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An integrated particle model for fluid–particle–structure interaction problems with free-surface flow and structural failure

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ABSTRACT

Discrete Element Method (DEM) and Smoothed Particles Hydrodynamics (SPH) are integrated to investigate the macroscopic dynamics of fluid–particle–structure interaction (FPSI) problems. With SPH the fluid phase is represented by a set of particle elements moving in accordance with the Navier–Stokes equations. The solid phase consists of physical particle(s) and deformable solid structure(s) which are represented by DEM using a linear contact model and a linear parallel contact model to account for the interaction between particle elements, respectively. To couple the fluid phase and solid particles, a local volume fraction and a weighted average algorithm are proposed to reformulate the governing equations and the interaction forces. The structure is coupled with the fluid phase by incorporating the structure's particle elements in SPH algorithm. The interaction forces between the solid particles and the structure are computed using the linear contact model in DEM. The proposed model is capable of simulating simultaneously fluid–structure interaction (FSI), particle–particle interaction and fluid–particle interaction (FPI), with good agreement between complicated hybrid numerical methods and experimental results being achieved. Finally, a specific test is carried out to demonstrate the capability of the integrated particle model for simulating FPSI problems with the occurrence of structural failure.

1. Introduction

Fluid–particle–structure interaction problems have been frequently encountered in the flooding events with the collapse of infrastructures (*e.g.* buildings and bridges), where the particles could be soil, sediment and/or debris. Particularly, stone bridges which are one of the most common masonry bridges in the UK were widely built in the past due to the availability of stone and easy construction, and many of those historic and listed masonry bridges are still in service in the UK. Masonry bridges were built through the application of rock blocks with high compressive strength to transmit the loads to the ground. In fact, masonry bridges cannot resist a high amount of the shearing load in comparison with modern concrete bridges, therefore they are at risk of being damaged and even collapsed due to the occurrence of flooding, which imposes enormous impacts on local transportation, and it is costly to get them repaired/rebuilt. Preventing or mitigating such unexpected accidents could be attained through proactive reinforcing or strengthening techniques which are preferred in order to make the bridges more resistant to scouring and buoyancy effects caused by flooding. To address this challenging

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Mathematical notation for subscripts

f	Fluid–particle element
p	Solid particle element
s	Structure particle element
max	Maximum value of parameter
i	Particle element i
j	Particle element j
$bend$	Bending value of parameter
$twist$	Twist value of parameter
ext	External value of parameter

Mathematical notation for superscripts

c	Direct contact force between solid particles
l	Lubrication force
d	Drag force
b	Buoyancy force
ps	Interaction between solid particle and structure particle
fs	Interaction between fluid–particle and structure particle
pf	Interaction between solid particle and fluid–particle
$normal$	Normal component of parameter
$shear$	Shear component of parameter
$dash$	Dashpot in linear contact model
$crit$	Critical value of parameter

problem, a combination of interdisciplinary knowledge of geotechnical, hydraulic and structural engineering are required to better understand the complicated interaction mechanism among bridges, flood water and soil/sediment/debris. This also raises a demand for a robust and reliable computer model to fulfil the requirement of large-scale simulation in order to predict the simultaneous interaction between soil/sediment/debris, flood and bridges/buildings. Up to now, there are various computational or numerical models for fluid–structure interaction (FSI) (De Hart et al., 2003; Souli et al., 2000; Wall et al., 2006) or fluid–particle interaction (FPI) (Génevaux et al., 0000; Adeniji-Fashola and Chen, 1990; Sarkar et al., 2009), and they have been extensively studied in terms of problem scales and numerical methods. However, to the authors' best knowledge, computational models that are capable of handling the simultaneous interaction between fluids, particles and structures are rarely reported.

One of the challenging issues involved in FPSI problems is the contact detection and subsequent collision and separation between two particles or between a particle and a structure/boundary. It becomes even more complicated when a fracture of the structure is allowed to create new surfaces which may interact with the particles and fluids. Therefore an explicit *Lagrangian* method to capture the movement of individual particles is required. Although both *Eulerian* and *Lagrangian* methods have been well developed for fluid flow and structural analysis, but to integrate particles with fluid and structure a single *Lagrangian* computational framework would usually be preferred.

When simulating a discontinuous system of particles, discrete element method (DEM) is usually considered due to its simplicity and capability of handling the contact and interaction between particles. The interaction forces at the contacts are governed by a force–displacement law driven and used to determine the movement of each individual particle according to the Newton's Second Law. In addition, DEM can model the deformation (and failure) of a structure by simply adding a bond at the contact between a pair of particles to represent the material properties (elasticity and strength) of a structure. Comprehensive applications of DEM have been reported in modelling mixing processes of particles (Ketterhagen et al., 2009; Rhodes et al., 2001) and fracture of various engineering materials and structures such as rock (Zhuang et al., 2012), ceramics (Tan et al., 2009), concrete (Cundall and Strack, 1979) and composites (Yang et al., 2010), etc.

For the *Lagrangian* simulations of fluid flow, there are two widely-used mesh-free methods, *e.g.* Smoothed Particles Hydrodynamics (SPH) (Monaghan, 1994) and Moving Particle Simulation (MPS) (Koshizuka and Oka, 1996). In these two methods, Navier–Stokes equations, which are partial differential equations (PDEs), are transformed into ordinary differential equations (ODEs) through kernel approximation and particle approximation respectively, and the fluid domain is consequently dissolved into discrete particles with certain particle spacing. Both SPH and MPS provide approximations for partial differential equations (*e.g.* Navier–Stokes equations), but a weighted averaging process applied in MPS is different from taking the gradient of the kernel function in SPH. It should be noted that another meshfree but *Eulerian* method, Lattice Boltzmann method (LBM) (Chen and Doolen, 1998) solves Newtonian fluid flow with collision and separation models on a fixed space grid/lattice. As SPH and MPS methods are intended to approximate mathematical equations in the domain only by nodes without being connected by meshes, each discrete particles move continuously in accordance with surrounding particles, thus complex boundary flow and free surface flow can be easily accounted for. Due to this benefit, they have been