viscous shear rate. From an engineering point of view, it is crucial to predict this phenomenon's occurrence and nature. In our experiments, the granular bed consisted of two sizes of glass beads whose mean diameters are  $d_s = 2.00$  mm and  $d_l = 3.17$  mm, and the channel was filled with sodium iodide (NaI) solution at 35% (w/w) in glycerin. We imposed a mean fluid velocity ranging from 0.095 m/s to 0.36 m/s by rotating  $\Omega$  the flume lid (5 to 20 RPM), which ensured the particles transport as bedload. Under these conditions, we filmed the bedload layer with a digital camera to record the real-time positions of single particles by acquiring the fluorescence intensity from a laser dye traversing the fluid (refractive index matched RIM technique). We automatically identified and tracked the particles along images by using numerical scripts, from which we computed parameters such as velocity profiles and particle trajectories. The mechanisms of segregation of coarse beads towards the granular surface over time were identified and are explained in this work.

**Keywords:** Bed-load layer, sediment transport, laminar flow, granular segregation, shearing

## 1. INTRODUCTION

The motion of grains within the bedload layer is known as bedload transport, and is widely found in many industrial applications. For example, in oil or mining production pipelines, horizontal drilling, sewer systems, dredging lines. From an engineering point of view, it is crucial to predict the occurrence and nature of this phenomenon since the sediment transport, and the growth of bed-forms significantly influence flow characteristics, pressure drop, mixing properties, and sediment transport itself (Kidanemariam and Uhlmann, 2014). In environmental processes such as, rivers, sandy beaches, dryland rivers, and hillslope sediment, high sediment fluxes during extreme flows destabilize river channels, causing loss of property and public infrastructure, increasing flooding problems, compromising water quality and aquatic habitat, and threatening human life (Frey and Church, 2011), this is why important to understand the bedload transport behavior.

In these conditions, the movement of particles within bedload can be characterized by the Shields number  $\theta$  (Shields, 1936), which determines the relationship between fluid shear stress modulus  $\tau_f$  over a granular bed and the particle weight. When this number is above a critical value  $\theta_c$  to overcome grain friction (Bagnold (1973), Prancevic *et al.* (2014)), it causes an incipient motion of few particles. Up to a value of five times the critical Shields number,  $5*\theta_c$  (Raudkivi, 1998), the particles move by rolling, sliding, and/or small jumps in a layer known as bedload, which is typically viewed as a thin surface layer of moving grains in frequent contact with an underlying granular bed that is ostensibly static (Charru *et al.*, 2004) (Houssais *et al.*, 2015).

Generally, the sediments are usually composed of particles with different grain sizes, densities, shapes, or surface properties with a heterogeneous distribution, the transport of particles driven by a fluid implying an auto sorting or segregation of granular materials. As a result, that larger particles tend to accumulate over the bed surface or at flow fronts, e.g., if by segregation, coarse beads go towards the bed surface and, being more frictional than the fine grains, so they can feedback on the bulk flow, causing flow fingering, levee formation, and more extended run out of geophysical mass flows (Gray, 2018), according to Frey and Church (2011) and Dudill *et al.* (2018) the segregation is mainly responsible for the limited ability to predict sediment flux and river morphology.

The segregation of particles by size results from the interaction between large and small particles, where small par-

ticles can percolate without external forcing, only by gravity, and where percolation generates deformation of the bed, (Bridgwater and Ingram, 1971; Savage and Lun, 1988; Dudill, 2016). Chassagne *et al.* (2020) mentioned that the dynamic segregation, also named as gravity-driven segregation (Gray, 2018) results from both combinations of Kinetic sieving (Middleton, 1970) and the squeeze expulsion (Savage and Lun, 1988). The first one is based on the idea that, when sheared, granular media experience velocity fluctuations creating holes between particles, while for the other one small particles are more likely to fall and tend to push large particles upwards, causing a net flux downward for the small particles and upward for the large.

The literature review on dry granular flows underlines the qualitative understanding of size-segregation for simple flow (Savage and Lun, 1988; Golick and Daniels, 2009; May *et al.*, 2010; Maurin *et al.*, 2016). Bedload transport can be seen as a granular flow where the coupling with the fluid induces strong gradients in the vertical direction and a complex forcing, which could challenge the classical picture of segregation (Chassagne *et al.*, 2019). Thereby, Charru *et al.* (2004) studied the evolution of a mono-dispersed granular bed sheared by a viscous Couette flow during the erosion and deposition processes. The authors observed that after a particular time, the bed begins to compact due to the local rearrangement of the particles, increasing thus the threshold for particle motion. They also developed two models: one for the stationary erosion and deposition processes, and the other for the transient evolution, allowing them to understand the linear relationship between the compaction of the granular bed and the Shields number. Following the studies of Charru *et al.* (2004), Houssais *et al.* (2015) and Ferdowsi *et al.* (2017b) did experiments using an annular flume and employing refractive-index matching between the fluid and particles (Wright *et al.*, 2017). As the optical technique allowed measurements within the bed, the authors ran experiments from shear rates lower than the critical one to shear rates high enough to obtain the bedload. Houssais *et al.* (2015) showed that there is a regime called creeping-soil which appears even for shear rates lower than the threshold for particle motion; this regime usually appears just beneath the bedload layer and where grains present a solid-like behavior. The authors also identified a kink point from the velocity profiles, which marks the boundary between the bedload layer and the creeping regions. Ferdowsi *et al.* (2017b) studied size segregation experimentally in laminar bedload transport, and concluded that the bedload transport in the near-surface layer drives rapidly advective segregation that is shear rate dependent. The creeping grains beneath the bedload layer give rise to slow but persistent diffusion-dominated segregation. They performed dry granular flow simulations with discrete element models and also modified parameters such as the coefficient of advection-diffusion from Gray and Thornton (2005) continuum model's, which allowed the continuum model to reproduce the discrete simulations quantitatively. This previous experimental study has been made on gravity-driven segregation (Gray, 2018) in bedload transport, and more remains to be done for a clear understanding of the processes at play.

In this paper, we investigate the mechanism of segregation of coarse grains within a bi-dispersed granular bed sheared by a Couette viscous flow, using an annular flume and employing refractive-index matching between the fluid and particles (Bai and Katz, 2014). The evolution of the motion of the particles was observed from the inception of motion until the transport of the particles as bedload. In our experiments, the granular bed consisted of two sizes of glass beads whose mean diameters are  $d_s = 2$  mm and  $d_l = 3.17$  mm, and the channel was filled with a viscous flow composed of sodium iodide (NaI) solution at 35% (w/w) in glycerin. We imposed a mean fluid velocity of 0.095 m/s to 0.30 m/s by rotating  $\Omega$  the flume lid (5 to 20 RPM), ensuring the particles transport as bedload. Under these conditions, we acquired images of the bedload layer every 10 seconds for a long time with a digital camera to record the real-time positions of single particles. The coarse particles are identified and tracked automatically along images by using numerical scripts, and we show some results such as velocity profiles and particle trajectories. The mechanisms of coarse beads segregation towards the granular surface by shearing were identified and are explained in this work.

## 2. EXPERIMENTAL SETUP

The experimental setup consisted of closed-top annular flume (Fig. 1a), of mean radio  $R = 18$  cm, and an internal section of 40 mm-width  $w$  and 30 mm-height  $H$ . The flume lid is connected to an electrical drive by a shaft for rotating it. The channel walls are smooth to allow slip between particles and the boundary to approximate an infinitely deep and wide channel. The picture of the Fig 1b, shows of the experiment with camera, and an illuminated 2D plane of particles. A bi-disperse granular bed, showing in Fig. 1c, had a 24 mm-height  $h$  and consisted of glass spherical particles with both small and large diameters,  $d_s = 2.00$  mm and  $d_l = 3.17$  mm, respectively and density  $\rho_p = 2.5$  g/cm<sup>3</sup> was immersed in a fluid of viscosity  $\eta = 160$  mPa.s and density  $\rho_f = 1.50$  g/cm<sup>3</sup>. The ratio of the total volume employed of small to large particles is  $V_{small}/V_{large} = 1.5$ , and the particle size ratio  $d_l/d_s = 1.58$ . A fluid gap of 6 mm  $h_f$  is sheared from above by rotating the flume lid at a constant rate  $\Omega$  to apply a uniform fluid shear stress  $\tau_f$  over bidisperse granular bed. Shields number  $\theta_s$  for the small grains was determined from Eq. (1) (Shields, 1936)

$$\theta = \frac{\tau_f}{(g(\rho_p - \rho_f)d_s)} \quad (1)$$

where  $g$  is the modulus of the acceleration of gravity.

The fluid-flow velocity at the flume lid in the channel center was calculated as  $= \Omega * R$ . Thus, the fluid shear stress

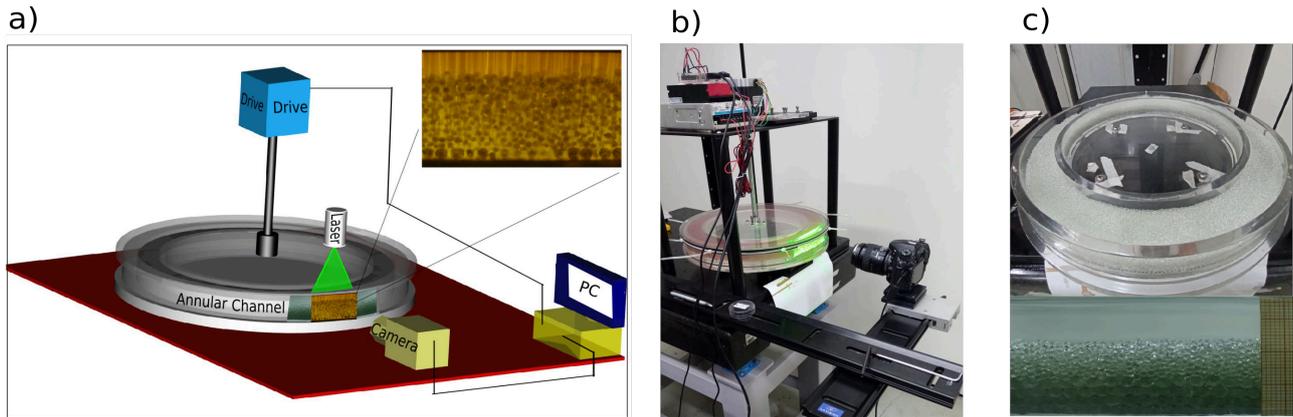


Figure 1. a) Schematic diagram of the experiment, showing position of the camera and laser plane used for imaging inside the granular bed. b) Picture of the experiment with camera, and an illuminated 2D plane of particles. c) Annular channel filled with glass particles as inverse segregation.

is then calculated as  $\tau_f = \frac{\eta * U}{h_f}$ . Reynolds number value is estimated as  $Re = \frac{\rho_f * U * h_f}{\eta}$  with low values ranging from 5 to 20.6 for the experiments. Thus ensuring that both turbulence and secondary flows are suppressed (Charru *et al.*, 2004), which has a ratio of radial viscous stress to the azimuth viscous stress for our experimental conditions less to 4%.

The bed at the start of each experiment was composed of particles forming an approximately flat granular bed. The grains were initially deposited in an inverse-segregated state following the preparation protocol inspired by Golick and Daniels (2009), with large grains at the bottom, and then subject to driving stress equivalent to  $20 * \theta_c$  for 1 min to suspend and mix the large and small populations entirely. Next, fluid shear was halted, and the suspension left for 30 min to allow sedimentation, relaxation, and compaction of the granular bed (Ferdowsi *et al.*, 2017b), prior to the beginning of the experiment ( $t=0s$ ).

An incipient movement of few particles was imposed by rotating the flume lid at  $\Omega=5$  RPM. In this condition the critical Shields number is  $\theta_c=0.12$ ; this value was similar to reported by (Ouriemi *et al.*, 2007) (Charru *et al.*, 2004) (Houssais *et al.*, 2015). Afterwards, the experiment were conducted at three Shields numbers as showing in Tab. 1.

Table 1. Experimental parameters

Parameters	Experiment 1	Experiment 2	Experiment 3	Experiment 4
RPM	5	10	15	20
Shields numbers	$\theta_c$	$2.1 * \theta_c$	$3.1 * \theta_c$	$4.2 * \theta_c$
Reynolds number	5	10.4	15.5	20.6

The fluid shear was initiated at the specified Shields stress and applied for 24 h or longer. To visualize granular dynamics, we ensure the fluid's refractive index with the particles to a value of 1.52 because the material glass particle is of soda-lime, it was possible to get with sodium iodide (NaI) solution at 35% (w/w) in glycerin. In these conditions, we record laser-excited fluorescence of a dye dispersed in the fluid, which allows us to image a vertical profile of grains in the center of the channel. We used a Nikon 7500 digital camera to record the real-time positions of single particles, acquire single images at a rate of one every 10 s for 24 h or longer, and sample slow dynamics in the system. The number of acquired images for each test was 7500 images which we analyzed using numerical codes written in order to process the obtained images.

### 3. RESULTS

#### 3.1 IMAGES

Figure 2a, shows an instantaneous snapshot of the granular bed in the center of the channel obtained during our experiment. We observed that the index-match of the fluid with the particles is suitable, allowing us to visualize the circular section of both coarse and small particles while the light sheet thin from the laser crosses the bed.

We compare our images, Fig 2a, with a image of reference Fig 2b extracted from Ferdowsi *et al.* (2017a). We can see that the sharpness of the image within the bed in our experiment is worse than Ferdowsi experiments', we note a shading that reduces somewhat the particle visualization; this difference between images is due to the materials used by Ferdowsi *et al.* (2017b) which required a refractive index equal to 1.47 and were highly spherical and optically clear (PMMA) (Bai and Katz, 2014).

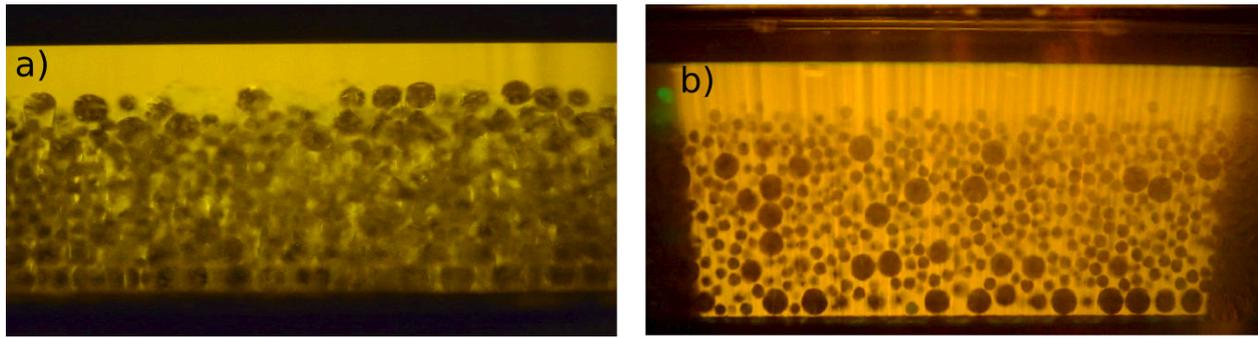


Figure 2. a) Image obtained from our experiments. b) Image extract from (Ferdowsi *et al.*, 2017a).

Through numerical scripts, the images were processed, obtaining information as the centroid of bright spots to sub-pixel accuracy; thus, we localized the dark circle center that represents the particles within the bed in the center of the channel; this will observe from Fig 3, there we can see that were detected the centroid of bright for each coarse particle. At the same time, there are some areas without being detected. It is substantial to improve the process of detecting the particles, using some tool for filtered of image and achieve to detect the particles.

Figures 3a and 3b show the configuration of the bed at the beginning of experiment 2, and at the end of experiment 4, respectively (see Tab. 1), the yellow curve inside both figures is the mean intensity of color in the vertical direction, from which it is possible to determine the compaction of the bed qualitatively due to the rearrangement of particles. The horizontal blue line shows the top boundary of the bed. It is possible to detect more particles over the bed's surface in Fig 3b than Fig 3a. This is due to the segregation of the coarse particles with as increasing the Shields number.

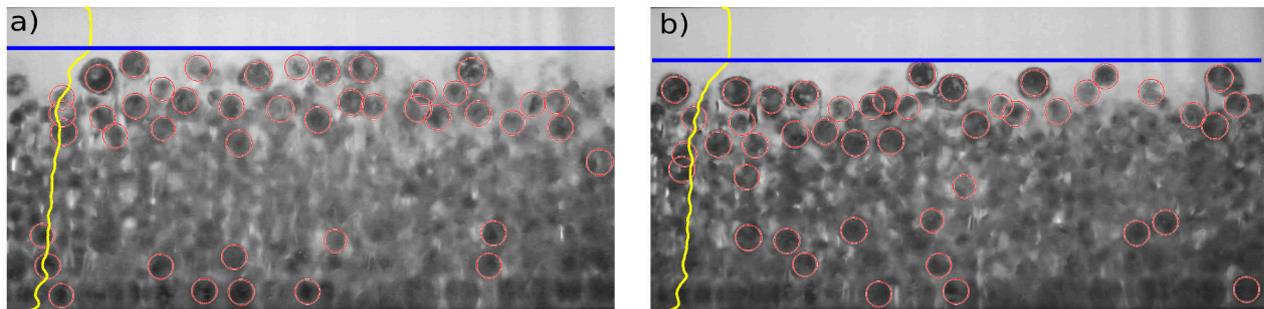


Figure 3. Configuration of the bed. a) At the beginning of experiment 2. b) At the end of experiment 4.

### 3.2 BED BEHAVIOR

We estimate the particle velocity frame by frame by using the Lagrangian particle tracking from Ouellette *et al.* (2006) that stitch positions at different frames into tracks. Thus, we plot the instantaneous velocity in Fig. 4a and Fig. 4b. We can see the instantaneous velocities of coarse particles located over and within of the bed, which have values of the order of  $10^{-2}$  m/s (orange and red color) and under  $10^{-3}$  (blue and light blue color), respectively.

Figure 4c, shows the semi-log graph of the packing fraction, obtained from the instantaneous images based on the intensities of color. The low intensity (dark color) corresponds to the bed section. Here, the liquid phase is occupied only inside interstices between the particles, and the high intensity (bright color) corresponds only to the liquid phase without particles. Inset shows the maximum value of the packing fraction is 0.6.

We can see an increase of packing fraction and compaction of the bed from the Fig 4c, due to the rearrangement of particles as Shields number increased from  $2.1 \cdot \theta_c$  (blue line), until  $4.2 \cdot \theta_c$  (red line).

In Fig 5a, we observed the long-time average coarse particle velocity divided by diameter. Two behaviors within the bed are detected. The first is where the bed's velocity is negligible. The second is where the bed has a perceptible movement; these two behaviors are directly related to the creeping and bedload layer region, respectively (Houssais *et al.*, 2015).

Figure 5b shows the long-time average velocity at the vertical direction; we can see positive velocity values within the bedload layer. This is due to the segregation of the coarse particle.

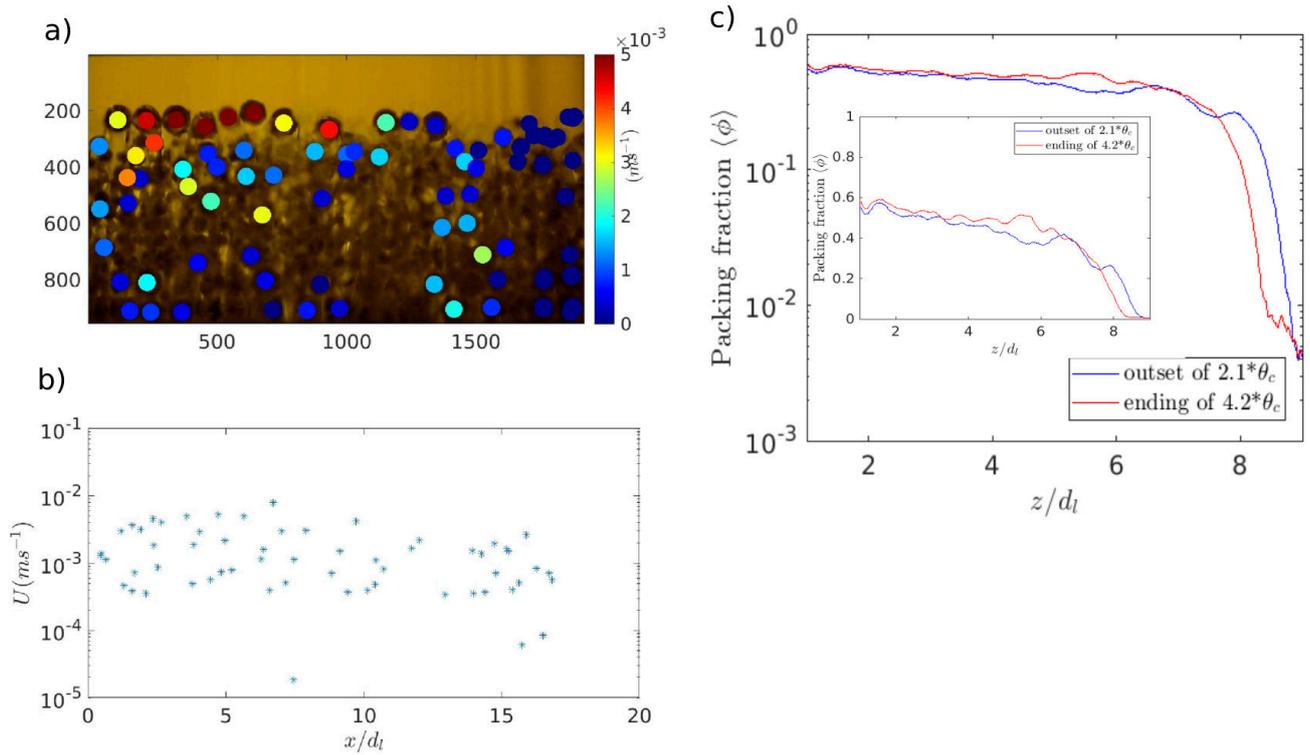


Figure 4. a) Instantaneous detection of coarse particles at  $3.1 \cdot \theta_c$ . b) Instantaneous velocity of coarse particles at  $3.1 \cdot \theta_c$ . c) Instantaneous packing fraction.

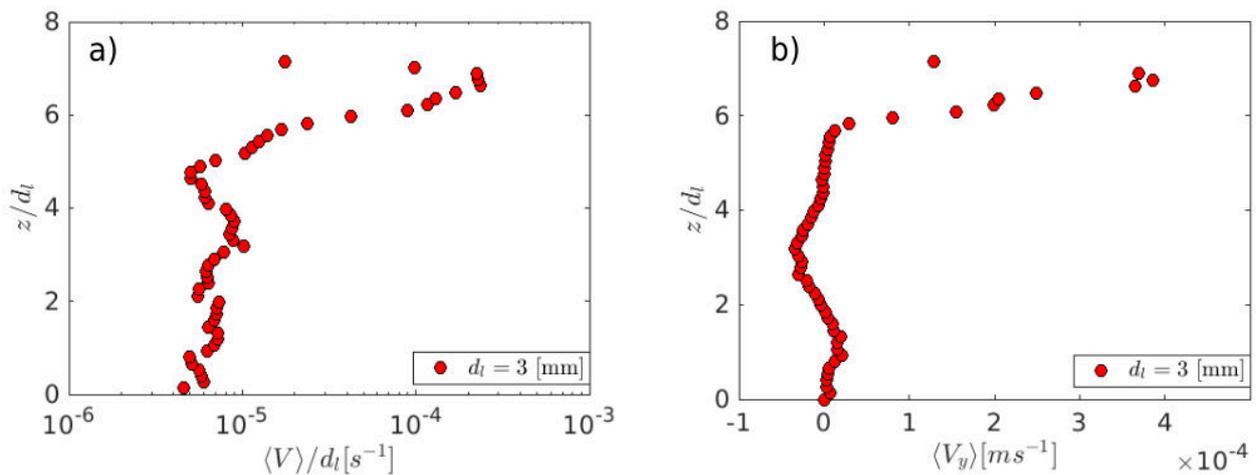


Figure 5. Long-time averaged coarse particle velocity at  $3.1 \cdot \theta_c$ . a) Velocity divided by diameter. b) Velocity at the vertical direction.

#### 4. CONCLUSIONS

This work investigated the segregation of coarse grains in a bi-dispersed granular bed sheared by a viscous Couette flow. For the analysis, we made use of the refractive-index matching between the fluid and the glass particles. We used glycerin as a working fluid, whose measured viscosity changed considerably (around 10%) from the values found in the literature. It was possible to observe the compaction of the bed due to the rearrangement of the particles. We also verified that the segregation of coarse particles increased with the Shields number. Furthermore, we obtained the instantaneous velocity of the coarse particles at a given time using the image processing method. We observed that the velocity within the bed is directly related to the creeping region (where velocity is negligible) and bedload layer (where there is noticeable movement). Thus, the segregation of coarse particles was more noticeable within the bedload layer.

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