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A NUMERICAL STUDY OF COARSE GRAINS SEGREGATION WITHIN A GRANULAR BED

Jaime Gonzalez Maya [a,b]
Fernando David Cúñez Benalcázar [a]
Erick de Moraes Franklin [a]
[a] University of Campinas, School of Mechanical Engineering, Rua Mendeleyev, 200, Campinas, 13083-860, Brazil
[b] Escuela Politécnica Nacional, Petroleum Department, Quito, Ecuador
jaime.gonzalez@epn.edu.ec, fernandodcb@fem.unicamp.br, franklin@fem.unicamp.br

Abstract. *In this work, we performed numerical simulations to investigate the segregation of coarse grains within a bi-dispersed granular bed sheared by a Couette flow, by using a Lagrangian-Eulerian approach (CFD-DEM). The granular bed consisted of two sizes of glass beads (d_1 = 2mm and d_2 = 3mm),where the concentration of big particles was 1%, which were placed randomly inside a 10cm-long rectangular channel filled with glycerin that mimics an infinitely long and wide river. We imposed a mean fluid velocity of 0.02 m/s at the channel lid, ensuring the particles transport as bedload. Under these conditions, it was possible to observe the segregation of coarse beads towards the granular surface over time with characteristic trajectories and velocities. Data from the numerical simulations were post-processed using numerical scripts, from which parameters such as velocity profiles and particle trajectories were computed.*

Keywords: *Bed-load layer, segregation, sediment transport.*

1. INTRODUCTION

The transport of sediments by fluid flows is widely encountered in many industrial and environmental applications. For example, it can be found in rivers, oceans, petroleum pipelines, sewer systems, and dredging lines. However, it remains difficult to understand. The over-saturated mining that occurs in rivers, natural disasters such as earthquakes and major storms, and climate changes lead to major consequences for public safety, management of water resources, landscape evolution, and environmental sustainability. High sediment fluxes during extreme flows destabilize river channels causing loss of property and public infrastructure, increase flooding problems, compromise water quality and aquatic habitat, and may threaten human life (Frey and Church, 2011). From an engineering point of view, it is important to predict the occurrence and the nature of this phenomenon, since the sediment transport and the growth of bedforms significantly influence flow characteristics such as resistance, mixing properties, and sediment transport itself (Kidanemariam and Uhlmann, 2014). Therefore, understanding the processes of sediment transport and erosion is critical to forecasting hazard cascades and flood risk under extreme scenarios. In fluid-driven granular flows, the transport of particles (sand, coarser gravel, sediment) by bedload is commonly found, were the particles move by rolling, sliding and/or saltating in a layer known as bedload (Ali and Dey, 2017).

The transport of sediments as bedload transport has been studied by using numerical simulations and experimental devices;by applying a simple shear with different conditions such as confined channels and free surface beds. For numerical simulations, there are some studies which have used the Lagrangian-Eulerian approach, where the particles motion/interactions are resolved as a discrete medium, while the fluid flow is computed as a continuum medium by resolving the Navier-Stokes equations. For the experiments, some studies have designed and built annular flumes that mimic an infinitely-long river, where it is possible to observe the evolution of the particles motion from the inception of the motion until the transport of the particles as bedload. Charru *et al.* (2004) studied the evolution of a granular bed sheared by a viscous Couette flow during the erosion and deposition processes. The authors observed that after a certain time, the bed begins to compact due to the local rearrangement of the particles, increasing thus the threshold shear rate 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) made experiments using a similar annular flume and employing refractive-index matching between the fluid and particles. As the optical technique allowed measurements within the bed, the authors ran experiments from shear rates lower than the critical one to shear rates higher enough to obtain the bedload. Their results showed that there is a regime called creeping-soil which appears even for shear rates lower than the threshold for particles motion, this regime usually appears just beneath the bedload layer, and where grains present a solid-like behavior. From the velocity profiles, the authors also identified the presence of a kink point which marks the boundary between the bedload layer and the creeping regions.

Although experiments usually deal with monodisperse beds, the bed material in fluvial gravel systems is formed 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 (segregation by shearing) (Duran, 2000). For shear-induced size segregation, the fine particles can percolate through a moving bed due to a large difference of the particles size, this phenomenon being called as kinetic sieving. Here, the usual result is a downward flux of the smaller particles and an upward flux of larger particles, as observed in river deposits (Frey and Church, 2011). Thus, several experimental, computational and mathematical studies have been developed to understand the segregation process in river beds. May *et al.* (2010), Ferdowsi *et al.* (2017), and Chassagne *et al.* (2020) used a continuum particle-size segregation model proposed by Thornton-Gray and Hogg (2006) and tried to obtain new insights into the mechanics of segregation within a bed-load layer. They modified this model and its parameters such as the coefficient of advection-diffusion, that allowed the continuum model to quantitatively reproduce the discrete simulations. The authors concluded that the bedload transport in the near-surface layer drives rapidly an advective segregation that is shear rate dependent. Ferdowsi *et al.* (2017) also found that creeping grains beneath the bedload layer give rise to slow but persistent diffusion-dominated segregation. According May *et al.* (2010), the limitation of using this continuum mixture-theory model, for a discrete process where the number of discrete objects is comparatively small, is that the model segregates in finite time rather than exponentially approaching a final re-segregated state. In spite of these limitations, all results were validated with data from experiments and numerical simulations. Finally, Jing *et al.* (2017) Observed that the upward migration of large particle is due to particle rotation associated with shear, and proposed that one the origin of preferential upward movement is high connectivity with increase greater contact forces they carry (interparticle friction), such as driving mechanism of upward percolation velocity. The authors also observed that the segregation of large particles can be suppressed with insufficient friction strength. While small particles percolate through voids without enduring contacts.

The main goal of this study is to capture the segregation of coarse grains within a bi-dispersed granular bed sheared by a viscous Couette flow, by performing numerical simulations. We used the open source code CFDEM ($https://www.cfdem.com/$) which couples the open-source codes OpenFOAM (CFD) and LIGGGHTS (DEM). The granular bed is consisted of two sizes of glass beads ($d_1 = 2$mm and $d_2 = 3$mm) that were placed randomly inside a 10cm-long rectangular channel filled with glycerin that mimics an infinitely long and wide river (stream-wise (x) and span-wise (y) directions with periodic boundary conditions). By imposing a mean fluid velocity of 0.02 m/s at the top of the channel, was possible to observe the segregation of coarse beads towards the granular surface over time with characteristic trajectories and velocities. Here, we show results of the bed velocity profiles which indicate the presence of the creeping regime just below the bedload layer, and obtain the trajectories of coarse particles.

2. FORMULATION OF THE NUMERICAL MODEL

In this numerical investigation, we used an Eulerian-Lagrange approach, where the fluid phase is described by the Navier-Stokes equations for multiphase flows and is solved by using the open source code OpenFOAM ($https://www.openfoam.org$); and the discrete phase is computed by using Newton's second law, where each particle interaction is computed based on Discrete Element Method-DEM by using the open source code LIGGGHTS, (Kloss *et al.*, 2012), ($https:/www.liggghts.com$). Finally, OpenFOAM and LIGGGHTS are coupled with the open source code CFDEM (Zhou *et al.*, 2010), ($https://www.cfdem.com/$).

2.1 Governing equations

The two types of particle motion, translational and rotational, are computed based on Newton's second law obtained from the linear and angular momentum equations Eq. (1) and Eq. (2), respectively:

$$m_p \frac{d\vec{u}_p}{dt} = \vec{F}_{fp} + \vec{F}_{pres} + \vec{F}_{vm} + m_p\vec{g} + \sum_{i\neq j}^{N_c}(\vec{F}_{c,ij}) + \sum_{i}^{N_w}(\vec{F}_{c,iw}) \tag{1}$$

$$I_p \frac{d\vec{\omega}_p}{dt} = \sum_{i\neq j}^{N_c}(\vec{T}_{p,ij}) + \sum_{i}^{N_w}(\vec{T}_{p,iw}) \tag{2}$$

where m_p and $\vec{u}_p$ are the mass and the velocity of the particle, respectively. The terms on the right-hand side of Eq. (1) represent the forces generated by the liquid; drag force $\vec{F}_{fp}$ $=-\vec{F}_{fp}$, forces due to pressure and stress gradients $\vec{F}_{pres}$$=-V_p\nabla P + V_p\nabla\cdot\vec{\vec{\tau}}_f = V_p\rho_f(\frac{D\vec{u}_f}{D_t} - \vec{g})$ being ($\frac{D\vec{u}_f}{D_t}$ the material derivative, virtual mass force $\vec{F}_{vm}$, acceleration of gravity $\vec{g}$, contact forces between particles $\vec{F}_{c,ij}$ and contact forces between particles and the tube wall $\vec{F}_{c,iw}$. In Eq. (refeq2, I_p and $\vec{\omega}_p$ are the moment of inertia and angular velocity of a particle, respectively, and the terms on the left-hand side, $\vec{T}_{p,ij}$ represents the torque generated by the tangential component of the contact force between particles *i* and *j*, and $\vec{T}_{p,iw}$ the torque generated by the tangential component of the contact force between particle *i* and the wall. The inter-particle forces and torques are summed over the N_c - 1 particles in contact with particle *i*, where N_c is the total number of particles in contact. The particle-wall forces and torques are summed over the N_w particles in contact with the wall. The contact forces between particles and between particles and the wall are computed based on the soft-particle method (Cúñez and Franklin, 2019).

Locally-averaged incompressible Navier-Stokes equations compute velocity and pressure fields. The mass and momentum equations are given by Eqs. (3) (4), respectively:

$$\frac{\partial \rho_f \alpha_f}{\partial t} + \nabla \cdot (\rho_f \alpha_f \vec{u}_f) = 0 \tag{3}$$

$$\frac{\partial \rho_f \alpha_f \vec{u}_f}{\partial t} + \nabla \cdot (\rho_f \alpha_f \vec{u}_f \vec{u}_f) = -\alpha_f \nabla P + \alpha_f \nabla \cdot \vec{\vec{\tau}}_f + \alpha_f \rho_f \vec{g} + \vec{F}_{pf} \tag{4}$$

where P is the pressure, $\vec{\vec{\tau}}_f$ is the stress tensor, and $\vec{u}_f$ and α_f represent the mean velocity and volume fraction of the fluid phase, respectively. Coupling between liquid phase and particles is achieved through the momentum exchange coefficients $\vec{F}_{pf}$, (Li *et al.*, 2017), and it can be computed by Eq. (5)

$$\vec{F}_{pf} = \frac{1}{V_{cell}} \sum_{\forall_p \in_{cell}} \frac{V_p \beta}{1 - \in_f} (\vec{u}_p - \vec{u}_{fp}) \tag{5}$$

where V_{cell} and V_p are the volumes of the considered cell and particle, respectively, β is the coefficient of momentum transfer between phases (due to the drag force), , and $\vec{u}_{fp}$ is the liquid velocity at the particle position. The latter is usually obtained by interpolation and determined for each particle.

2.2 Numerical setup

We considered a 100 mm-length on direction *x*, a 10 mm-width on direction *y* and 27 mm-height on direction *z* as size rectangular channel. In the following, subscripts *l* and *s* denote large and small particles, respectively. Large particles of diameter $d_l = 3$ mm and small particles of diameter $d_s = 2$ mm (size ratio $d_l/d_s = 1.5$) settle deposited by gravity inside a channel, in order to form a 20 mm fixed bed with 2546 particles. The particle and fluid densities are fixed respectively as ρ_p = 2500 kg m^{-3} and ρ_f = 1261 kg m^{-3}, and the viscosity is ν = 0.0012 m^2 s^{-1}. The bed is composed of 1% of large particles (24 coarse particles). We set periodic boundary conditions in the stream-wise (x) and span-wise (y) directions of the channel, no-slip condition on the bottom wall, at the top of channel the velocity is gradually increased from $\vec{u}_f$ = 0.01 m s^{-1} to a constant velocity of $\vec{u}_f$ = 0.02 m s^{-1} in the first 5 seconds of real time simulation. The section of liquid on the bed measure h_f = 7 mm, over this section we assurance the laminar Couette flow, within the condition mentioned we calculated. The Reynolds number based on the height of the fluid is $Re_p = \vec{u}_f h_f/\nu$ = 0.12 and the Shields number $\theta = \vec{\vec{\tau}}_f/(gd_l(\rho_p - \rho_f))$ = 0.18 for small particles, for in order to grantee laminar regime and shear rates close to the threshold of particles motion.

A three dimensional geometry of horizontal channel was created, and hexahedral coarse mesh was generated with 1200 elements, each element having a volume of 22.27 mm^3 which is bigger than the volume of large particles, assuring the volume fraction required by the numerical method.

3. RESULTS

In this section, we present the results of the main behavior of the coarse grains segregation in a bi-dispersed granular bed sheared by a viscous Couette flow applying a mean top channel velocity of 0.02 m s^{-1}.

Figures 1(a) 1(b) present instantaneous snapshots of the bed for times t = 0 and t = 600 seconds, respectively. We observe in the Fig. 1(a) that the surface of the bed is distributed uniformly along the channel, where all large particles are randomly distributed within the bed, while in the Fig. 1(b) we observe that the bed surface is irregular because there is formation of a ripple that is transported along the bed surface. Here we can observe that some large particles are pushed to the bed surface and segregate, while large particles which are located in the bottom of the channel remain fixed.

In Fig. 2, we observe the evolution mean velocity of grains within the bed from t = 0 to t = 600 seconds; to each 200 seconds. The mean bed velocity at each level varies in maximum and minimum ranges for height lower than 0.010 m and t>100 seconds; this is due to the movement of grains ripples on the bed that influence on lower bed section, wherein the particles will organize to keep fixed.

We observe that below the level z = 0.011 m the granular motion within the bed decreases as time elapses, while above the level z = 0.011 m the gradient velocity of $\frac{\partial \vec{u}_p}{\partial z}$ increases progressively until the top of the bed. Further above the level z = 0.015 m the increase of velocity is similar for any time.

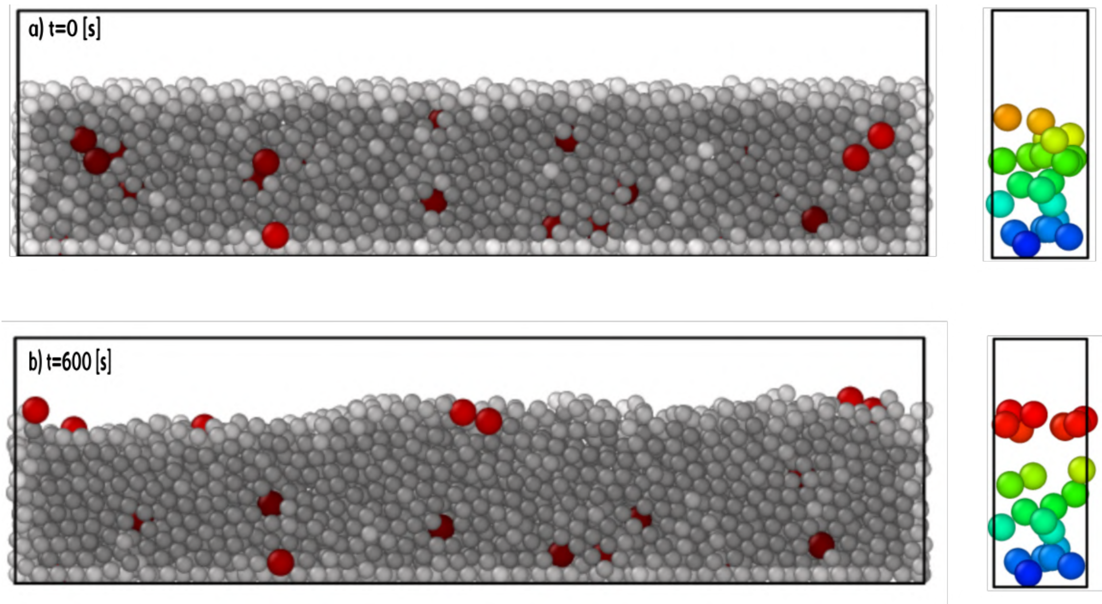

Figure 1. Snapshots of the particles position inside the granular bed for: a) initial condition at t = 0s b) condition at t = 600 s.

Also, there is an interesting value of velocity between positions z = 0.019 m and 0.020 m. In this section the velocity gradient has a considerable decrease, we consider that it is due to the direct contact between grains, with a transition from creeping to granular flow, (Houssais *et al.*, 2015)

The presence of ripples periodically increases the bed surface level to z = 0.023 m, this will observe from Fig. 1 and Fig. 2.

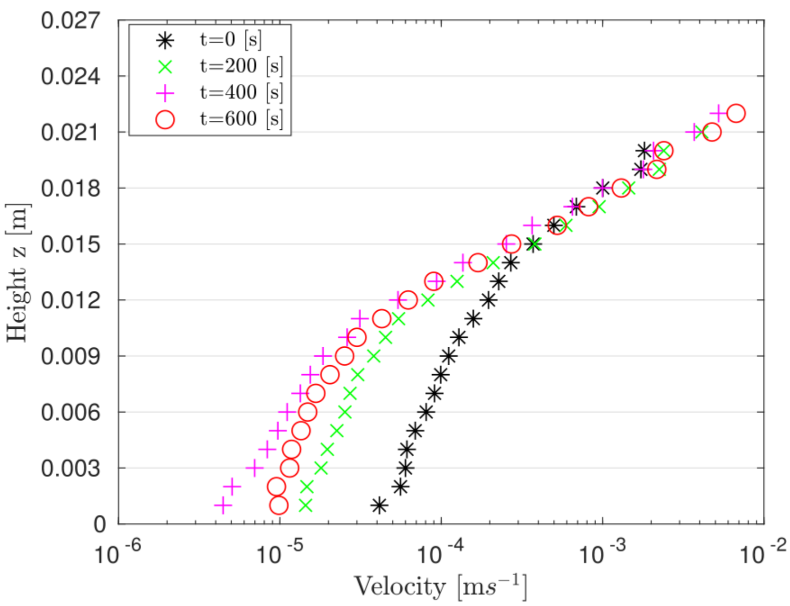

Figure 2. Profile of mean velocities within the bed; *Re* = 0.12 and θ = 0.18

Figure 3, show the trajectories of coarse particles, we observe the evolution of the motion of large particles over time and the mean velocity, we can distinguish two important positions, the first one a positions above the z = 0.01 m level where there is the presence of segregation of coarse beads towards the granular surface where only eight particles had segregated within time of simulation (600 seconds), and the second below this level where there is no segregation and its velocities in this positions is lower to U = 5.0^{-5} ms_{-1}.

Within the first section, we can observe that the large particles rapidly segregated, before to t = 100 seconds these particles were initially located (z = 0.015 m) closer to the bed surface. Particles that were located close to the level z = 0.013 m segregated in the following 100 seconds, and the particles near the level z = 0.011 m required more time to segregate. During the 600 seconds of simulation of this work, 8 particles segregated.

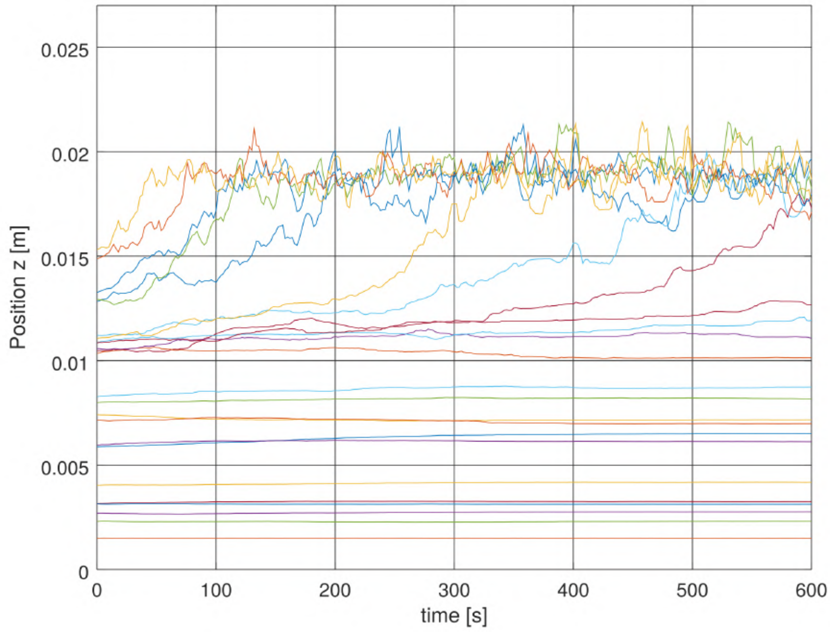

Figure 3. Trajectories of coarse particles

4. CONCLUSIONS

This work investigated the segregation of coarse grains within a bi-dispersed granular bed sheared by a viscous Couette flow. We observed that eight particles segregated during a simulation time run of 600 seconds.

Two critical levels were observed within the bed: (i) z = 0.011 m where large particles located below this level did not segregate, and (ii) z = 0.015 m where particles located near this level rapidly segregate.

The transition between the bedload layer and the creeping regime occurs within z = 0.012 m and 0.013 m.

Mean velocity with the bed Fig. 3 shows decreasing velocity on the deep of bed as time progresses, for positions below to z = 0.010 m, this affects over particle move making that the particles are fixed.

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