The Effect of Neighboring Particles on the Dynamics of a Particle Settling in a Viscous Fluid

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Multiscale Modeling for Particulate Flows

- Resolved Discrete Particle (Direct Numerical Simulation) Model
- Unresolved Discrete Particle (Discrete Element) Model
- Two-Fluid (Continuum) Model

Larger geometry
DNS simulation method: *Proteus*

- Fluid velocity and pressure fields
  - Lattice-Boltzmann method or finite difference method based Navier-Stokes fluid solver; fixed regular grid.
- Particle-fluid interactions
  - Immersed boundary method; moving boundary nodes
- Particle-particle interactions
  - Soft-sphere collision scheme
  - Hybrid repulsive-force/lubrication scheme
- Particle dynamics
  - Newton’s equations of motion (translational and rotational motions)

Validations of Proteus

• Sedimentation of a spherical particle in a viscous fluid
  – Experiment measurement using PIV by ten Cate et al.*

• Fluidization of 3000 glass beads**


Some simulation results by the *Proteus*
Slip velocity of solid particles at a solid wall

Time-space averaged velocity

10,000 spherical particles in a jet fluidized bed
Comparable study between DNS and TFM

Sedimentation of light particles in an enclosure

Top: DNS (2016 particles); Bottom: TFM simulation.
Particles Clustering

Nanoparticles/adhesive particles agglomerations
A particle settling in a solid-liquid suspension

- Consider the settling of a heavy particle in a solid-liquid suspension that contains a large number of neutral particles in comparable size.
- Particle settling velocity has two limits:
  - $U_\infty$, solid fraction =0, no surrounding particles;
  - 0, solid fraction=1.
- Effect of the surrounding particles to the dynamics of the settling particle w.r.t.
  - the size of the suspended neighboring particles
  - the solid fraction of the suspension flow
Physical and simulation parameters

• Physical properties (*)
  – Settling particle diameter $d=15\text{mm}$, density $\rho_p=1500\text{kg/m}^3$;
  – Fluid viscosity $0.058\text{ kg/m.s}$, density $=960\text{ kg/m}^3$.

• Simulation parameters:
  – $\delta x=d/16$; $\delta t=2.5\times10^{-4}\text{s}$;
  – Flow domain: regular grid $96\times96\times480$;
  – Particle: $789$ surface nodes for one particle
  – Periodic boundary conditions
  – At zero solid fraction, $U_\infty = 0.27\text{m/s}$; flow Reynolds number $\sim 68$.

Effect of the size of neighboring particles

- Consider three cases at the same solid volume fraction $\phi = 10\%$

<table>
<thead>
<tr>
<th>Case No.</th>
<th>Diameter of neighboring particles</th>
<th>Number of neighboring particles</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1d</td>
<td>200</td>
</tr>
<tr>
<td>2</td>
<td>0.625d</td>
<td>819</td>
</tr>
<tr>
<td>3</td>
<td>0.375d</td>
<td>3793</td>
</tr>
</tbody>
</table>

- Question:
  - Which case the heavy particle falls the fastest?
Settling of a heavy particle in suspension flows with different size of particles

Case 1: $N=200$  
Case 2: $N=819$  
Case 3: $N=3793$
Settling of a particle in suspension flows with different size of particles

Pressure contours on the centered x-y plane (z=0)
Settling velocity of the heavy particle

Resistance: drag force + collision force
Almost the same slope in $z$-$t$ graph. The mean settling velocity = slope = 0.21 m/s.
Horizontal positions of the heavy particle

- The migration in the horizontal directions increases with the size of neighboring particles
Effect of solid fractions

- The neutral particles are chosen to be the same size as the settling particle.
- 10 cases are studied.

<table>
<thead>
<tr>
<th>Case No.</th>
<th>Number of surrounding particles</th>
<th>Volume solid fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>100</td>
<td>0.049</td>
</tr>
<tr>
<td>3</td>
<td>200</td>
<td>0.097</td>
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<tr>
<td>4</td>
<td>250</td>
<td>0.121</td>
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<tr>
<td>5</td>
<td>300</td>
<td>0.145</td>
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<tr>
<td>6</td>
<td>350</td>
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<td>400</td>
<td>0.194</td>
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<tr>
<td>8</td>
<td>450</td>
<td>0.218</td>
</tr>
<tr>
<td>9</td>
<td>500</td>
<td>0.242</td>
</tr>
<tr>
<td>10</td>
<td>630</td>
<td>0.305</td>
</tr>
</tbody>
</table>
Initial distributions of particles at eight different solid fractions
Settling velocity at different solid fractions

- Higher solid fraction leads to the increased drag force and the number of collisions
After a brief unsteady transition at the beginning, the slope in $z$-$t$ graph is nearly a constant for each case.
Mean terminal velocity

- Mean terminal velocity:

\[ \bar{v}_z = \frac{dz}{dt} = \text{slope in } z-t \text{ graph.} \]

- Correlation:

\[ \frac{V(\phi)}{V(0)} = (1 - \phi)^{2.25}, \quad (0 \leq \phi \leq 0.3) \]

<table>
<thead>
<tr>
<th>Solid fraction</th>
<th>Mean terminal velocity</th>
<th>Simulation (m/s)</th>
<th>( V(\phi)/V(0) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td></td>
<td>0.265</td>
<td>1</td>
</tr>
<tr>
<td>0.049</td>
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<tr>
<td>0.194</td>
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<tr>
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<tr>
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<tr>
<td>0.305</td>
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<td>0.130</td>
<td>0.48</td>
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</tbody>
</table>
Mixture theory

- Effective density and viscosity of solid-liquid suspension:

\[ \rho_m = \rho_f, \quad \mu_m \approx \mu_f \left(1 + 2.5\phi + 5.2\phi^2 + \ldots\right) \quad \text{(Batchelor*)} \]

or

\[ \mu_m \approx \mu_f \left(1 + 2.5\phi + 10\phi^2 + \ldots\right) \quad \text{(Thomas**)} \]

Force balance:

\[ C_d(\phi) \frac{1}{2} \rho_m V_t^2(\phi) \frac{\pi d^2}{4} = \left(\rho_p - \rho_f\right) \frac{1}{6} \pi d^3 \]

Empirical drag law:

\[ C_d(\phi) = (0.63 + \frac{4.8}{\sqrt{\text{Re}(\phi)}})^2 \]

Only unknown: \[ V_t(\phi) \]

Possible cause: the mixture theory doesn’t account for the particle-particle collisions which are critical when particles have comparable sizes.
Future Work

– Different types of neighboring particles
  • Non-neutral
  • Cohesive
  • Polydisperse
  • Non-spherical

– Different types of flows
  • Flows of different Reynolds numbers
  • Flows in fluidization beds

– From a single particle to a large number of particles