ARTICLE IN PRESS
JID: CAF [m5G;March 9, 2018;2:48]
Computers and Fluids 000 (2018) 1–8
Contents lists available at ScienceDirect
Computers and Fluids
journal homepage: www.elsevier.com/locate/compfluid

Parallel simulations for a 2D x/z two-phase flow fluid-solid particle model

M. Uh Zapata [a,*], D. Pham Van Bang [b], K.D. Nguyen [b]

[a] CONACYT – Centro de Investigación en Matemáticas A. C., CIMAT Unidad Mérida, Sierra Papacal, CP, Mérida, Yucatán 97302, Mexico
[b] Laboratory for Hydraulics Saint Venant, Université Paris-Est, ENPC-EDF-CEREMA, Chatou 78400, France

ARTICLE INFO

Article history:
Received 23 January 2017
Revised 7 February 2018
Accepted 1 March 2018
Available online xxx

Keywords:
Two-phase flow
Sediment erosion
Domain decomposition
MPI
SOR
Bi-CGSTAB

ABSTRACT

The importance of the two-phase flow model relies upon the correct simulation of specific problems in which the passive tracer model fails; however, the mathematical and numerical models need to be improved in order to reproduce fluid-solid particle interactions of greater complexity. Such is the case with regard to simulating erosion patterns suffered upon horizontal granular beds by means of a vertical water jet as shown here. Moreover, sequential platforms have proven to be insufficient in providing the required computational power needed to obtain fast and detailed simulations. In this paper, a fully parallel algorithm for a two-dimensional x/z two-phase Eulerian approach is presented and applied for the numerical solution of the erosion of sediment beds. The parallelization is designed by a row and column block domain decomposition technique using a distributed memory platform with Message Passing Interface (MPI). Arising from the numerical method, a Poisson problem for the pressure is solved at each time step. The discretization results in a non-symmetric variable-coefficient linear system which is solved using several parallel Successive Over-Relaxation (SOR) algorithms, including partitioning and coloring methods. The specification of the optimal relaxation parameter to achieve efficiency is found numerically. Results show that SOR methods achieve faster convergence rates and the simulation time achieves an order similar to that required for the typical, widely-used Bi-Conjugate Gradient Stabilized (Bi-CGSTAB) method. The performances of the algorithms are evaluated in terms of speedup and efficiency. The results indicate that the parallel code significantly improves the results of the sequential calculation in general.

1. Introduction

Many numerical studies regarding two-phase flow have been developed in recent years. However, there are very few existing two-phase models for sediment transport using the Eulerian-Eulerian formulation as presented in this paper. Some numerical examples considering this approach include dredged sediment releases and suspended-sediment transport [1,2]. In all of these problems, the ability to obtain fast and detailed simulations can help us to formulate faster predictions and to better describe how the physical phenomena takes shape. However, due to the amount of data generated, the resolution of the discretization, and large domain size, sequential platforms have proven to be insufficient in providing the required computational power. Thus, in previous works, numerical simulations only been reduced to cases with low resolution mesh sizes, confined domains or few seconds. Hence, parallelization of two-phase flow problems has become essential for this and further research.

On the other hand, the erosion of sediment beds by a vertical water jet has been studied for possible application in industrial settings. In hydraulic engineering, it has been proposed for assessing the erodibility of soil material [3] and for water injection dredging in harbors [4]. However, few numerical studies have been developed for this problem. Most methods use a CFD software package to compute the fluid motion only above the sediment bed, meanwhile the sediment bed is considered as an impermeable wall [5,6]. Other models are based on two-phase approaches in which the Eulerian and Lagrangian model are used for the fluid and solid phase, respectively [7]. This approach allows for a microscopic description of the solid particle motion; however, it is limited by the number of solid particles. Finally, in the Eulerian-Eulerian two-phase model, the computing domain is extended to the true non-erodible bed. In the governing equations, the continuity and motion equations are solved for both fluid and solid phases, with interaction terms between them. The main physical processes, such as fluid-solid particles, particle-particle interactions,

* Corresponding author.
E-mail address: angeluh@cimat.mx (M. Uh Zapata).

https://doi.org/10.1016/j.compfluid.2018.03.019
0045-7930/© 2018 Elsevier Ltd. All rights reserved.

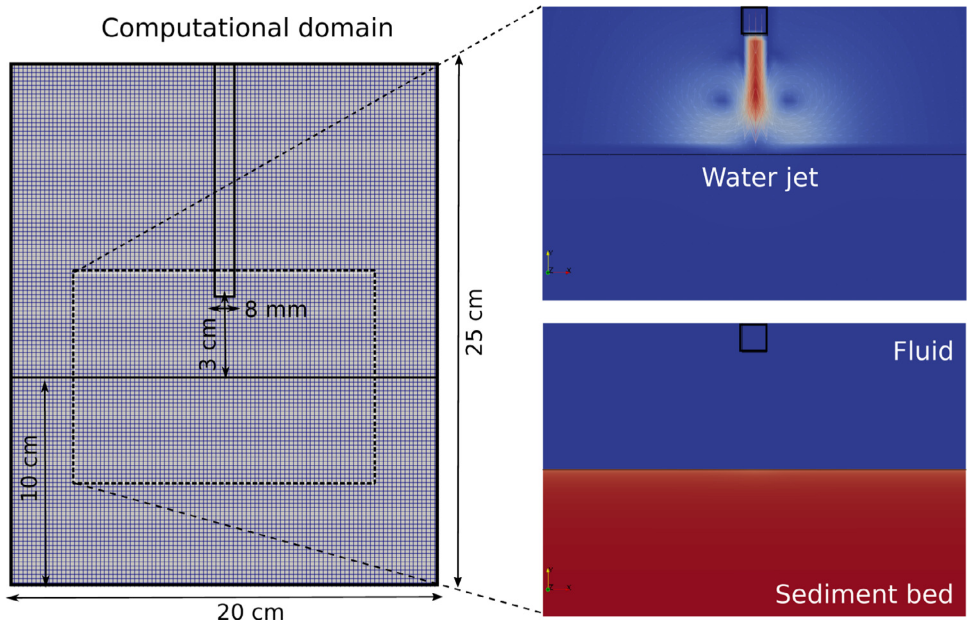

Fig. 1. Schematic representation for the simulation of the erosion of sediment beds by a vertical water jet.

particle-wall collisions and fluid-bottom exchanges, are integrated into the equations of motion and treated as momentum exchanges between phases. To the best of the authors' knowledge, only the work developed by Qian et al. [8] has implemented an Eulerian-Eulerian model; however, the simulations present an unrealistic liquid-like motion of the solid particles of the sediment bed.

In this paper, the numerical approach is based on a second-order finite volume method initially developed by Guillou et al. [9] and extended for the jet erosion problem for which the schematic representation is described in Fig. 1. The algorithm applies a projection method to decouple the pressure and velocity obtaining an additional Poisson equation to solve the fluid pressure.

The full code is parallelized with MPI. The parallelization consists of an overlapping domain decomposition technique for the fully two-phase flow equations. In this method, the computational domain is decomposed in several sub-domains and the data is spread to the distributed memory. The disadvantage of this formulation is the deterioration of the parallel performance with an increase in the amount of the data communication across the processors. Consequently, for good performance, the communication frequency between processors is limited to smaller values and the topology of the sub-domains is as simple as possible.

Moreover, the solution of linear systems should be performed efficiently because of the high expenses required for their calculation. Several iterative methods are widely used such as SOR, Bi-CGSTAB and Generalized Minimal Residual methods. In all cases the parallel algorithms are not easily implemented [10,11]. The proposed numerical algorithm makes use of the SOR method due to its robustness, efficiency and simplicity in implementation; however, the parallel version is also challenging. Several alternative and efficient parallel versions of the SOR method can be found in the literature [12–15]. One of the most widely-used methods is the multi-coloring SOR method [12]. In the case of a rigid-surface, the two-colors red/black SOR (r/b SOR) method is only required for the two-phase flow problem. Another efficient parallel SOR method proposed by Xie et al. [14], improves the convergence rate with a novel use of inter-processor data communication by domain partitioning and is referred to as the PSOR method.

The purpose of this paper is therefore to present an efficient parallel implementation based on block decomposition, MPI and SOR parallel methods which can be applied to different two-phase flow models with high resolution meshes, large domain sizes and extended simulations. This new version of the code is utilized in the initial analyses of the two-phase flow model for the erosion of sediment beds by means of a vertical water jet. The remainder of this paper is organized as follows: Sections 2 and 3 briefly present the mathematical and numerical background of the model, respectively. In Section 4, the block domain decomposition technique is described, followed by the description of the parallel SOR methods. Numerical simulations which validate the current method and its parallelization are presented in Section 5. Finally, some conclusions are given in Section 6.

2. The two-phase flow mathematical model

The formulation of the two-phase flow Eulerian-Eulerian model is based on the averaged governing equations provided by Drew and Lahey [16]. For a constant width-integrated 2-D x/z two-phase flow model, the set of equations can be written as:

$$\frac{\partial(\alpha_k\rho_k)}{\partial t} + \nabla\cdot(\alpha_k\rho_k\mathbf{u}_k) = 0, \tag{1}$$

$$\frac{\partial(\alpha_k\rho_k\mathbf{u}_k)}{\partial t} + \nabla\cdot(\alpha_k\rho_k\mathbf{u}_k\otimes\mathbf{u}_k) = \nabla\cdot\left(\alpha_k\left(-p_k\bar{\bar{I}} + \bar{\bar{\tau}}_k + \bar{\bar{\tau}}_k^{Re}\right)\right) + \alpha_k\rho_k\mathbf{g} + \mathcal{M}_k, \tag{2}$$

where $k = f$ and $k = s$ stands for the fluid and the solid phase, respectively. The values α_k represent the volume fraction with $\alpha_f + \alpha_s = 1$, ρ_k is the density, $\mathbf{u}_k = (u_k, w_k)$ is the Reynolds average velocity vector, $\mathbf{g}$ is the gravity, and $\bar{\bar{I}}$ is the identity matrix. The stress of phase k is decomposed into an isotropic (or pressure, p_k) part and a deviatoric (or shear, $\bar{\bar{\tau}}_k$) counterpart. The last term, $\mathcal{M}_k$, in the right-hand side refers to the momentum transfer between phases. Notice that the classical Navier-Stokes equations are recovered for the fluid phase when $\alpha_s = 0$ or $\alpha_f = 1$.

In the original model, the shear stress of any phase k is the sum of a viscous and a turbulent stress $\bar{\bar{\tau}}_k^{Re}$. The former one is provided