VALIDATION OF NUMERICAL APPROACH FOR THE SEDIMENT OF MULTI-SIZE PARTICLES IN A FLUID CONTAINER

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다양한 크기를 갖는 입자들의 유체 용기 내부에서의 침전에 대한 수치적 접근방법의 검증

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In this paper, we reported the verification of numerical simulation approach for sedimentation of the multi-size particles in a container. The comparison between experimentally measured values and numerically evaluated values on settle down process of fully mixed mixture is carried out. In an attempt to represent the natural particle size distribution, various diameters of single particles are simulated and the results are compared with the outcome of the multi-size computation. When the empirical formula for mean particle size estimation is adopted to define the sediment diameter, computation and comparison are conducted.

Key Words : CFD(전산유체역학), Solid-Fluid Mixture(고체-유체 혼합물), Sediment(침전물), Deposition(퇴적)

1. Introduction

Deposition problem is one of the oldest and general water treatment procedures for human life. If we consider a sedimentation tank, that process is used to take away the suspended solid particles in turbid liquid by the mechanism of gravitational settling. There are many important considerations that directly affect the sedimentation process such as the surrounding circumstances, the variations in the flow rate, the type of the tank inlet and outlet and the each suspended particles' settling velocities coming from the differences of particle size and appearance (surface roughness). Thus, there have been continued a vast amount of data accumulation on this long standing issues[1-3].

Although the experimental determination is the best way to understand this phenomenon, it is not recommendable in a considerable proportion of cases because of its time and space restrictions and the measurement difficulties of valuable data. For that reason, many researchers have focused on the development of numerical schemes for the purpose of clear evaluation on the sedimentation process and acquisition of more valuable data based on computational fluid dynamics (CFD). Fluid flow and settling process of suspended particles are predicted by solving the Navier-Stokes equations that describe the conservation of mass and momentum with reasonable source terms coming from the empirical relations. There are well known two different methods to estimate the suspended particles' behaviors. The Eulerian and Lagrangian approaches deal with the solid particles in liquid that consist of various diameters as a continuum and individual particles, respectively. The Lagrangian model, so called particle tracking, is useful because both efficiency and spatial distribution of deposits can be obtained[4,5]. However, if the problems which need a lot of computing power are considered (it requires large numbers of cells), its huge computation time is another

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bottleneck that have to be concerned. The Eulerian model is an alternative technique for the problems which have large characteristic length. Even though the Eulerian model has demerits in terms of the accuracy of results, it is better approach in terms of time efficiency.

The particle size distribution was not considered in general problems which have been studied numerically for a long time in environmental and civil engineering. Under this condition it is not easy to obtain the quantitative result, because only one diameter of solid particles is applied. If the spacial accuracy of sediment with time is required, i.e., the settling position of solid particles is affected by relative velocity between the solid and the liquid, multi-size particles model has to be introduced and for more reasonable estimation. It contributes to accurate dynamic simulation of settle down process. In this paper, we reported the verification of numerical approach that include multi-size particles. The comparison between the experiment and the numerical simulation on the settle down process of fully mixed mixture is conducted.

2. Numerical approach

The model which is introduced in this study works by emulating the entrainment of sediment at the packed bed interface, the drifting, and deposition of sediment due to gravity. When coupled with the three-dimensional fluid dynamics computed by the equations of mass and momentum conservation, the model is able to simulate the deposition and entrainment of sand, silt and other non-cohesive sediment. In this study, the commercial CFD software FLOW-3D ver. 9.4 has been used to carry out the simulations[6]. The considered model estimates the motion of sediment flow by predicting the erosion, advection and deposition of sediment. Momentum balances for each sediment phase i and the mean flow are written.

$$\frac{\partial \boldsymbol{u}_{s,i}}{\partial t}+\bar{\boldsymbol{u}}\cdot\nabla \boldsymbol{u}_{s,i}=-\frac{1}{\rho_{s,i}}\nabla P+\boldsymbol{F}-\frac{K_i}{f_{s,i}\rho_{s,i}}\boldsymbol{u}_{r,i} \quad (1)$$

$$\frac{\partial \bar{\boldsymbol{u}}}{\partial t}+\bar{\boldsymbol{u}}\cdot\nabla \bar{\boldsymbol{u}}=-\frac{1}{\bar{\rho}}\nabla P+\boldsymbol{F} \quad (2)$$

Here $\boldsymbol{u}_{s,i}$ and $\bar{u}$ are the velocities of sediment species i and the mean bulk fluid, respectively, $\rho_{s,i}$ is the microscopic sediment density and $\bar{\rho}$ is the mean mixture density. In the above equation, $f_{s,i}$ is the volume fraction of sediment species i, P is the pressure, K_i is the drag function for sediment species i, F is the body force, and $\boldsymbol{u}_{r,i}$ is relative velocity between fluid and solid particle.

$$u_{r,i}=u_{s,i}-u_f \quad (3)$$

and mean velocity is

$$\bar{u}=\left(1-\sum_{i=1}^{N}f_{s,i}\right)u_f+\sum_{i=1}^{N}f_{s,i}u_{s,i} \quad (4)$$

where N is the total number of sediment species. Subtracting Eq. (2) from (1) gives

$$\frac{\partial u_{drift,i}}{\partial t}+\bar{u}\cdot\nabla u_{drift,i}=\left(\frac{1}{\bar{\rho}}-\frac{1}{\rho_{s,i}}\right)\nabla P-\frac{K_i}{f_{s,i}\rho_{s,i}}u_{r,i} \quad (5)$$

where $u_{drift,i}=u_{s,i}-\bar{u}$ is the drift velocity. Assuming that the motion of the sediment is nearly steady at the scale of the computational time and that the advection term is very small, the result of equation (5) is

$$u_{r,i}=\frac{\nabla P}{\bar{\rho}K_i}\left(\rho_{s,i}-\bar{\rho}\right)f_{s,i} \quad (6)$$

where the mixture density, $\bar{\rho}$, is

$$\bar{\rho}=\sum_{i=1}^{N}f_{s,i}\rho_{s,i}+\left(1-\sum_{i=1}^{N}f_{s,i}\right)\rho_f \quad (7)$$

Note that in many simulations the pressure gradient can become very noisy, particularly close to the free surface. For most problems the ratio of pressure gradient to mixture density is typically equal to the acceleration of gravity, g. With this assumption we get

$$u_{r,i}=\frac{g}{K_i}\left(\rho_{s,i}-\rho\right)f_{s,i} \quad (8)$$

A reasonable choice for the drag function K_i combines form drag and Stokes drag is

$$K_i=\frac{3}{4}\frac{f_{s,i}}{d_{s,i}}\left(C_{d,i}\parallel u_{r,i}\parallel+24\frac{\mu_f}{d_{s,i}\rho_f}\right) \quad (9)$$

where $d_{s,i}$ and $C_{d,i}$ are the diameter and the drag

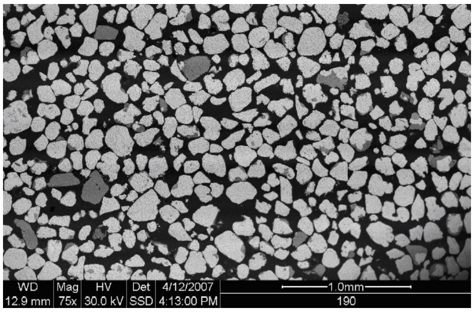


Fig. 1 Particles of sediment

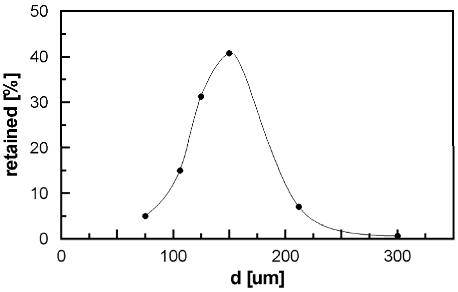


Fig. 2 Particles size distribution

coefficient for sediment species i, respectively. μ_f is the fluid viscosity. Finally, the drift velocity is computed from the relative velocity using the definition of the drift and relative velocities.

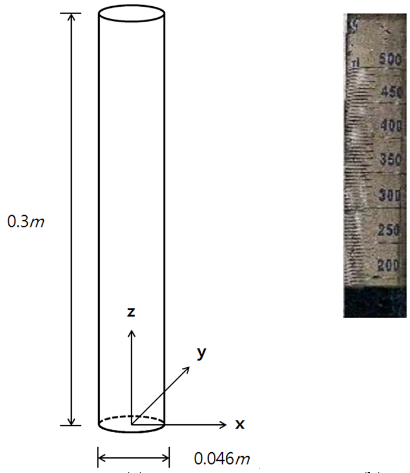
$$u_{drift,i} = (1-f_{s,i})u_{r,i} - \sum_{i=1}^{N} f_{s,i}u_{r,i} \tag{10}$$

Equations (8), (9) and (10) are solved via the quadratic formula to find drift velocity.

3. Sedimentation of particles with size distribution

The manner for reasonable comparison between experiment and numerical simulation on settle down process of fully mixed mixture is elucidated in this chapter. The explanation is focused on the way to handle the result data from lab-scale experiment and simulation which are conducted under same condition. As shown in Fig. 1, photo-micrograph of solid particle and scale bar (near right bottom) are discernable.

Fig. 2 indicates the particle size distribution from the coarsest to the finest. The ordinate represents the fraction



(a) (b)

Fig. 3 Schematics of experimental system (a) and settling of sediment (b)

of each particle. Fig. 3 shows the experimental setup that is considered in this study. The experiment was performed in a long mess cylinder (industrial product; diameter [D]: 0.046 *m*, height [h]: 0.3 *m*). The experiment began with the blend of tap water (ρ_w=1,000 kg/m^3, μ=0.00112 Ns/m^3) and particles which have different size and same density (ρ_s=4,750 kg/m^3). Table 1 lists the particle distribution that had been both conducted experimentally and simulated. The sediments had a diameter of 75 μm and 300 μm for the finest and coarsest sediments, respectively. The moisture contents (MC) of solid-fluid mixture which is applied in the experiment is 50% and as mentioned above, this value of MC is applied for all numerical simulation.

3.1 Experiment

In order to measure the settling height of sediments the experiment is repeated until the evaluated data is sufficiently regarded as a representative value of the time history on deposition process. Once fully mixed mixture is placed on the flat and immovable table, the only force acting on the sediments is gravity. Even though the initial velocity exists during the early stage of settling process,

Table 1 Particle size distribution

Microns	Average retained [%]
300	0.6
212	7.0
150	40.8
125	31.3
106	15.0
75	5.0

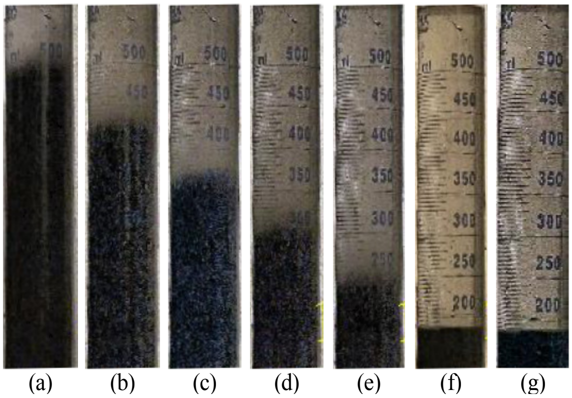


Fig. 4 Experimental results for settling down of sediment. Times, t, are: (a) 2.0, (b) 4.0, (c) 6.0, (d) 8.0, (e) 10.0, (f) 16.0, (g) 60.0 [second]

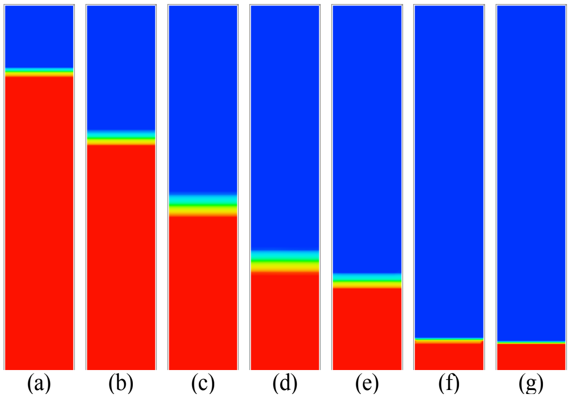


Fig. 5 Numerical results for settling down of sediment. Times, t, are: (a) 2.0, (b) 4.0, (c) 6.0, (d) 8.0, (e) 10.0, (f) 16.0, (g) 60.0 [second].

we consider the sediment diameter and density this primary disturbance has no effect on the most important physical behavior. To capture a time history of settle down process a high speed camera was introduced. The high speed camera (IMPERX VGA210-L), which is capable of taking 210 frames per a second, was used to capture the images (640 by 480 pixels, mono). For a clear wave boundary, the back light illuminating system with white screen was adopted. The obtained picture was digitized through the graphical image processing, also used for continuous measurement on the height of boundary line between the pure water and mixture which has very few particles, based on each pixel's brightness index.

3.2 Numerical simulation

3-D computation was carried out under the same condition not only the real shape of mess cylinder but also the sediment volume fraction and other leading parameters as in the experiment. The enough time required for complete settle down is 60 seconds in all cases of experiment. All simulations lasted for a physical time of 60 seconds to ensure an entire settling of particles, and were considered on a 3-D single mesh block with 96,250 uniform cells, each about a 2 *mm* cube. In order to define the boundary line, we had to adopt appropriate scheme as done in the experiment. First, the time history of distribution of sediments in the mixture was converted via two-dimensional *x-z* plane (y=0) into mass per unit volume (macroscopic density [ρ_m]). Then, we measured the height of contour line both the values of macroscopic density are 1,010 and 1,001 kg/m^3 (if ρ_m=1,000+, the cell has very few particles). If we consider a single cell size, there are some differences between two values of height. From these heights the valid boundary line height is obtained through a simple average at all computation time. This method corresponds to the approach that is used for obtaining the boundary line height in experiment.

For the thorough understanding of the way to reach the accurate simulation result for a settle down process with multi-size distributed sediments, it needs to be compared with that of single-size distributed sediments. The finest (75 μm) and coarsest (300 μm) sediments are selected for comparison group. Also, to explain the weakness that happen when the well known mean particle size distribution is adopted to define the representative sediment diameter an additional computation is accomplished. For this case, the general technique to decide the mean particle size which is elucidated by Mugele and Evans is selected[7]. That equation is shown as below.

$$\bar{d}_{qp}^{\,q-p} = \frac{\Sigma(d^q \triangle n)}{\Sigma(d^p \triangle n)} \quad , \quad \triangle n = \frac{\triangle N}{N} \tag{11}$$

where p and q indicate subscripts for mean diameter, d, $\triangle N$ and N are each number of particle and the total number of particle, respectively (q=1, p=0). From this relation, the obtained mean particle diameter is 137 μm.

4. Result and discussion

Fig. 4 shows the time series of deposition procedure of solid-fluid mixture from fully mixed state (2.0s) to complete settle down (60s). Because of density difference

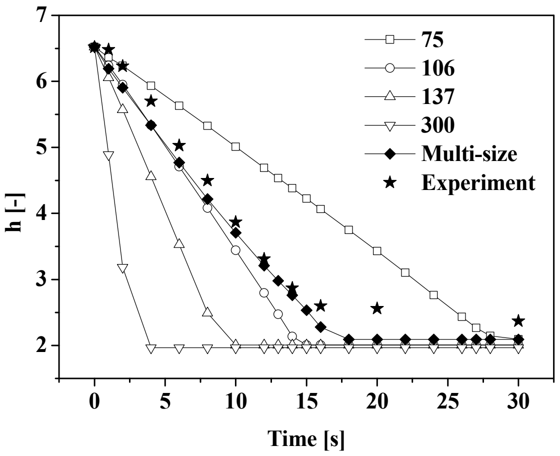


Fig. 6 Time history of settling height

between solid and fluid, the mixture is almost clearly separated within 16.0*s*. Fine particles are slowly sunken during measurement time. This is a natural outcome coming from the difference of solid particle size. The finer particles are more sensitive to fluid velocity. In other words, the small particles are more affected by the flow of liquid. The outcome of numerical simulation which correspond to the condition of experiment is illustrated in Fig. 5. The flooded contour means macroscopic density (1,010 ~ 1,001 kg/m^3). There is good agreement between the experimentally measured values and the numerically estimated values. The measured boundary line (between the water and the sediment) height with time can be seen in Fig. 6. The minute change of height from 16.0*s* to 60.0s is clearly found.

When the various diameter of particles are adopted, the evaluated numerical data is more close to measured values. In Fig. 6, the computation results that is based on interested single size particles are shown. It is found that the finest particle take more time than others for complete deposition. As mentioned above, the known empirical relation was treated to obtain the mean particle size. The estimated mean diameter is 137 *μm* and this size of particles are tried to observe its attribute during deposition process.

Inevitably, even if mean value of diameter is applied which is based on most widely accepted averaging equation, the predicted values present a great differences and that mean diameter cannot represent the real size particle distribution. The results from mean diameter are nothing but another outcome of deposition of single size

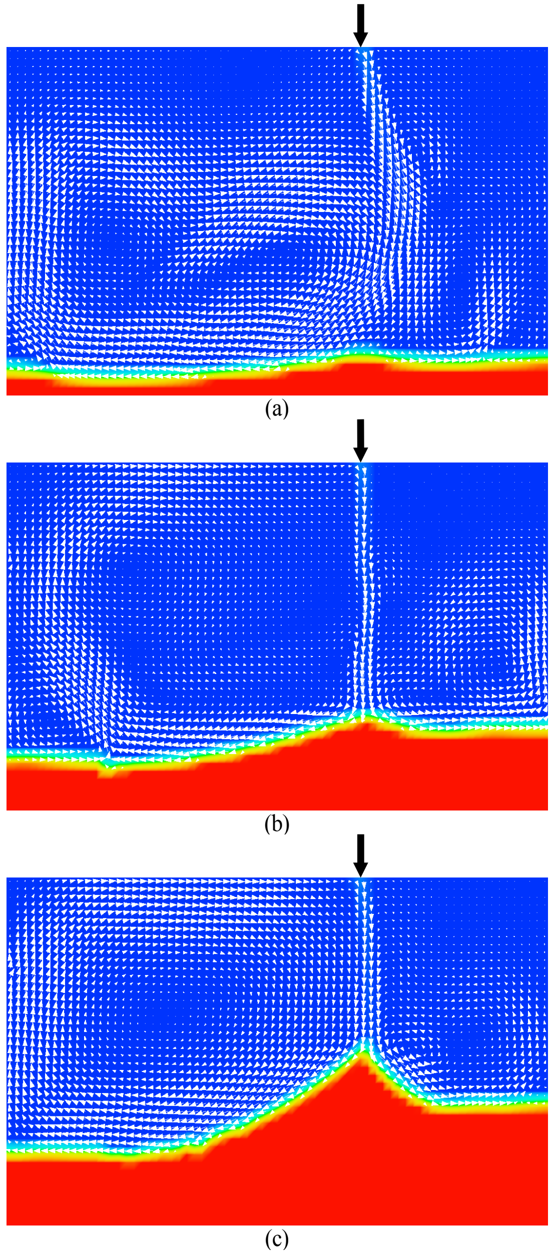


Fig. 7 Sample numerical results for settling down of sediment in a large scale fluid container. Times, t, are: (a) 900.0, (b) 1,800.0, (c) 2,700.0 [second].

particles. As appears by above a few statements, if we want to get a high exactitude the all size of diameters should be considered for numerical simulation of settle down process.

Fig. 7 shows a sample simulation result as an extended case to practical scales. This simulation is carried out for iron-sand carrier which is under construction. Solid particles and liquid mixture are loaded to each container of carrier from on-land facility. The dimension of simplified 2-D container is 40 *m* by 26 *m* and one single length of cell is 0.5 *m*. The arrow mark indicates the position of injection nozzle. Through this nozzle, the solid-fluid (50/50) mixture is loaded so the sedimentation height growth begins with local area of bottom just under the injection nozzle. Fig. 7 indicates the high resolution result (refer to boundary line between water and solid particle) and through this meticulous computation, comparatively appropriate estimation could be suggested on many cases of application in real engineering application.

5. Conclusion

The verifications of numerical simulation approach that include multi-size particles are presented. Sedimentation processes of particles strongly depend on the size of the particles. It was pointed out that the computational results better represent the experimental observation when aggregation of the particles are represented in the computation. The proposed way to observe the settling procedure should be accepted for more reasonable estimation.

References

[1] 1994, Gidaspow, D., *Multiphase flow and fluidization: continuum and kinetic theory descriptions*, Academic Press.

[2] 1997, Soulsby, R., *Dynamics of Marine Sands*, Thomas Telford Publications.

[3] 1998, Clayton, T., Sommerfeld, M. and Yutaka, T., *Multiphase flows with droplets and particles*, CRC Press.

[4] 2010, Mastbergen, D.R. and Von den Berg J.H., "Experimental investigation of flow pattern and sediment deposition in rectangular shallow reservoirs," *International Journal of Sediment Research*, Vol.25, pp.258-270.

[5] 2003, Mastbergen, D.R. and Von den Berg J.H., "Breaching in fine sands and the generation of sustained turbidity currents in submarine canyons," *Sedimentology*, Vol.50, pp.625-637.

[6] 2010, Brethour, J. and Burnham J., "Modeling sediment erosion and deposition with FLOW-3D sedimentation & scour model," *FSI-10-TN85*.

[7] 1951, Mugele, R.A. and Evans H.D., "Droplet distribution in sprays," *Industrial and Engineering Chemistry*, Vol.43, pp.1317-1324.