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Dam-break of mixtures consisting of non-Newtonian liquids and granular particles

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ABSTRACT

This paper revisits the classical dam break problem based on coupled Computational Fluid Dynamics and Discrete Element Method (CFD-DEM) modeling and analysis. We consider the collapse of mixtures comprised of non-Newtonian liquids and particles, and compare them with cases of a particle-water mixture, a dry particle column and three pure liquids. In all cases, the fluid is simulated by the CFD, while the granular particles are modeled by the DEM. Interactions between the fluid and the particles are considered by exchanging interaction forces between the CFD and DEM computations. Both the macroscopic and microscopic characteristics of the particle system, the liquid and the mixture during the dam break are examined, with particular attention placed on the effect of solid-liquid interaction and the distinct flow behaviors considering non-Newtonian liquid in a mixture in comparison with water. The non-Newtonian liquids are found to conform with the particles well during the collapse process, in contrast to the separated profiles of water and particles. In comparison with pure liquid cases and dry particle case, the solid-liquid interactions are found to play a crucial role in affecting all aspects of the flow behavior of a mixture during its collapse, including the initiation of the collapse, the conformity of flow profile, the evolution of flow front and the energy change. The underpinning physical mechanisms are analyzed and correlated to the macro observations.

1. Introduction

Dam break refers to the collapse of an infinite or finite volume of fluid, particles or their mixture onto a horizontal or inclined channel. It represents a wide range of practical problems that are of great engineering importance [1]. The collapse of water-reserving dams or earth-filling tailings dams are among the most widely known examples. The failure of these dams may cause catastrophic damages to both human life and properties. For example, the overflow of reservoir water of Vajont dam in Italy caused by a landslide in 1963 killed 1910 people. More recently, the collapse of Situ Gintung water dam in Tangerang of Indonesia in 2009 claimed nearly 100 lives. Several recent devastating failures of mine/waste tailings dams have drawn global attentions on their threat to the environment and human life. One example is the collapse of Bento Rodrigues tailings dam occurring in Mariana, Brazil, on Nov. 5, 2015. The collapsed slurry wave flooded the town of Bento Rodrigues, killed at least 17 people and polluted several nearby rivers and over 15 km^2 of land [2]. A tailings dam of jade mine collapsed in northern Myanmar on Nov. 21, 2015 killed at least 113 people. Indeed, there have been over 40 similar major failures of tailings dams reported around the world since 2000 [3].

The scientific value of dam break has long been recognized, as an idealized problem for benchmark and verification for a range of theories and approaches in both mathematics and physics [4]. In as early as 1892, Ritter [5] has derived a theoretical solution for the flow front of water based on a simple dam break model. Late analytical studies have examined various aspects of dam break, including the effect of flow resistance [6, 7, 8, 9]. The majority of past studies on dam break considered the collapse of either pure fluids or dry particles, with only quite a few on particle-water mixtures [10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20]. The focus of the present study is placed on the collapsing of a mixture composed by granular particles and non-Newtonian fluids, in reference to engineering problems relevant to tailings dams or environmental flows such as volcanic lava, slurry and mud flows wherein the fluid involved is typically non-Newtonian [21]. Dam break of pure non-Newtonian fluids such as slurry and gel has been studied in [13, 14]. Other examples involving non-Newtonian fluids include the slump tests [22, 23, 24] on fresh concrete in civil engineering and Bostwick tests [25, 26, 27] for salad dressings in food industry. Consideration of non-Newtonian fluids indeed enables better explorations of more complex natural flows such as slurry than considering Newtonian fluids like water only.

Conventional continuum-based studies on dam break have commonly considered a particle-fluid mixture as an equivalent fluid or two fluids [28]. They have largely neglected the intricate interactions

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between the fluid and the particle phases which could affect significantly the collapse behavior of the mixture. In this study, a coupled CFD-DEM approach [29, 30, 31, 32, 35, 36, 37] is employed to investigate the collapse of a mixture consisting of fluid and particles, where we will demonstrate that fluid-particle interactions within the mixture can be well captured. The CFD and DEM are used to model the fluid and particle phases in the mixture, respectively. The interactions between the fluid and particles are considered by exchanging fluid-particle interaction forces between the CFD and DEM computations. The coupled CFD-DEM simulations can capture both micro and macro flow characteristics during dam break, which could offer new insights into the microstructural origins underpinning macroscopic collapse and flow of a mixture.

2. Methodology, formulation and model setup

To simulate the dam break of a particle-fluid mixture, we employ the CFD [38] to solve the locally averaged Navier-Stokes equation for the fluid phase, and use the DEM [39, 40] to solve the Newton's equations governing the granular particles. Two open source software packages, namely, the OpenFOAM [41] and the LIGGGHTS [42], are adopted for the CFD and the DEM modules, respectively. The coupling between the CFD and the DEM is considered by exchanging interaction forces including drag force, buoyant force and viscous force. The coupling is implemented by a modified interface program based on the CFDEM originally developed by Goniva et al. [29] and later extended by Zhao and Shan [30]. Detailed solution procedures can be found in [30].

2.1. Governing equations for the particles and the fluid

The DEM [43] is employed to model the particle system in the mixture and to solve the following Newton's equations governing the translational and rotational motions of a particle i in the particle system

$$\begin{cases} m_i \dfrac{d\boldsymbol{U}_i^p}{dt} = \sum\limits_{j=1}^{n_i^c} \boldsymbol{F}_{ij}^c + \boldsymbol{F}_i^f + \boldsymbol{F}_i^g \\ I_i \dfrac{d\omega_i}{dt} = \sum\limits_{j=1}^{n_i^c} (\boldsymbol{M}_{t,ij} + \boldsymbol{M}_{r,ij}) \end{cases} \tag{1}$$

where m_i and I_i are the mass and moment of inertia of particle i, respectively. $\boldsymbol{U}_i^p$ and ω_i denote the translational and angular velocities of particle i, respectively. n_i^c is the number of total contacts for particle i. $\boldsymbol{F}_{ij}^c$ is the contact force acting on particle i by particle j or walls. $\boldsymbol{F}_i^f$ are the particle-fluid interaction forces acting on the particle. $\boldsymbol{F}_i^g$ is the gravitational force of particle i. $\boldsymbol{M}_{t,ij}$ and $\boldsymbol{M}_{r,ij}$ are the torques acting on particle i by the tangential force and the rolling friction force [44], respectively. The contact force $\boldsymbol{F}_{ij}^c$ is calculated as follows based on Hertzian-Mindlin contact law as illustrated in Fig. 1:

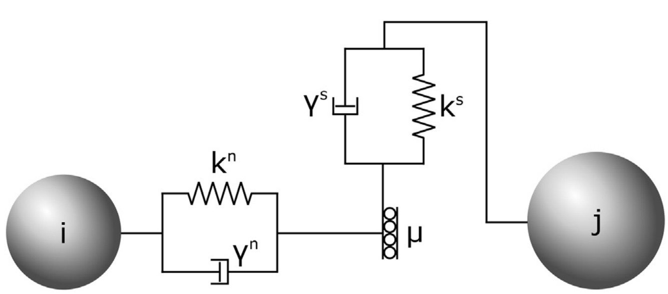

Fig. 1. Illustration of the Hertzian-Mindlin contact law used in the DEM simulation and the model parameters adopted (the normal and tangential stiffness: k^n and k^s; the damping coefficients for normal and tangential contacts: γ_n and γ_s; friction coefficient μ).

$$\boldsymbol{F}_{ij}^c = \left(k^n \delta_{ij}^{\boldsymbol{n}} - \gamma^n v_{ij}^{\boldsymbol{n}}\right) + \left[\left(\boldsymbol{F}_{spring}^{s0} + k^s \Delta\delta_{ij}^{\boldsymbol{t}}\right) - \gamma^s v_{ij}^{\boldsymbol{t}}\right] \tag{2}$$

where the terms on the right hand side refer to the normal spring force, the normal damping force, the shear spring force and the shear damping force, respectively. The total tangential force is the sum of shear spring force and shear damping force, denoted by the term in the square bracket. It increases until the shear spring force $\mathbf{F}_{spring}^s$ (i.e., $\boldsymbol{F}_{spring}^{s0} + k^s\Delta\delta_{ij}^{\boldsymbol{t}}$) reaches $\mu \boldsymbol{F}^n$, where μ is the friction coefficient and $\boldsymbol{F}^n$ is the total normal force in the first parenthesis. The tangential spring force is then held at $\boldsymbol{F}_{spring}^s = \mu \boldsymbol{F}^n$ during frictional sliding until the particles lose contact. $\boldsymbol{F}_{spring}^{s0}$ is the initial tangential spring force at the previous time step. k^n and k^s are the normal and tangential stiffnesses, respectively. $\delta_{ij}^{\boldsymbol{n}}$ is the overlap distance in the normal direction and $\Delta\delta_{ij}^{\boldsymbol{t}}$ is the incremental tangential displacement. γ^n and γ^s are the damping coefficients in the normal and tangential directions of the contact, respectively. $v_{ij}^{\boldsymbol{n}}$ and $v_{ij}^{\boldsymbol{t}}$ are the normal and tangential components of the relative velocity of the overlapped two particles.

The fluid phase in the mixture is considered to be continuous and is simulated with a discretized fluid domain in the CFD. The following continuity equation and the locally averaged Navier-Stokes equation are solved for each of the fluid cells

$$\begin{cases} \dfrac{\partial\left(\varepsilon_f \rho_f\right)}{\partial t} + \nabla \cdot \left(\varepsilon_f \rho_f \boldsymbol{U}^f\right) = 0 \\ \dfrac{\partial\left(\varepsilon_f \rho_f \boldsymbol{U}^f\right)}{\partial t} + \nabla \cdot \left(\varepsilon_f \rho_f \boldsymbol{U}^f \boldsymbol{U}^f\right) = -\nabla p - \boldsymbol{f}^p + \varepsilon_f \nabla \cdot \boldsymbol{\tau} + \varepsilon_f \rho_f \boldsymbol{g} \end{cases} \tag{3}$$

where ε_f denotes the void fraction (porosity). ρ_f is the averaged fluid density. $\boldsymbol{U}^f$ is the average velocity of the fluid in a CFD cell. p is the fluid pressure in the cell.$\boldsymbol{f}^p$ is the volumetric interaction force acting on the fluid by the particles within each cell. $\boldsymbol{\tau}$ is the viscous stress tensor. The fluid properties are assumed constant within each fluid cell.

We consider both Newtonian and non-Newtonian fluids in this study. The following constitutive equation is assumed to govern an incompressible, isothermal Newtonian fluid

$$\tau = \mu_f \dot{\gamma} \tag{4}$$

where μ_f is the fluid viscosity and $\dot{\gamma}$ is the shear rate. The Herschel-Bulkley model is considered for a non-Newtonian fluid [45, 46] as follows

$$\tau = \tau_c + \kappa \dot{\gamma}^n \tag{5}$$

where τ_c is the yield stress of fluid, κ is the consistency index and n is the flow index. The following constitutive equation is considered for a Bingham fluid

$$\tau = \tau_c + \mu_f \dot{\gamma} \tag{6}$$

It is evident that the Herschel-Bulkley model in Eq. (5) can recover a Bingham fluid in Eq. (6) when the flow index n is set to 1.

2.2. Fluid-particle interactions

The coupling between the particles and the fluid is considered through the exchange of interaction forces $\boldsymbol{F}_i^f$ in Eq. (1) and $\boldsymbol{f}^p$ in Eq. (3) between the DEM and CFD computations. The interaction force acting on a considered particle i from the fluid $\boldsymbol{F}_i^f$ is calculated by

$$\boldsymbol{F}_i^f = \boldsymbol{F}^b + \boldsymbol{F}^d + \boldsymbol{F}^v \tag{7}$$