Environmental Modelling & Software 97 (2017) 303–317

Contents lists available at ScienceDirect

Environmental Modelling & Software

journal homepage: www.elsevier.com/locate/envsoft

Three dimensional modeling of free surface flow and sediment transport with bed deformation using automatic mesh motion

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A R T I C L E I N F O

Article history:
Received 28 January 2017
Received in revised form
21 June 2017
Accepted 8 August 2017

Keywords:
3D numerical model
Free surface flow
Automatic mesh motion
River bends
Scour
Bridge piers
Mobile bed
openFOAM
Foam-extend

A B S T R A C T

This study presents the development of a 3D numerical code for flow-sediment interactions with associated bed changes in free surface flows. To capture the water-air interface, a novel volume of fluid (VOF) formulation is implemented using the ghost fluid method with one-side extrapolation for dynamic pressure. Equations for fluid flow and free surface motion are decoupled due to separation of time scales. Accordingly, time step size can be increased by a factor of 3-orders of magnitude and still preserve numerical stability and computational efficiency. A novel finite area method (FAM) is utilized to discretize Exner equation on irregular bed surface providing a 3D finite volume-like discretization on curved surfaces. The evolution of the water-sediment interface is captured by a novel vertex-based unstructured mesh dynamic motion solve using Laplace operator with variable diffusivity. The code is implemented in foam-extend and tested against two classical experiments. Good results are obtained with correct trends and lower absolute error compared to previous mobile bed models. This shows that the developed code has a good potential of being applied to mobile-bed hydraulic real problems.

Software availability

Software name: foam-extend-3.1 (Zagreb)
Developer: Original developer is OpenCFD Ltd. ESI Group and the OpenFOAM Foundation Ltd currently are permitted to use the name and domain name. The foam-extend release is the community edition of the open source CFD software OpenFOAM. It is a fork of the OpenFOAM open source CFD software and licensed under the General Public License, version 3
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Telephone: +44 (0) 20 3176 7190
Contact e-mail: h.jasak@wikki.co.uk
Year first available: 2004
Program language: C++/C#
Hardware required: Standard PC, Intel Xeon processor
Software required: Ubuntu 14.04 minimum
Availability: available free of charge
Website: http://wikki.gridcore.se/foam-extend

1. Introduction

The study of mobile-bed responses to flow and sediment interaction in channels is of significant importance to practical hydraulic engineering. There are two classes of relevant problems, one related to mobile-bed response at river bends and especially near training structures. These include wing dikes, spur dikes and V-notch weirs and are of importance to large-scale river geomorphic studies (e.g., Spasojevic and Holly, 1993; Diogo et al., 2016; Michele et al., 2016; Cyril et al., 2016 Mingfu and Qiuhua, 2017). The other important class is related to mobile-bed response around bridge piers and abutments, under pipelines, under marinas and around beach-protection structures. Flow interaction with sediment in these situations is strongly three-dimensional and characterized by strong secondary currents and vertical accelerations, which needs to be modeled by fully 3D numerical models with non-hydrostatic pressure assumptions.

Recently some attempts have been made to formulate a general

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http://dx.doi.org/10.1016/j.envsoft.2017.08.005
1364-8152/

3D model for sediment-flow interaction using the two-phase flow or drift flux models (e.g., Cao et al., 1995; Greimann et al., 1999). In this type of modeling, the governing conservation equations are formulated for flow and sediment phases separately. Interaction between two phases is accounted for using the stress tensor and the interfacial momentum transfer. However, there are many limitations that prohibit the application of this two-phase approach in practical hydraulic problems (Spasojevic and Holly, 1993), such as: limitations of computer resources for long term simulations; the requirements of additional modeling for many terms in the governing equations for system closures, such modeling requires unavailable experimental data; and finally the need for different treatment for many neglected terms that are deemed important in many practical applications including the turbulent fluid and sediment stress and the stress coming from sediment particle interactions.

Therefore, almost all 3D numerical flow and sediment models are developed based on simplifying sediment concepts, which classify sediment as suspended and bed loads and define a set of equation describing bed evolution. In scour problem, there are two main interfaces that need to be captured accurately for their significant impact on results. These are the water-air (free surface) interface and the water-sediment interface. For the free surface interface, 3D numerical codes can ignore the free surface variations and replace it by a rigid lid boundary. The level of this rigid lid is estimated using preliminary 1D or 2D model. It is applicable only to short reaches where water surface elevation exhibits gentle variations. Another approach is the surface tracking method, which uses an adaptive grid in the vertical direction to follow the free surface changes. The location of the free surface is calculated using free-surface kinematic condition. Casulli and Cheng (1992) and Wu et al. (2000) derived the 2D Poisson equation from the 2D depth averaged momentum equations and used it to obtain water level at each calculation step and move the adaptive grid for the free surface. The depth-averaged velocities and stresses in Poisson equation were calculated using depth-integrating the 3D results from the previous hydrodynamic simulation step. The final approach is the volume tracking methods that use fixed grids and determine the free surface through calculation of fluid volume at each cell, e.g., the marker and cell (MAC), the level set method (LSM), and the volume of fluid (VOF). The MAC method adopts a fixed grid, where location of fluid is determined by a set of marker particles. The evolution of the free surface is calculated by moving the markers with local interpolated flow velocity. However, it requires considerable computer memory and fails at regions of converging and diverging flows. To overcome these disadvantages, the VOF was proposed by Hirt and Nichols (1981). The VOF uses a continuous function, the volume of fraction, instead of the discrete marker particles to define the location of the free surface in an Eulerian approach. The VOF has been used by many researchers when modeling interaction of flow and sediment in free surface flows, e.g., Liu and Garcia (2008). They used a high resolution VOF method to track the free surface. This method treats the whole domain as the mixture of two fluids, where the volume of fraction of each fluid is used as weighting factor to determine mixture properties. However, the VOF method has serious drawback, where it cannot precisely capture the water surface at locations of sharp interfaces of volume fraction and special care is needed to recover free surface with importance of grid refinement (Wu, 2007).

On the other hand, the water-sediment interface poses more challenge in mobile bed models. The main reason is that it is, unlike the water-air interface, has a naturally irregular shape modified by river hydraulic structures such as dikes, weirs and bridge piers. Furthermore, the geomorphic evolution of this irregular shaped bed is uneven through the model domain with many extensive local rapid changes especially near river structures. The tracking of this irregular interface in 3D flow sediment models is mainly based on simplified grid adaptation methods that are applied only in the vertical direction, e.g., Olsen and Skoglund (1994). Most of the existing 3D models keep the vertical coordinate direction straight and vertical, to simplify the bed evolution issues through the adaptive grids (Spasojevic and Holly, 1993). And since many of the available models are based on structured grids, e.g., Spasojevic and Holly (1993), Olsen and Skoglund (1994), and Wu et al. (2000), the adaptive mesh motion with the fixation of the vertical coordinate direction is feasible but similar to manually moving each grid at each time step and thus not efficient (Liu and Garcia, 2008). Some researchers tried to provide alternatives, e.g., Spasojevic and Holly (1993) used a simple partial coordinate transformation, called the sigma-stretching. The sigma-stretching was applied for the vertical direction to allow for simple redistribution of fixed number of nodes along the depth at each time step. Others have tried to enhance the efficiency of adaptive motion by applying artificial numerical bed level smoothing through the employed Lax-Wendroff type discretization scheme (Wu et al., 2000). Grid movement becomes more complicated in unstructured grids and instabilities and/or grid invalidation is more likely to occur. Therefore, Liu and Garcia (2008) tried to solve this issue by using a simplified mesh motion based on Laplacian smoothing operator. Their simplified approach assumes sediment movement only in vertical direction and uses constant diffusivity operators with no cell decomposition where mesh movement is solved cell center. However, they stated that it is hard to implement the simplified mesh deformation in presence of interaction between moving objects and bed or for irregular boundary movement or for big amplitude bed movement.

On the other hand, the FV provides solution at cell centers and the motion would be required at the boundaries. It has been stated by Jasak and Tukovic (2007) that it would be impossible to construct an interpolation practice that stops the cell from flipping. In addition, due to the explicit nature of non-orthogonal correction, either the second-order accuracy of the boundedness needs to be sacrificed (Jasak and Gosman, 2000). Moreover, the mesh quality near the moving water-sediment interface is sacrificed by using a constant diffusivity. A distorted mesh and eventually a divergent numerical solution imply the need for a vertex-based automatic mesh approach to overcome these limitations in mobile bed simulations. While the flow, turbulence, and suspended sediment are solved in 3D domains, the bed load and Exner equation are solved on 2D bed grid. All available mobile-bed models construct two meshes, a 3D mesh for the flow field and a 2D one for the bed. The flow parameters are mapped from 3D mesh to 2D bed mesh to solve for Exner equation and calculate bed elevation change. Then, the new bed elevation is mapped back from the 2D bed mesh to the 3D fluid mesh. This mapping and re-mapping between the two meshes includes averaging and interpolation, which can lead loss of accuracy.

This paper aims at developing a new numerical model to simulate the 3D flow sediment interactions at free-surface river bends while overcoming many of the shortcomings in previous models regarding the importance aspects of air-water and water-sediment interface tracking. The developed numerical code has the following novel advantages:

- It is implemented in the open source FV software library foam-extend, which is a free computational fluid dynamics code unlike previous models that are either commercial or in-house and not available to research community
- It has the advantage of being linked to a wide range of turbulence closure models, which are readily available in foam-