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

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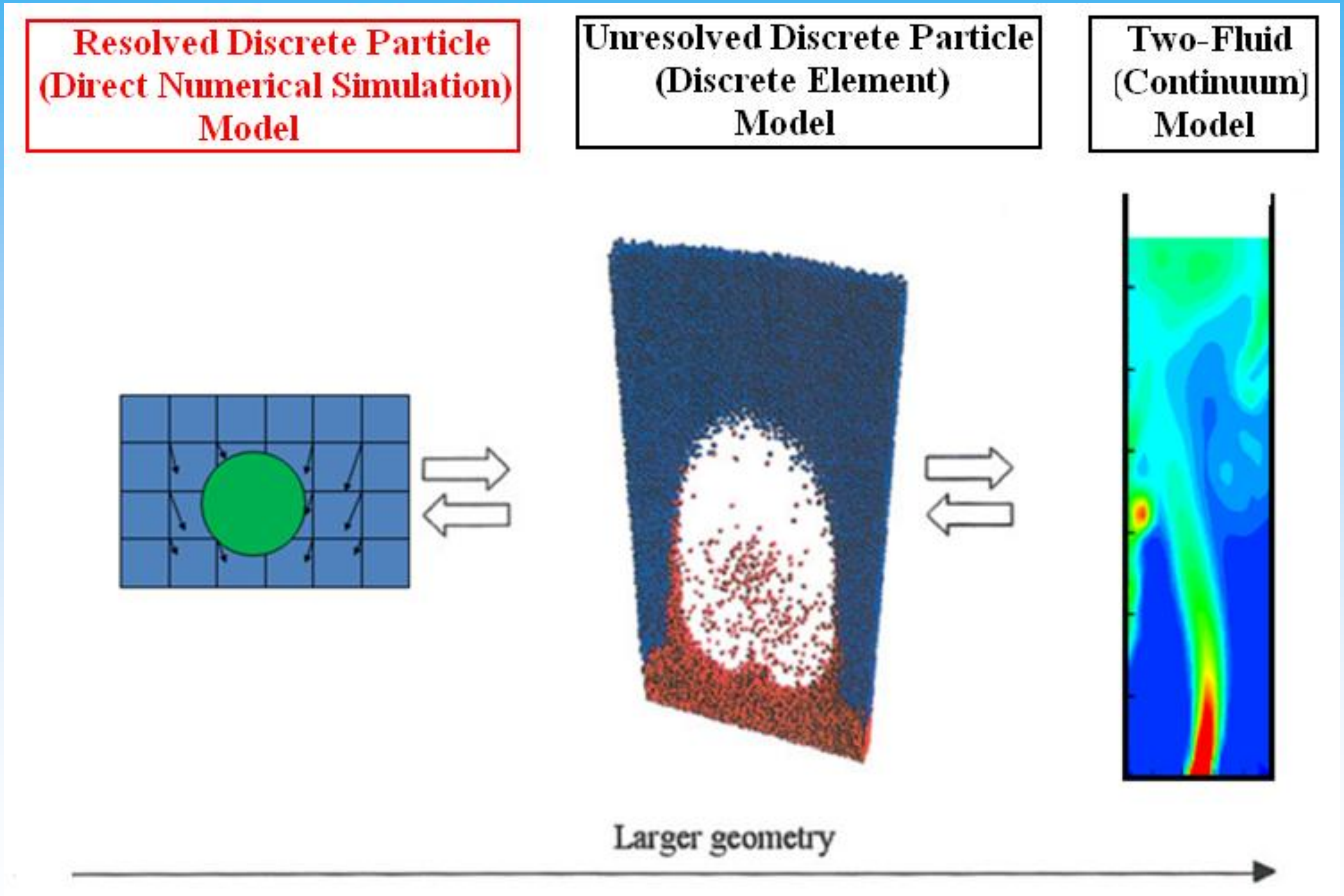
Multiscale Modeling for Particlulate Flows



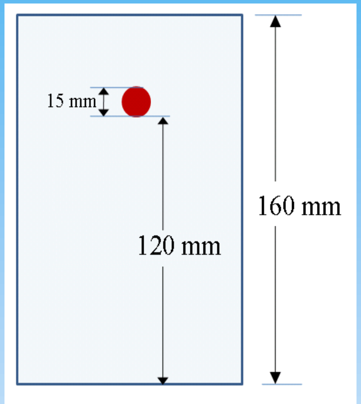
DNS simulation method: *Proteus**

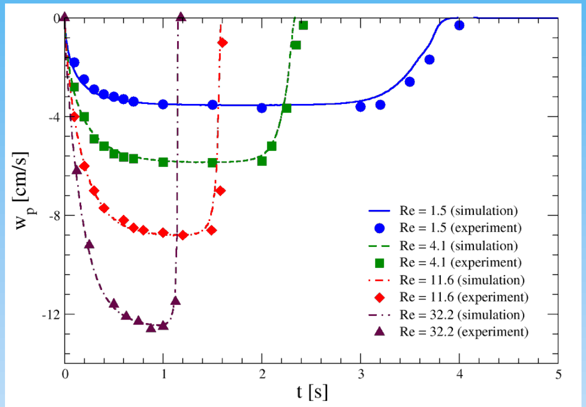
- Fluid velocity and pressure fields
  - Lattice-Boltzmann method or finite difference method based Navier-Stokes fluid solver; fixed regular grid.
- Particle-fluid interactions
  - Immersed boundary method; moving boundary nodes
- Particle-particle interactions
  - Soft-sphere collision scheme
  - Hybrid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

*Feng, Z.-G. and E. E. Michaelides, "***Proteus***: A direct forcing method in the simulations of particulate flow," *J. Comput. Phys.*, **202**: 20-51 (2005).

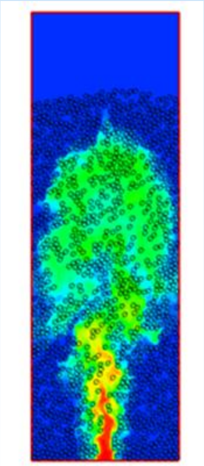
Validations of *Proteus*

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





- Fluidization of 3000 glass beads**



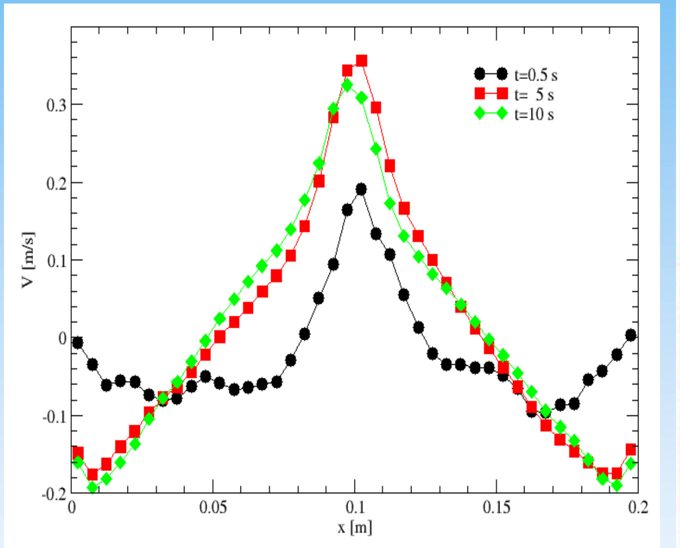
** Obuseh, C., Feng, Z.-G., and Paudel, B.D. (2012), "An experimental study of fluidization of bidisperse particulate flows," *Journal of Dispersion Science Technology* .

* A ten Cate, C. H. Nieuwstad, J. J. Derksen, and H. E. A. van den Akker(2002), "Particle imaging velocimetry experiments and lattice-Boltzmann simulations on a single sphere settling under gravity," *Phys. Fluids*, **14**: 4012-4025 .

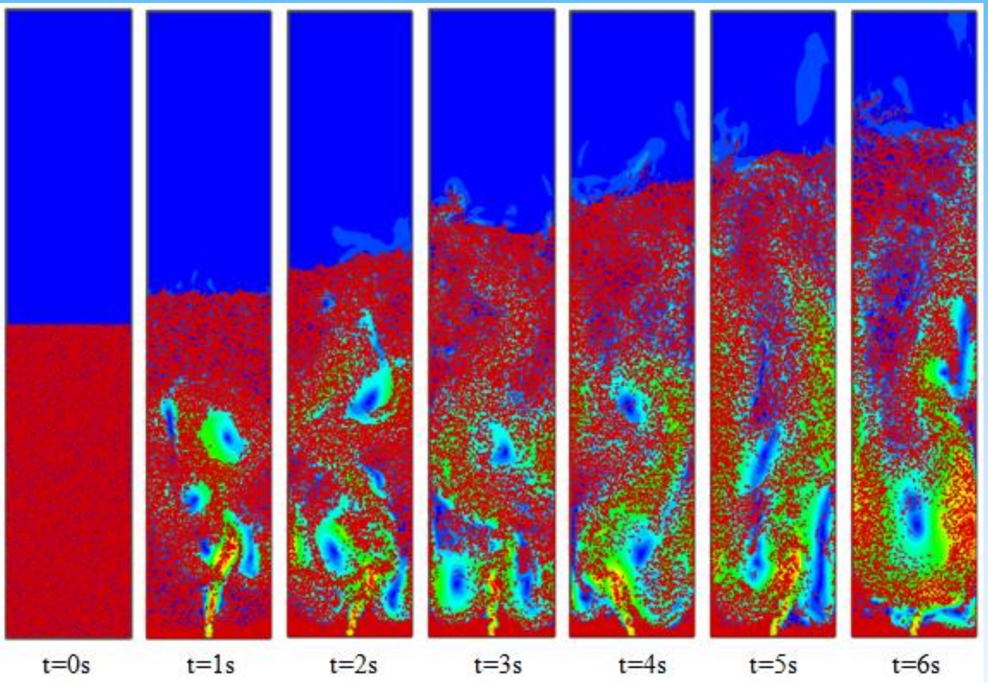
Some simulation results by the

Proteus

Slip velocity of solid particles at a solid wall



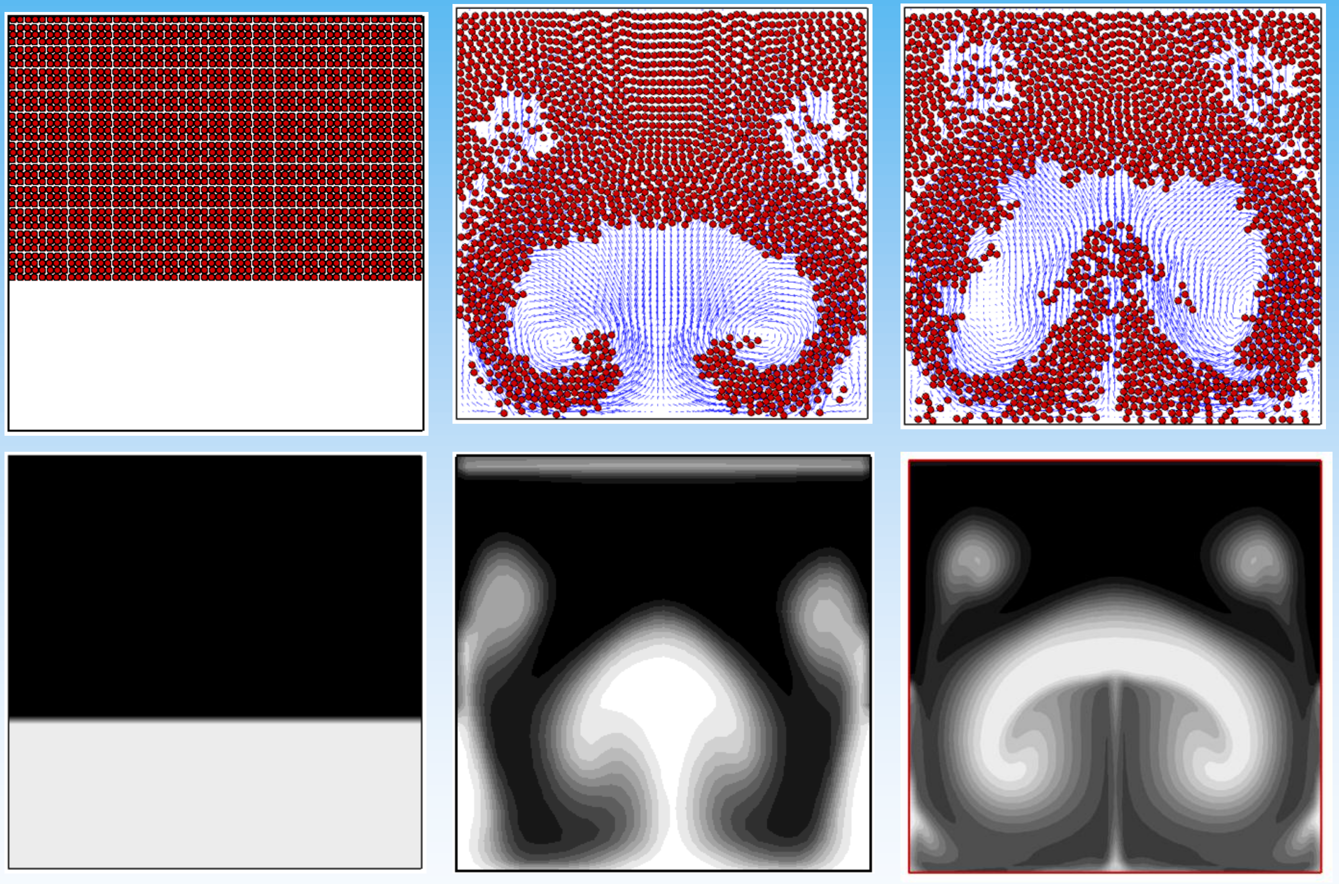
Time-space averaged velocity



10,000 spherical particles in a jet fluidized bed

Comparable study between DNS and TFM

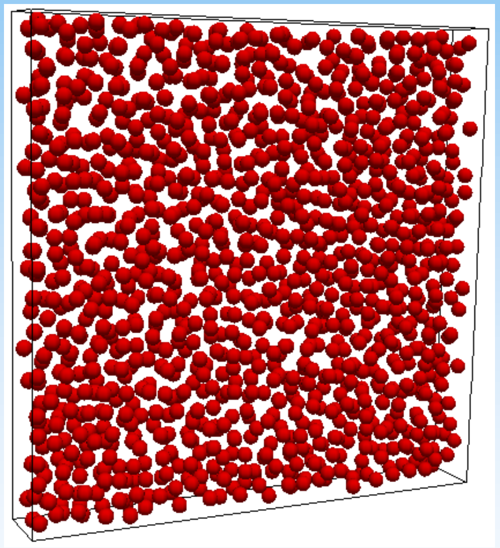
Sedimentation of light particles in an enclosure

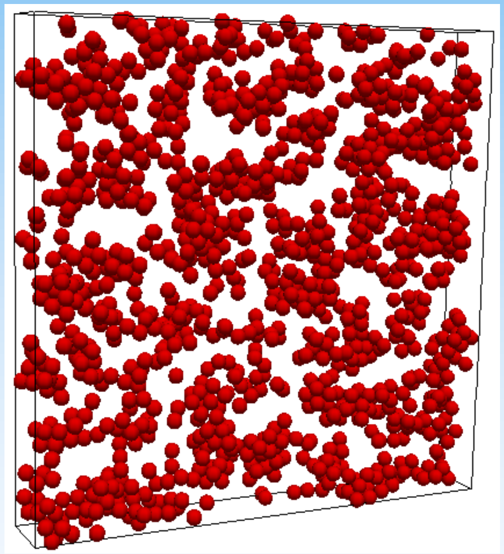


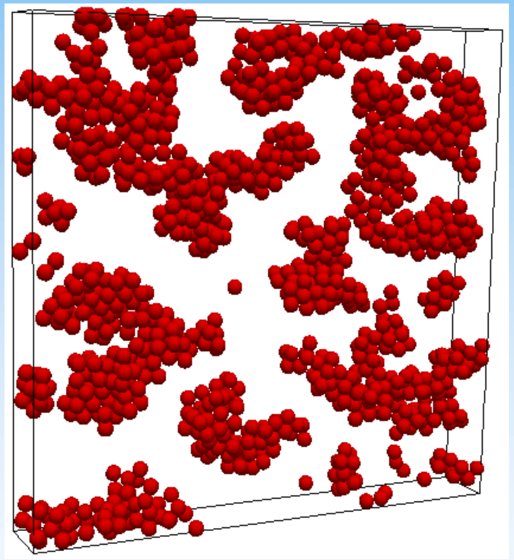
Top: DNS (2016 particles); Bottom: TFM simulation.

Particles Clustering

Nanoparticles/adhesive particles agglomerations

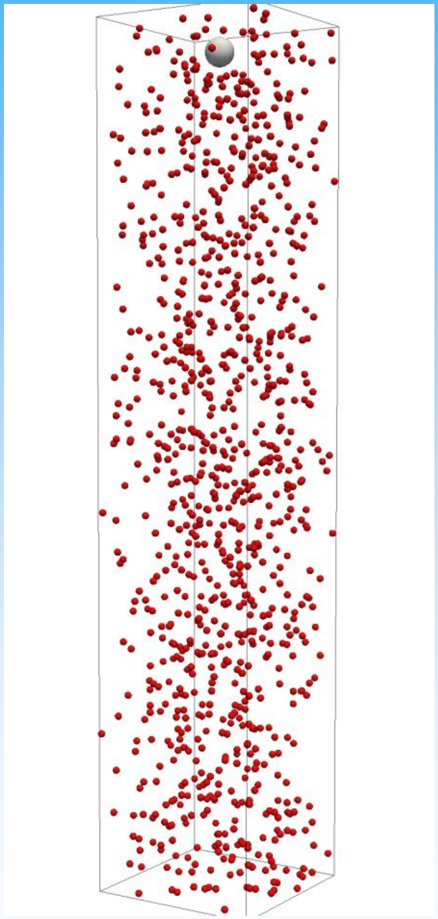






A particle settling in a solid-liquid suspension

- 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_∞, 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=15mm,density ρ_p=1500kg/m3;
  - Fluid viscosity 0.058 kg/m.s, density=960 kg/m3.
- Simulation parameters:
  - $\delta x=d/16$; $\delta t=2.5\times10^{-4}$ s;
  - Flow domain: regular grid 96x96x480;
  - Particle: 789 surface nodes for one particle
  - Periodic boundary conditions
  - At zero solid fraction, $U_\infty = 0.27 m/s$; flow Reynolds number ~68.

*A ten Cate, C. H. Nieuwstad, J. J. Derksen, and H. E. A. van den Akker(2002), "Particle imaging velocimetry experiments and lattice-Boltzmann simulations on a single sphere settling under gravity," *Phys. Fluids*, **14**: 4012-4025 .

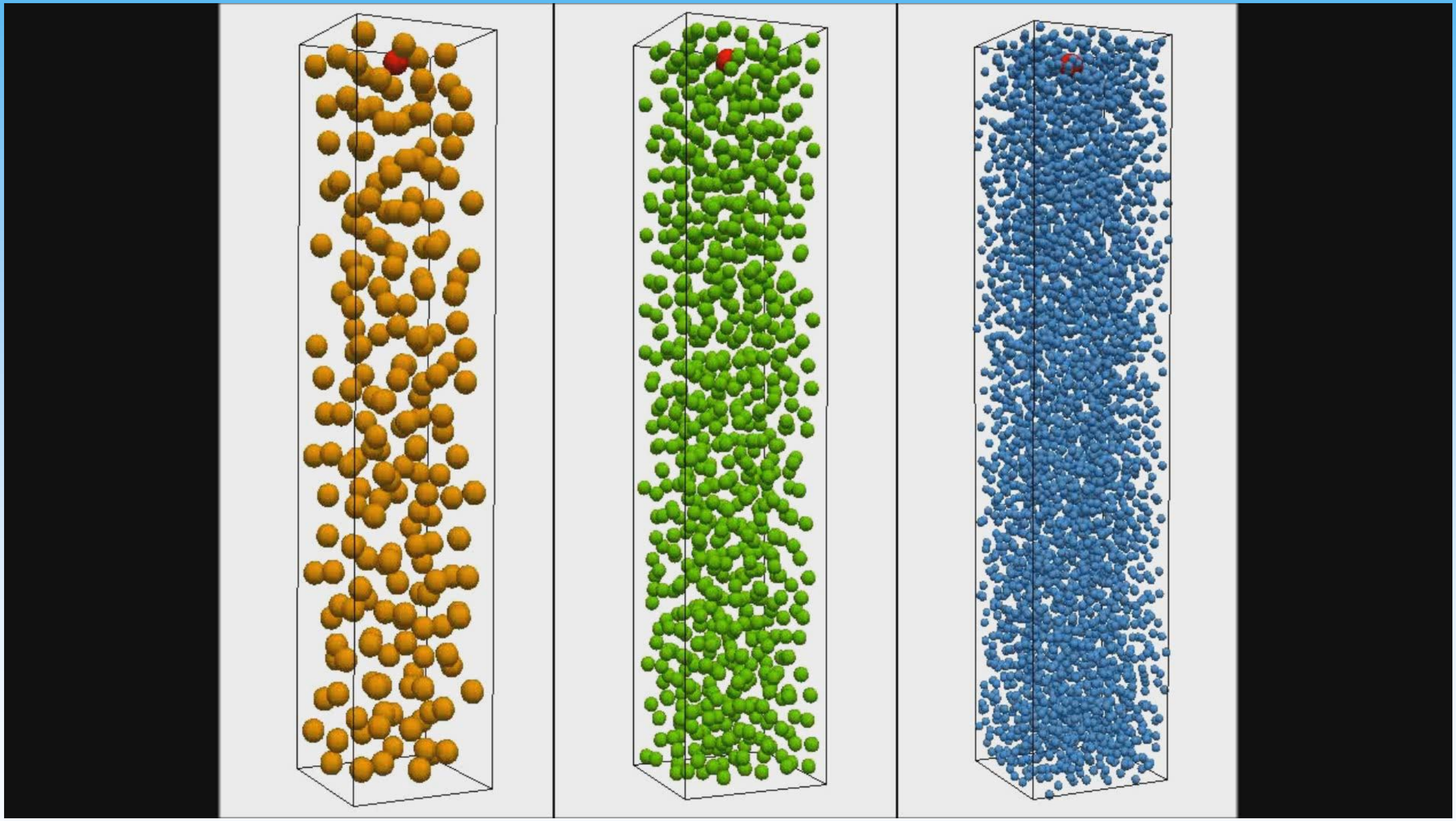
Effect of the size of neighboring particles

- Consider three cases at the same solid volume fraction ϕ=10%

Case No.	Diameter of neighboring particles	Number of neighboring particles
1	1d	200
2	0.625d	819
3	0.375d	3793

- Question:
  - Which case the heavy particle falls the fastest?

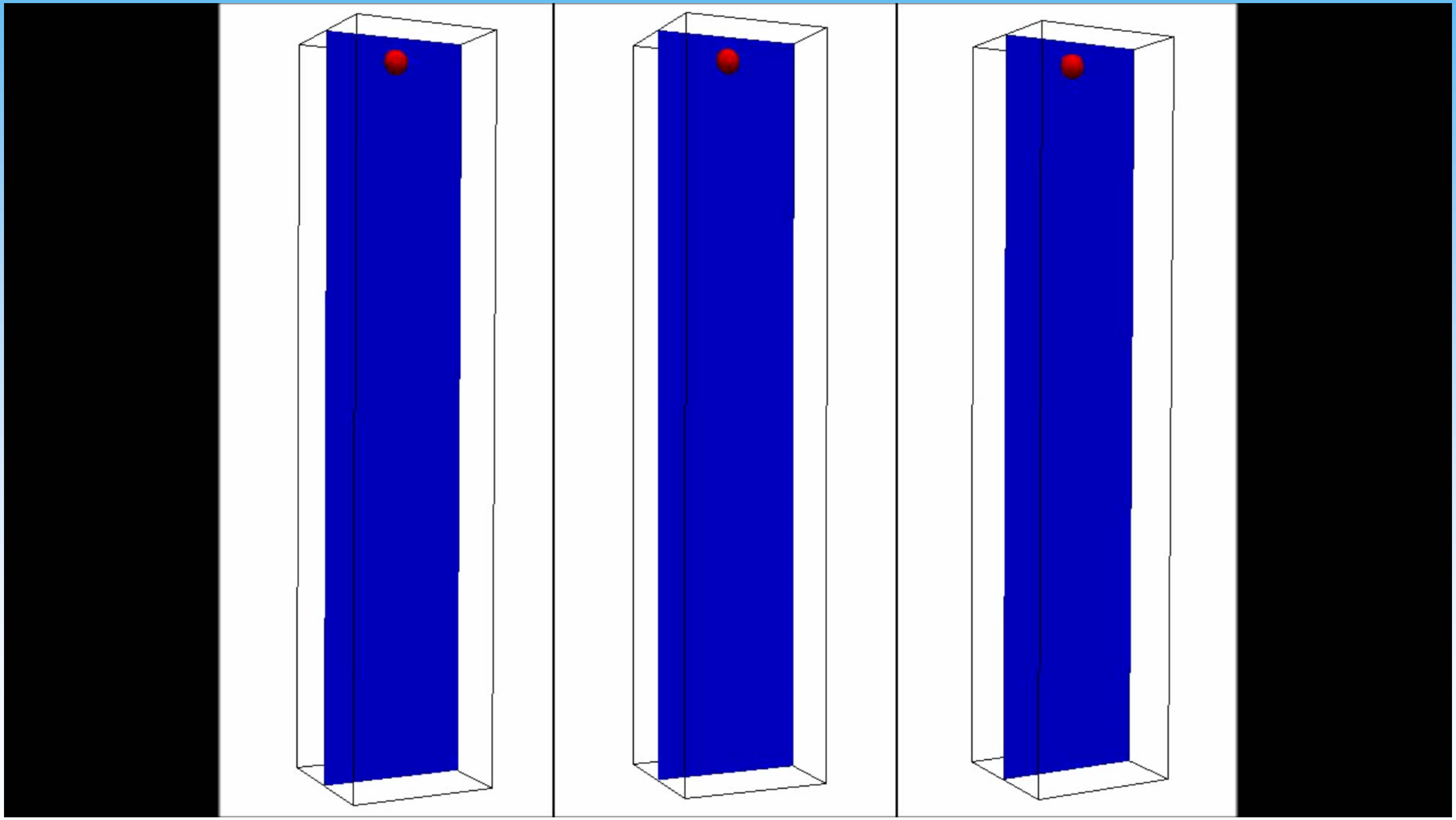
Settling of a heavy particle in suspension flows with different size of particles



Case 1: N=200   case 2: N=819   case 3: N=3793

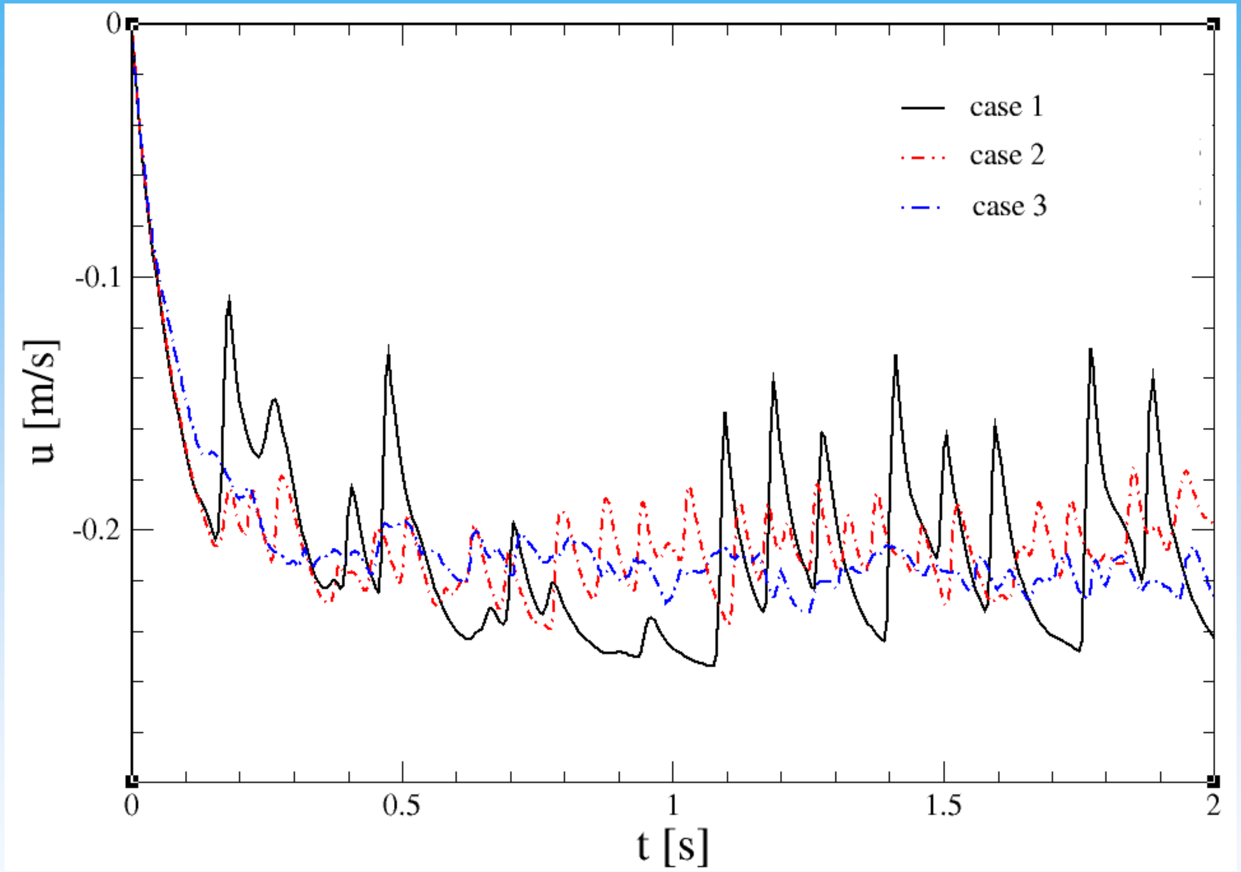
Settling of a particle in suspension flows with different size of particles

Pressure contours on the centered x-y plane (z=0)



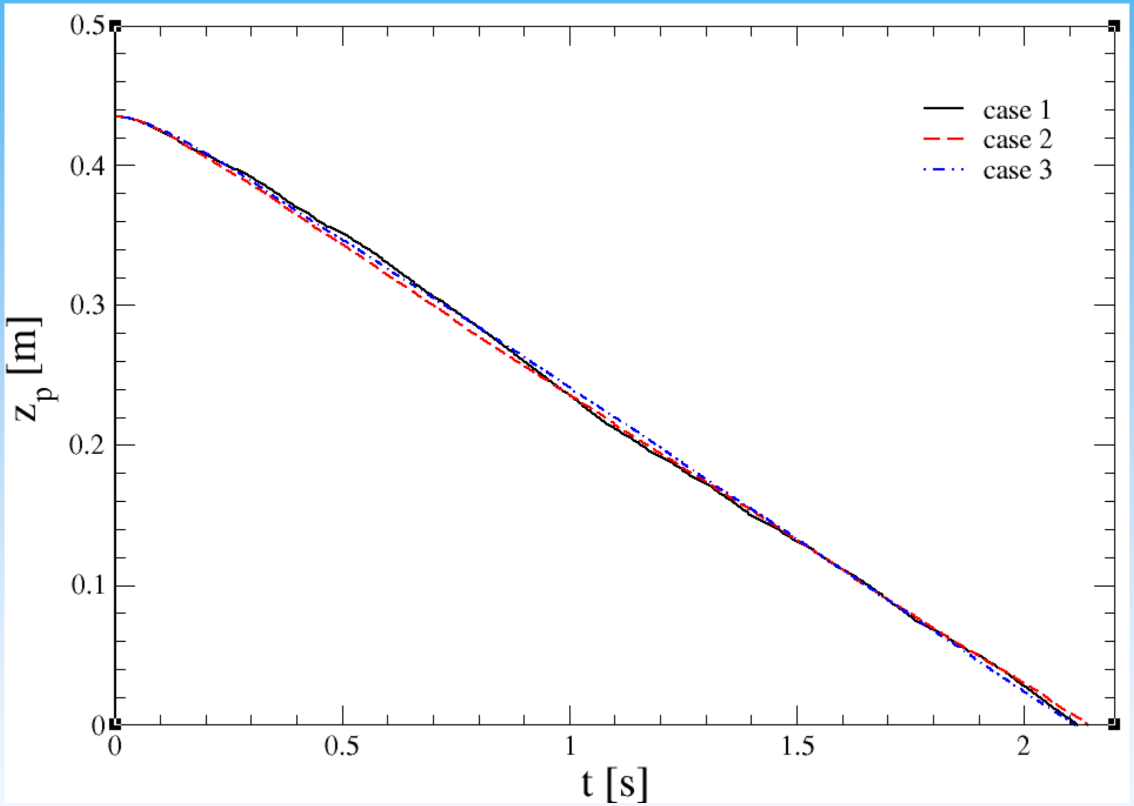
case 1 case 2 case 3

Settling velocity of the heavy particle



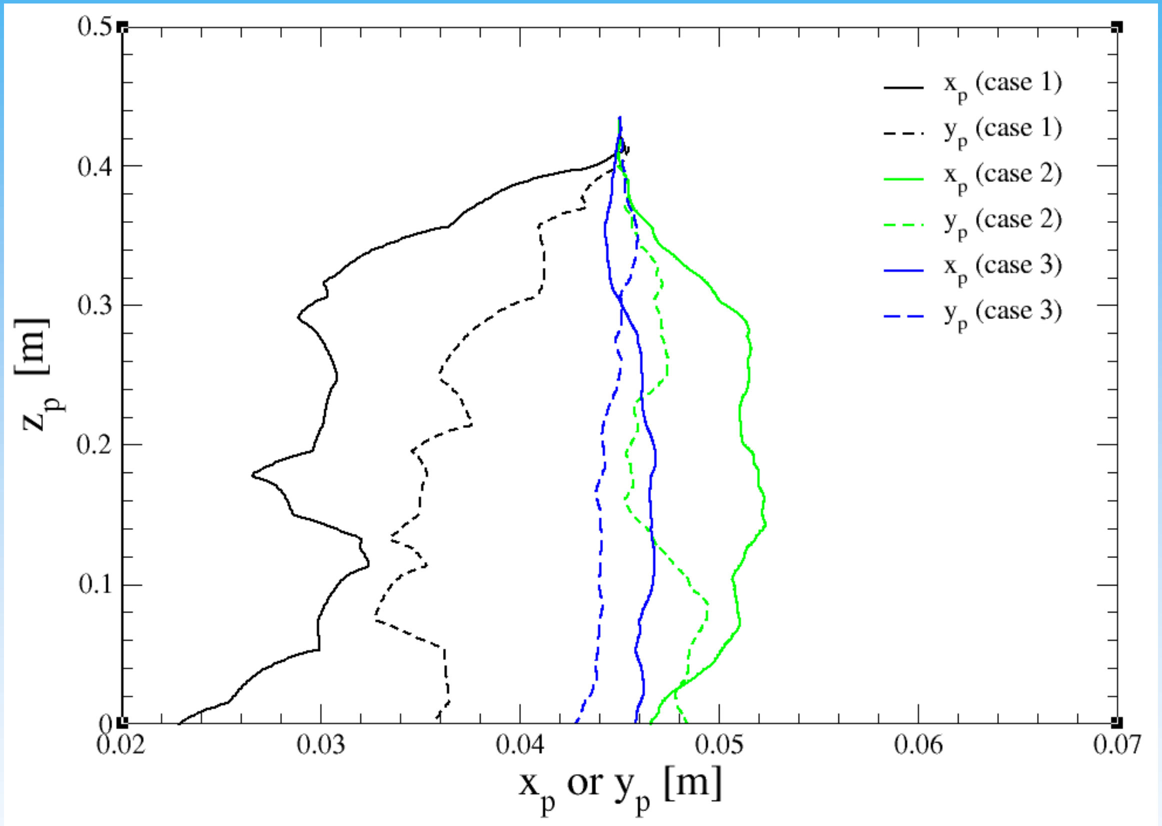
Resistance: drag force + collision force

Vertical position of the heavy particle



Almost the same slope in *z*-*t* graph. The mean settling velocity=slope=0.21 m/s.

Horizontal positions of the heavy particle



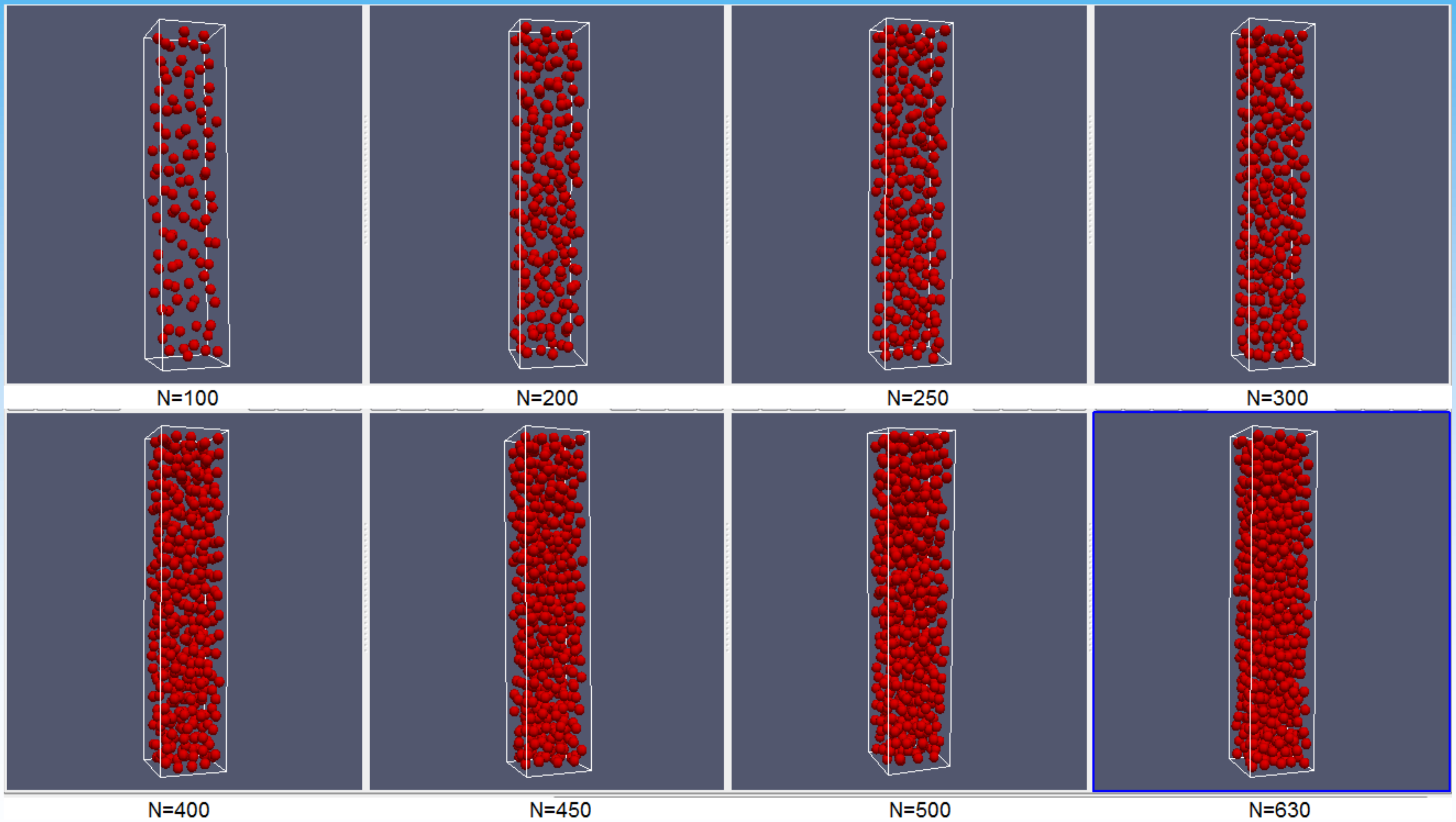
- The migration in the horizontal directions increases with the size of neighboring particles

Effect of solid fractions

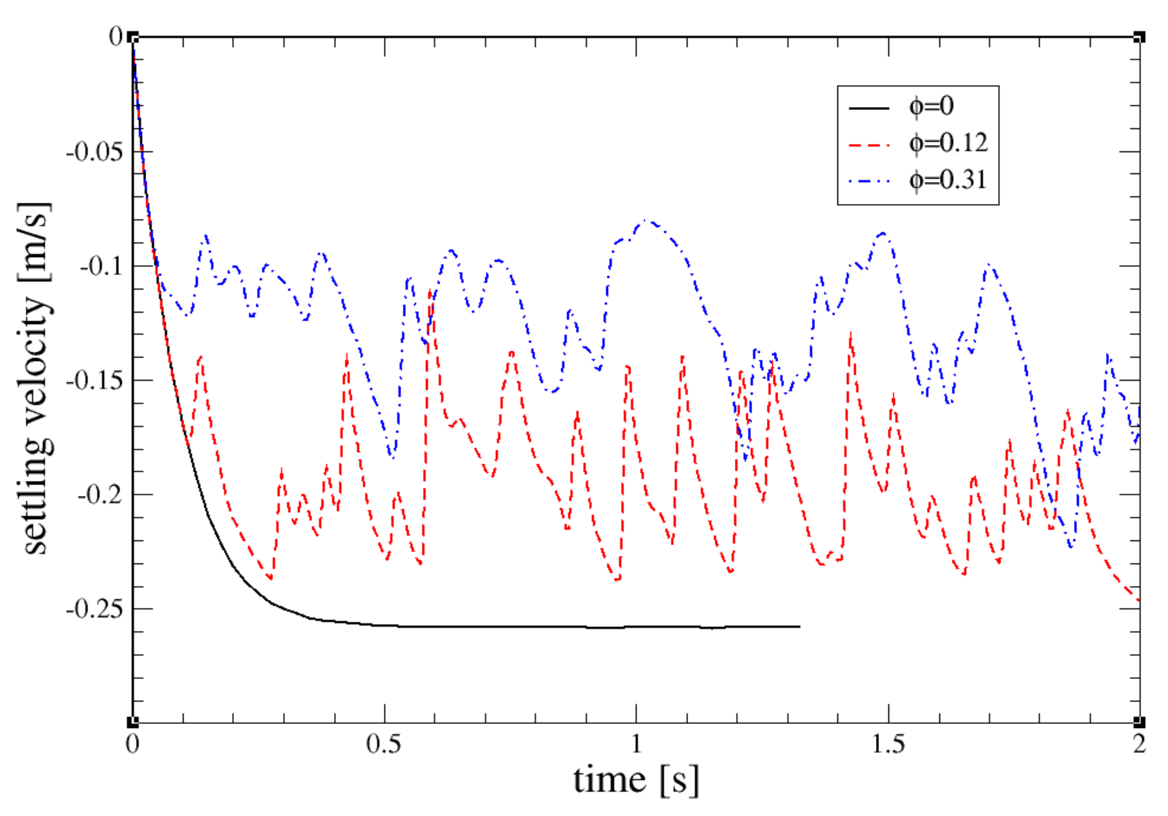
- The neutral particles are chosen to be the same size as the settling particle.
- 10 cases are studied.

Case No.	Number of surrounding particles	Volume solid fraction
1	0	0
2	100	0.049
3	200	0.097
4	250	0.121
5	300	0.145
6	350	0.170
7	400	0.194
8	450	0.218
9	500	0.242
10	630	0.305

Initial distributions of particles at eight different solid fractions

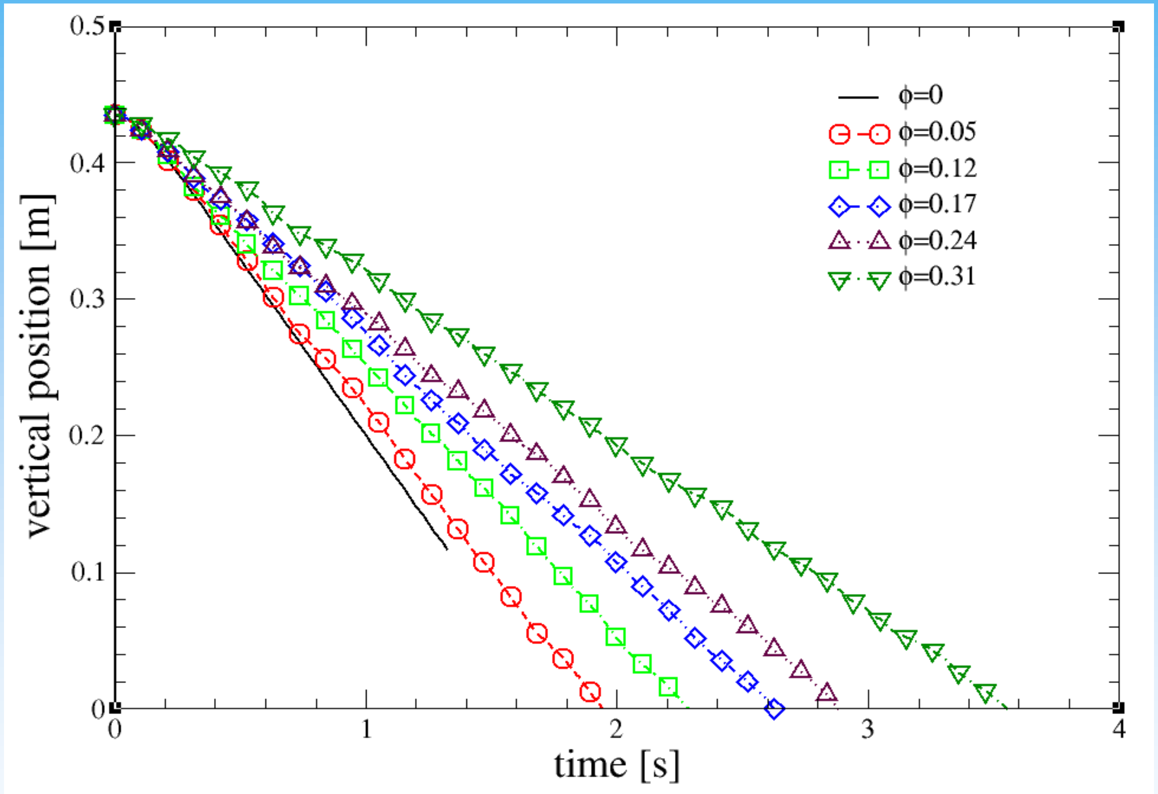


Settling velocity at different solid fractions



- Higher solid fraction leads to the increased drag force and the number of collisions

Vertical position of the settling particle at different solid fractions



After a brief unsteady transition at the beginning, the slope in *z*-*t* graph is nearly a const for each case.

Mean terminal velocity

- Mean terminal velocity:

$$\overline{v_z} = \frac{dz}{dt} = slope\ in\ z-t\ graph.$$

- Correlation:

$$\frac{V(\phi)}{V(0)} = (1-\phi)^{2.25}, \quad (0 \le \phi \le 0.3)$$

Solid fraction	Mean terminal velocity	
	Simulation (m/s)	V(ϕ)/V(0)
0	0.265	1
0.049	0.230	0.89
0.097	0.210	0.81
0.121	0.200	0.74
0.145	0.190	0.70
0.170	0.174	0.64
0.194	0.165	0.61
0.218	0.155	0.58
0.242	0.150	0.56
0.305	0.130	0.48

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:

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

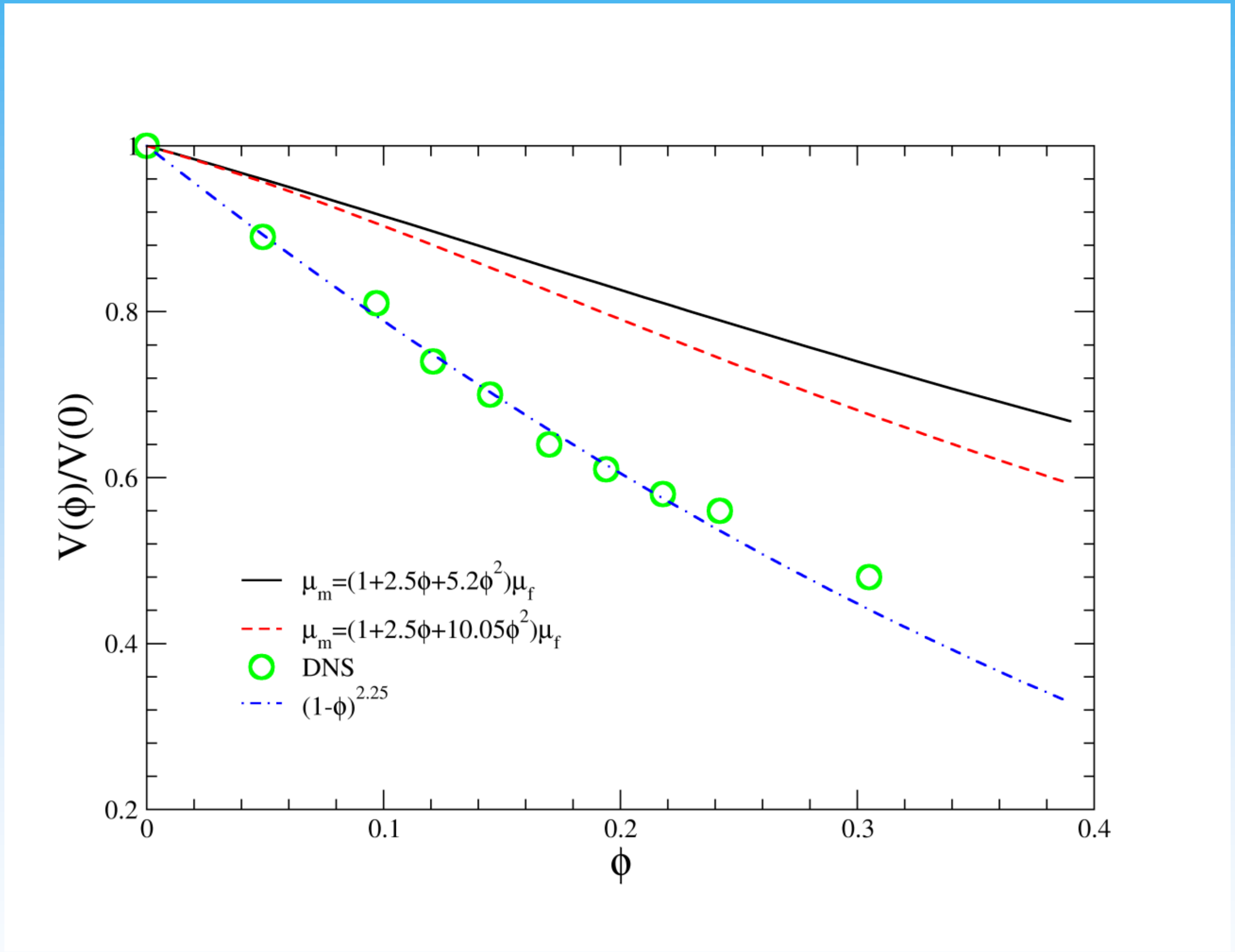
Empirical drag law: $C_d(\phi) = (0.63 + \frac{4.8}{\sqrt{\mathrm{Re}(\phi)}})^2$

Only unknown: $V_t(\phi)$

*G.K. Bachelor, 1967, *An Introduction to Fluid Dynamics, Cambridge University Press, Cambridge*

** Thomas, D., Transport characteristics of suspensions: VIII. A note on the viscosity of Newtonian suspensions of uniform spherical particles, *J. Colloid Sci., 20, 267–277, 1965.*

Theory and simulation results



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