Numerical simulation of dam break by a coupled CFD-DEM approach

Xingyue Li and Jidong Zhao

i) Ph.D. student, Department of Civil and Environmental Engineering, Hong Kong University of Science and Technology, Clear Water Bay, Hong Kong.

ii) Associate Professor, Department of Civil and Environmental Engineering, Hong Kong University of Science and Technology, Clear Water Bay, Hong Kong.

ABSTRACT

The breaking of dam can cause sudden debris flow which leads to hazardous consequences. This paper presents a coupled Computational Fluid Dynamics and Discrete Element Method (CFD-DEM) approach to study the dam break problem. The CFD is employed to investigate the fluid flow by solving the locally averaged Navier-Stokes equation, while the DEM is used to simulate the granular particle system based on the Newton’s equation of motion. The fluid-particle interaction is accounted for in the modeling by exchanging interaction forces such as the drag force and the buoyancy force between the CFD and the DEM. In simulating the dam break problem, a mixture of viscous fluid and uniform particles is initially confined within a cubic container with a removable side gate which is subsequently initiate the dam breaking. Four comparison cases are investigated, including a Bingham fluid-particle sample, a water-particle sample, a pure Bingham fluid sample and a dry particle sample. The Bingham model is employed to simulate a viscous fluid consisting of water and fine particles, which allows the DEM simulate big gravels and boulders only and lends a great computational efficiency. The simulations enable us to examine the flow patterns of different samples and interactions between particles to understand the mechanisms of dam break better.

Keywords: coupled CFD-DEM, dam break, Bingham fluid

1 INTRODUCTION

Numerous dam break models have been developed to study the behavior and consequence of dam break under various engineering backgrounds due obviously to its important relevance and consequence. For example, in ocean engineering, Newtonian fluids are commonly used in the dam break model to investigate the free surface flow which is of great importance to the coastal structures (Hogg and Pritchard, 2004; Greaves, 2006; Staroszczyk, 2010). Mining engineering is more concerned with the collapse of a granular system (e.g., granular pile) whereby dry particles can be used in the dam break model (Lajeunesse et al., 2005; Di Cristo et al., 2010a; Di Cristo et al., 2010b). In geotechnical engineering, the occurrence of mud flows, submarine landslides and volcanic lava commonly involves a mixture of granular particles and fluid. Most past studies have idealized the mixture as a Non-Newtonian fluid towards developing dam break models (Chambon et al., 2009; Saramito et al., 2013).

A thorough investigation of the dam break problem as an interacted fluid-particle mixture is scarce but important. Many aspects of dam break behavior cannot be effectively captured without full consideration of the interactions between the constituent fluid and particles. In particular, the study of a fluid-particle mixture breaking onto a horizontal bed, which will be treated here, can provide useful reference to the design of mining tailing after the failure of tailing dams (Macklin et al., 2003). In this study, the dam break problem will be treated by a coupled CFD-DEM numerical approach recently developed by Zhao and Shan (2013a, 2013b) and Shan and Zhao (2014). Focuses will be placed in this study on the influence of the property of the fluid and system and the rolling behavior of the particle system on the overall flow behavior of the mixture.

2 METHODOLOGY AND FORMULATION

The coupled framework treats the particle system of a mixture of fluid and particles based on the DEM (Cundall, 1979) to solve the following Newton’s

\[\frac{m_i}{dt} = \sum_{j=1}^{n_i} F_{ij} + F_i + F_i^f\]

\[\frac{I_i}{dt} = \sum_{j=1}^{n_i} (M_{ij} + M_{ij}^f)\]

(1)

equation governing the translational and rotational motions of any particle \(i\) in the system. \(m_i\) and \(I_i\) are the
mass and moment of inertia of particle \( i \), \( \mathbf{U}_i^p \) and \( \omega_i \) denote the translational and angular velocities of particle \( i \), respectively. \( n_i \) is the number of total contacts for particle \( i \). \( \mathbf{F}_{\text{c}} \) is the contact force acting on particle \( i \) by particle \( j \) or walls. \( \mathbf{F}_f \) is the particle-fluid interaction force acting on the particle, which include the drag force and the buoyancy force. \( \mathbf{F}_g \) is the gravitational force of particle \( i \). \( \mathbf{M}_{i,j} \) and \( \mathbf{M}_{i,j}^p \) are the torques acting on particle \( i \), which are generated by the tangential force and the rolling friction force.

The fluid system in the mixture is simulated by the CFD. By discretizing the fluid domain into fluid cells, the CFD is employed to solve the following continuity equation and the locally averaged Navier-Stokes equation for each cell:

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

\[
\frac{\partial (\varepsilon_f \rho_f \mathbf{U}_f)}{\partial t} + \nabla \cdot (\varepsilon_f \rho_f \mathbf{U}_f \mathbf{U}_f) = -\nabla p + \varepsilon_f \nabla \cdot \mathbf{t} + \varepsilon_f \rho_f \mathbf{g}
\]

where \( \varepsilon_f \) is the void fraction (porosity), \( \rho_f \) is the averaged fluid density. \( \mathbf{U}_f \) and \( p \) are the fluid velocity and pressure. \( \mathbf{f}^p \) is the volumetric interaction force acting on the fluid by the particles inside each cell. \( \mathbf{t} \) is the stress tensor.

In this study we consider the buoyancy force and the drag force as the interaction forces between the fluid and the particles, defined respectively by the following expressions (O'Sullivan, 2001; Koch and Hill, 2001; Kafui et al., 2002):

\[
\mathbf{F}_b = \frac{1}{6} \pi \rho d_i^3 \mathbf{g}
\]

\[
\mathbf{F}_d = \frac{U_f^p}{{\varepsilon}_f} (\mathbf{U}_f - \mathbf{U}_p)
\]

where \( \varepsilon_f \) represents the volume fraction of particles in the cell, which equals 1- \( \varepsilon_e \). \( \beta \) denotes the inter-phase momentum transfer coefficient due to drag:

\[
\beta = 18 \mu_f {\varepsilon}_e^2 \varepsilon_f (F_0(\varepsilon_p) + \frac{1}{2} F_1(\varepsilon_p) Re_p)
\]

where

\[
F_0(\varepsilon_p) = 0.0673 + 0.212 \varepsilon_p + \frac{0.0232}{\varepsilon_f^3}
\]

If \( \varepsilon_p < 0.4 \),

\[
F_0(\varepsilon_p) = 1 + 3 \sqrt{\varepsilon_p + 135} \varepsilon_p^2 \ln(\varepsilon_p) + 16.14 \varepsilon_p
\]

If \( \varepsilon_p \geq 0.4 \),

\[
F_0(\varepsilon_p) = \frac{10 \varepsilon_p}{\varepsilon_f^3}
\]

The particle Reynolds number is calculated by:

\[
Re_p = \frac{\varepsilon_f \rho_f |\mathbf{U}_f - \mathbf{U}_p|}{d_p \mu_f}
\]

where \( d_p \) is the diameter of the considered particle, \( \mu_f \) is the averaged viscosity of the fluid cell.

### 3 SIMULATIONS OF DAM BREAK

#### 3.1 Model setup

The setup of the dam break simulation follows exactly the experimental one presented by Greaves (2006) as shown in Fig. 1. Within a cubic container, a mixture of viscous fluid (shown in red) and a uniform packing of particles (in black) is initially confined within the bottom left corner. The right confining wall (in purple) of the mixture is then released to trigger dam break. At the bottom of the channel, a barrier with a height of 0.33m is modelled. Fig. 1 shows a front view of a three-dimensional model where the thickness is 0.1m. To investigate the influence of various conditions of the fluid and the particles on simulation results, four different samples are considered, namely, a Bingham fluid-particle sample, a water-particle sample, a dry particle sample and a pure Bingham fluid sample. We also consider the effect of rolling resistance of the particles, by setting the rolling friction coefficient \( \mu_r = 0.1 \) (see Zhou et al., 1999 for detail of the rolling resistance model). Consequently, a total of seven cases
Table 1. Summary of simulated cases for the dam break problem.

| Case name | Sample constituent(s)          | Interparticle rolling resistance coefficient $\mu_r$ |
|-----------|-------------------------------|---------------------------------------------------|
| BP        | Bingham fluid + particles     | 0                                                 |
| BPr       | Bingham fluid + particles     | 0.1                                               |
| WP        | Water + particles             | 0                                                 |
| WPr       | Water + particles             | 0.1                                               |
| DP        | Dry particles                 | 0                                                 |
| DPr       | Dry particles                 | 0.1                                               |
| BF        | Bingham fluid                | N.A.                                              |

Table 2. Model parameters adopted for the coupled simulation.

| Bingham fluid | Density                | 1700 kg/m$^3$ |
|               | Yield stress           | 4.55 Pa       |
|               | Viscosity              | 0.0088 Pa.s   |
| Particle      | Numbers                | 2787          |
|               | Diameter               | 0.04 m        |
|               | Density                | 2500 kg/m$^3$ |
|               | Young’s modulus        | 70 GPa (particle-particle contact)                |
|               |                       | 700 GPa (particle-wall contact)                  |
|               | Poisson’s ratio        | 0.3          |
|               | Restitution coefficient | 0.7          |
|               | Interparticle friction coefficient | 0.7 |
| Water        | Density                | 1000 kg/m$^3$ |
| Air          | Density                | 1 kg/m$^3$    |
|              | Viscosity              | 0.001 Pa.s    |
|              | Viscosity              | 1.48x10$^{-3}$ Pa.s |
| Simulation control | Time step (CFD) | 5x10$^{-5}$ s |
|              | Time step (DEM)        | 5x10$^{-7}$ s |
|              | Simulated real time    | 10 s         |

as summarized in Table 1, abbreviated respectively as BP, BPr, WP, WPr, DP, DPr and BF, are considered in the study. The parameter selection of the Bingham fluid and the particles is according to Paterson (2004) and Shan and Zhao (2014) which are summarized in Table 2.

3.2 Flow patterns

The dam break processes for all cases are compared in Fig. 2. In each figure, the upper panel shows the evolution of velocity field of the particles, while the lower panel depicts configuration of the whole sample. The influence of different factors on the behaviour of dam break are summarized as below.

(1) Fluid property

In the cases of WP and WPr, water is used to simulate the fluid, and Cases BP and BPr treat the fluid as the Bingham fluid, a special Herschel Bulkley fluid model, whose viscosity is roughly 10 times that of water. While the early collapse process of the dam break does not seem to be affected by the different fluids significantly, the influence of fluid emerges in its later development, especially to the particle system.

Taking the cases of BP and WP as a comparison. The mobilized zone of the particle system (shown in red in the contour) appears to be smaller in BP case than in WP when $t<0.5$s. But with time going on, more particles in the initially stationary corner zone are mobilized in BP, while the bottom particles of the initially moving zone in WP start to lose mobility (see time instants between 0.5 and 3.0s). The influence of fluid property is evident. As the start of the collapse, the more viscous Bingham fluid in the BP case will hold the particles to collapse than the less viscous water, which explains the more rapidly developed mobilized zone in WP than in BP. However, when later the Bingham fluid develops a relatively high velocity, its interaction with the particles tends to be more intense and far reached, and causes the mobilization of more bottom particles in BP case. In this process, the overall fluid velocity in Case WP is indeed higher than in Case BP. The Bingham fluid appears to flow consistently with the particles in terms of flow configuration in BP, while the water in the WP case apparently develops a much faster profile change than the particle system.

Also observed is the slope of the final deposition of particles in the BP case appreciably flatter than that in the WP case, due to the stronger interaction of fluid and particle system in the Bingham fluid case than in the water case. The comparison case of dry particle (Case DP) leads to a slightly greater slope angle than the above two cases.

(2) Particles rolling resistance

We also consider cases where the rolling friction coefficient $\mu_r$ is set to be non-zero to account for the effect of non-spherical particles (see Zhao and Shan, 2013b for details of the rolling resistance model), shown as cases BPr, WPr and DPr in Fig. 2.
Fig. 2. Velocity field of the particles and fluid during the dam breaking process for different cases. In subfigure, the top panel shows the velocity of the particle system, while the bottom displays a superposition of the mixture (gray for particles and other for the fluid).

with their respective free-rolling case ($\mu_r = 0$), the rolling resistance evidently inhibits the movement of many particles, leading to relatively larger low-moving and stationary zone during the collapse process. Its influence may well overrule the influence of fluid property, which results in a similar slope of the final deposition in the cases of BPr and WPr. In both BPr and WPr cases, there are a small number of particles being carried over the obstacle, while no particles have chance to climb over the obstacle in the Case of DPr.

Also notably, among the three cases, the final deposition of the particle system in the BPr case is more porous, WPr case in the middle and the pure dry particle case DPr is denser. The interactions imposed by the pore fluid are apparently attributable to the observed difference.

(3) Presence of fluid and particles

For the dry cases (DP and DPr) and the pure fluid case (BF), the flow patterns differ considerably. Comparison of the DP and DPr cases with their
respective case of the mixture has been made. The flow pattern in the pure fluid case BF is apparently more dramatic than in the cases where particles are present wherein the interaction imposed by the particle system in the later cases drags down the flow of the fluid.

3.3 Particle-particle contacts during the dam break

Fig. 3. The evolution of mean normal contact force in the dam break for three free-rolling cases.

Fig. 4. The evolution of kinetic energy of the particle system in dam break for three free-rolling cases.

Fig. 5. Force chain network of particles at 10.0 s in BP, WP and DP cases.

Bingham fluid imposes the strongest interaction with the particle system, which leads to a relatively weaker contact force network than the other two cases. Evidently, the final repose angle of the deposition may also play a role in the force chain network. Nevertheless Fig. 5 at least depicts that the sand pile is greatly affected by its formation process wherein many interesting physical phenomena, such as pressure drop, are focal topics in the community of granular physics.

4 CONCLUSIONS

A CFD-DEM coupled method has been applied to simulating the dam break process and investigating the flow patterns and particle-particle contact for various samples. The simulation results show that the conditions and properties of fluids and particles influence the flow patterns of the mixture as well as final deposition of the particles significantly.

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