Coupled DEM-CFD Investigation of Granular Transport in a Fluid Channel

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Abstract This paper presents three dimensional numerical investigations of granular transport in fluids, analysed by the Discrete Element Method (DEM) coupled with Computational Fluid Mechanics (CFD). By employing this model, the relevance of flow velocity and granular depositional morphology has been clarified. The larger the flow velocity is, the further distance the grains can be transported to. In this process, the segregation of solid grains has been clearly identified. This research reveals that coarse grains normally accumulate near the grain source region, while the fine grains can be transported to the flow front. Regardless of the different flow velocities used in these simulations, the intensity of grains segregation remains almost unchanged. The results obtained from the DEM-CFD coupled simulations can reasonably explain the grain transport process occurred in natural environments, such as river scouring, evolution of river/ocean floor, deserts and submarine landslides.

Keywords granular transport, fluid channel, DEM-CFD, segregation

1. Introduction

Granular transportation and deposition in fluids are relevant to subjects of public safety, water research management, and environmental sustainability [1]. Actually, this topic is at the centre of a wide range of practical and fundamental subjects. For example, this process is very important in understanding how beaches, rivers and deltas evolve, mountains erode and landscapes form. The related research topics can be the sediment transport in rivers, along lake and ocean shores, transport of desert sand, soil erosion, drift of snow and so on. Based on previous research, the coarse and fine grains behave differently regarding their motions in fluid [2]. In this process, the segregation of grains along the flow path and the depositional depth is dominant. This phenomenon has been widely observed in river scouring, evolving of ocean coastal line and submarine landslides [3]. For instance, in typical submarine landslides, the fine grains can be transported to the sliding front, while the majority of coarse grains normally deposit near the slope source region [4]. In this process, the displaced fine grains are entrained by fluid currents and can normally travel to very long distances, representing significant hazards to the offshore and seabed infrastructures, such as the telecommunication cables, pipelines, wind and tidal turbines [3,5-8]. In addition, the grain sizes can characterize different river patterns, and by bridging the regional hydrology and geomorphology, it can also reflect the sediment transport process [9]. For example, the downstream variation of riverbed grain sizes would reflect the morphological evolution of the river channel [10]. Therefore, it is important to understand the characteristics of granular transport in fluid and depositional morphology of sediments.

The current research investigates the transport of solid grains driven by open channel flows via a coupled discrete-continuous method, aiming to provide new insights into the relationship between the flow velocity and granular depositional morphology.

2. Model configuration

The numerical investigation of granular transport reported in this paper is based on the idea that the motion of particles is completely governed by the Newtonian equations of motion, in which the inter-particle collisions are modelled by the soft particle approach and the fluid flow is calculated by the
Navier-Stokes equations [11-13]. Consequently, the Discrete Element Method (DEM) [14] and Computational Fluid Dynamics (CFD) [15] techniques can be used to study the mechanical and hydraulic behaviour of particles and fluid flow, respectively. By coupling these two methods, a complete analysis of the granular transport in a fluid channel can be made [16]. In this study, the DEM and CFD open source codes ESyS-Particle [17,18] and OpenFOAM [19] were employed for the simulations presented herein. The governing equations of particle motion are expressed as below:

\[ m_i \frac{d^2 \vec{x}_i}{dt^2} = m_i \vec{g} + \vec{F}_c + \vec{f}_{\text{fluid}} \]  

(1)

\[ I_i \frac{d \vec{\omega}_i}{dt} = \sum \vec{r}_c \times \vec{F}_c + \vec{M}_r \]  

(2)

where \( m_i \) is the mass of a single particle \( i \); \( \vec{x}_i \) is the position of its centroid; \( \vec{g} \) is the gravitational acceleration; \( \vec{F}_c \) is the contact force exerted by the neighbouring particles, which is calculated using a linear-spring model [14]; \( \vec{f}_{\text{fluid}} \) is the force exerted by fluid flow on the particle; \( I_i = 2m_i r^2 / 5 \) is the moment of inertia about the grain geometric centroid, with \( r \) being the particle radius; \( \vec{\omega}_i \) is the angular velocity; \( \vec{r}_c \) is the vector from the particle mass center to the contact point; \( \vec{M}_r \) is the rolling resistance moment induced by the non-spherical particle shape and interlocking between particles.

The force exerted by the fluid flow on the particle \( \vec{f}_{\text{fluid}} \) consists of two components: the buoyant \( \vec{f}_b \) and drag forces \( \vec{F}_d \). The buoyant force is calculated as follows:

\[ \vec{f}_b = -\nu_p \nabla p \]  

(3)

where \( \nu_p \) is the volume of particle \( i \); \( p \) is the pressure of fluid flow.

The drag force is induced by the relative motion between particle and fluid [20]. It is calculated by the Di Felice [21] empirical correlation as:

\[ F_{di} = \frac{1}{2} C_d \rho_f \frac{\pi d_p^2}{4} n^2 |U - V|(U - V)n^{(x+1)} \]  

(4)

where \( C_d = \frac{24}{\text{Re} (1 + 0.150 \text{Re}^{0.841}) + \frac{0.407}{1 + 8710/\text{Re}} } \) is the drag force coefficient [22]; \( \rho_f \) and \( U \) are the fluid density and velocity; \( d_p \) and \( V \) are diameter and velocity of a particle, respectively; \( x = 3.7 - 0.65 \exp \left[ - \frac{(1.5 - \log_{10} \text{Re})^2}{2} \right] \), with \( \text{Re} = \rho_f d_p n (U - V) / \mu \) the Reynolds number defined at the particle size scale, with \( n \) being the fluid volume fraction in CFD mesh cells, \( \mu \) being the fluid viscosity. In the current analyses, \( x \) ranges from 3.4 to 3.7.

The governing equations of fluid flow are shown as follows:

\[ \frac{\partial(\rho_f n)}{\partial t} + \nabla \cdot (\rho_f n \mathbf{U}) = 0 \]  

(5)

\[ \frac{\partial(\rho_f n \mathbf{U})}{\partial t} + \nabla \cdot (\rho_f n \mathbf{U} \mathbf{U}) - n \nabla \cdot \mathbf{\tau} = -n \nabla p + n \rho_f \vec{g} + \vec{f}_d \]  

(6)
where \( \overline{F_d} = \sum_{i=1}^{N} \frac{F_d}{V_{mesh}} \) is the drag force per unit fluid volume, with \( V_{mesh} \) being the volume of a fluid mesh cell and \( N \) being the number of particles within the cell; \( \tau \) is the fluid viscous stress tensor.

The input parameters are listed in Table 1. The values of these input parameters have been calibrated by research reported in Utili et al. [18] and Zhao et al. [2].

**Table 1.** Input parameters for the simulations presented herein.

| DEM Parameters          | Values         | CFD Parameters          | Values         |
|-------------------------|----------------|-------------------------|----------------|
| Particle diameter, \( d \) (mm) | [1.8, 3.8] | Fluid density, \( \rho_f \) (kg/m\(^3\)) | 1000           |
| Granular density, \( \rho_s \) (kg/m\(^3\)) | 2650         | Viscosity, \( \mu \) (Pa·s) | 0.001          |
| Normal stiffness, \( K_n \) (N/m) | 3.0\times10\(^7\) | Flow velocity, \( U \) (m/s) | 0.1, 0.5, 1.0  |
| Shear stiffness, \( K_s \) (N/m) | 2.7\times10\(^7\) | Simulation Parameters | Values         |
| Particle friction angle, \( \phi_p \) (°) | 30            | Gravity, \( g \) (m/s\(^2\)) | -9.81          |
| Coefficient of rolling stiffness, \( \beta \) | 1.0          | DEM Time step size, \( \Delta t \) (s) | \( 10^{-7} \) |
| Coefficient of plastic moment, \( \eta \) | 0.1          | CFD Time step size, \( \Delta t_f \) (s) | \( 10^{-5} \) |
| Coupling frequency*, \( \alpha \) | 100          | Coupling frequency*, \( \alpha \) | 100            |

* The coupling frequency is the number of iteration steps used in the DEM in one coupling interval.

In the DEM model, the linear-elastic and rolling resistant contact model has been used. Here, the rolling law is employed with the only aim of accounting for the shape effect of non-spherical particles (as quantified by the two parameters, \( \beta \) and \( \eta \)). The law accounts for moments arising from the fact that the line of action of the normal contact force in the case of non-spherical particles no longer passes through the centre of mass of the particles and hence generating rotational moments [23,24].

The model configuration of the granular transport is shown in Figure 1.

![Figure 1. Schematic view of the grain transport model](image)

As shown in Figure 1, the granular transport model consists of the solid phase (DEM component) and the fluid phase (CFD component). During the simulation, the two components work as follows:
1) The DEM component
   (1) Grain container: a DEM engine (coded as a C++ class) can continuously generate
dispersing particles within a cubic box. Particles are coloured as red, pink, yellow, blue
and cyan as their diameters decrease gradually. The grain container is placed 0.05 meter
above the fluid channel.
   (2) An initial downward velocity (2 m/s) has been set to all grains, so that they can drop quickly
into the open water channel and thus speed up the simulation.
   (3) Coarse granular bed: a layer of polydisperse coarse grains are paved on the bottom of the
water tank to simulate the frictional floor.
   (4) In this research, the height of the grain container and the initial granular downward velocity
would determine the grain velocities near the upper surface of the fluid channel. The choice
of these two parameters turns out to be crucial for this type of simulations. However, we
also understand the granular velocity would reach a constant value in fluid, as determined
by the grain diameter and fluid viscosity \[2\]. Thus, the height of grain container and initial
downward velocity are chosen without any detailed parametric analyses.

2) The CFD component:
   (1) An open fluid channel has been placed horizontally on the floor. The dimension of the fluid
channel is 0.03 m × 0.4 m × 0.1 m. The upper boundary has been set as open air condition.
Left and right side walls and the bottom floor have slip boundary conditions. The back and
front boundaries are inlet and outlet of the flow channel.
   (2) A constant fluid flux (Q) is maintained by pumping water into the tank from the inlet at a
constant velocity.
   (3) The inlet flow velocity has been set as 0.1 m/s, 0.5 m/s and 1.0 m/s in a series of simulations.

3. Results

The granular transport for fluid flow velocities of 0.1 m/s, 0.5 m/s and 1.0 m/s are illustrated as a
series of snapshots, as shown in Figure 2. According to Figure 2, the solid grains are continuously
generated in the grain container and dropped downwards into the flow channel. Grains falling into the
channel are entrained in the flow, as the fluid flows from the left to the right sides. As the flow
velocity increases from 0.1 m/s to 1.0 m/s, the majority of grains are transported to a long distance
away from their source region. This is especially true for fluid velocity equals to 1.0 m/s, in which all
grains accumulate in the outlet region of the channel (the DEM model has been set as an enclosed
parallelepiped, such that the grains cannot move out of the DEM domain.). After a distance of
transport, the flow velocity might slow down, or other mechanisms such as the gravity of grains,
friction forces acting on grains, will cause the grains to deposit along the base of the channel. The
coarse grains will settle quickly and deposit near the flow inlet region, while the fine grains can
suspend in the fluid and be transported to the flow front. Finally, all grains will settle continuously
onto the base of the channel. In Figure 2 (a) (b), the segregation of solid grains is evident, that most of
the coarse grains (coloured as red) are deposited near the flow inlet region, while finer grains can be
transported further to locations near the flow outlet region. In the meantime, the fluid velocity
increases near the deposit surface. The distribution of flow velocity field changes with the shape of
grain deposits. However, the grain segregation phenomenon is not evident for simulations shown in
Figure 2 (c), in which fast moving flow can transport all grains to the outlet region and grains with
different sizes are mixed in the deposit.
In order to quantify the grain segregation phenomenon shown in Figure 2, a series of particle size distribution (PSD) curves of sediments at the time 2.5 seconds after the initiation of flows are plotted below in Figure 3. In this section, the stable sediments layer has been divided into three parts (i.e., left, middle and right), with each part containing approximately the same amount of grains. According to Figure 3, it can be observed that regardless of the flow velocity in these three different tests, the PSD curves have similar shapes. The majority of coarse grains accumulate at the left section, as represented by a PSD curve dramatically different from the initial PSD curve. For grains in the middle section, the PSD curve deviates below the initial PSD curve, indicating that the portion of accumulated coarse...
grains in this region is larger than the initial value at generation. In the right section, the PSD curve locates slightly above the initial PSD curve, as the majority of fine grains have been transported there.

![PSD curves for U = 0.1 m/s](image1)

(a) PSD curves for U = 0.1 m/s

![PSD curves for U = 0.5 m/s](image2)

(b) PSD curves for U = 0.5 m/s

![PSD curves for U = 1.0 m/s](image3)

(c) PSD curves for U = 1.0 m/s

Figure 3. Particle size distribution of sediments in different tests

4. Conclusions

This paper presents a numerical investigation of the behaviour of granular transport in a fluid channel via the DEM-CFD coupling simulations. By varying the flow velocity in the channel, three distinctive types of granular transport phenomena have been observed. The main concluding points are summarized as below:

(1) The locations of the deposited grains are closely related to the flow velocity. The larger the flow velocity is, the longer distance the grains can be transported to.
(2) The segregation of solid grains is evident during the granular transport, in which the majority of coarse grains would accumulate near the source region, while the fine grains can be transported to the flow front. Though the flow velocity is dramatically different for a series of simulations, the PSD curves of the sediments are almost the same.
(3) The discussions presented above can reasonably explain the mechanisms of grain segregation occurred in river scouring, evolution of river/ocean floor, deserts and submarine landslides.
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6. References

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