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A New 3D Hydrostatic-Assumption Model for Turbidity Current Simulation

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ABSTRACT

3D hydrostatic-assumption (HA) models have been widely used in environmental flows where 3D effect is important but hydrostatic assumption is sufficiently valid. This is the case for most eco-hydraulic issues in reservoirs. This study reports the research and development of a new 3D HA model named SRH-3D suitable for turbidity current simulation in reservoirs. SRH-3D adopts a new mesh type and new numerical algorithms. In the paper, a brief review is provided with regard to the existing 3D HA models along with shortcomings. The governing equations and the new numerical methods are then presented for turbidity current simulation. Selected test cases are reported to show the capability of the new model.

KEY WORDS: Turbidity Current; 3D Model; Hydrostatic Assumption; Reservoir Sedimentation

INTRODUCTION

There are many instances where one-dimensional (1D) and two-dimensional (2D) depth-averaged models are insufficient for environmental modeling. One such example is turbidity currents in reservoirs. A 2D layer-averaged model has been developed by Lai et al. (2015) for reservoir turbidity current modeling; but limitations have been found when sediment sluicing needs to be modelled. The need for three-dimensionality led to the development of three-dimensional (3D) environmental fluid dynamic (EFD) models. In theory, non-hydrostatic 3D EFD models are the most general and accurate, subject mainly to the accuracy of turbulence and relevant physical models. However, these EFD models are yet to be practical for large scale environmental flows due to prohibitive requirements of computing power or difficulties in using the models. A good alternative is to evoke the hydrostatic assumption, leading to the development of 3D hydrostatic-assumption (HA) models. These models are much easier to use, fast in simulation turn around, and have the potential for most practical applications.

This study reports the research and development of a new 3D HA model, named SRH-3D. The new model aims to achieve the following objectives: (a) to develop a 3D HA model suitable for field simulation of turbidity currents in reservoirs on a desktop PC; and (b) to design numerical methods that may overcome some shortcomings of the existing 3D HA models.

A BRIEF REVIEW

Many 3D HA models have been developed for lake, reservoir and oceanic and costal simulation. Examples include ECOMSED, RMA10, GBTOXe, EFDC3D, ROMS, CH3D-SED, and Delft3D, among others. Readers may refer to the review by Papanicolaou et al. (2008). Following models have been reviewed with more details in the present study: POM and ECOMSED (Blumberg and Mellor 1983; 1987); Delft3D-Flow (Roelvink and van Banning 1994; Lesser 2000); EFDC3D (Hamrick, 1992); and CH3D-WES (Johnson et al., 1993; Spasojevic and Holly, 1994; Gessler et al., 1999). It is found that most 3D HA models adopt curvilinear structured mesh horizontally and either sigma-grid or Z-grid vertically. For example, Delft3D-Flow uses an orthogonal quadrilateral mesh horizontally and sigma-grid or Z-grid vertically.

The mesh system used by existing models is one of the weaknesses. Structured horizontal mesh is not easy to generate and often inefficient for representing complex terrains and bathymetry. Vertical mesh method has its own pitfalls. The sigma-grid transforms the governing equations from physical space to computational space. It has the benefit of fixed free surface and bed elevation representation; however, it encountered many problems. For example, it might not have the adequate resolution around a density interface causing significant errors in the modeling of horizontal density gradients in areas with steep bottom topography (Leendertse, 1990; Stelling and van Kester, 1994). The Z-grid was developed to overcome the problems of the sigma-grid and to simulate the weakly forced stratified water systems. The Z-grid uses the physical-coordinates that avoided equation transformation. The vertical point distribution, however, is not arbitrary and its co-ordinate lines are horizontal. Different number of vertical points is used in different areas and grid lines are nearly parallel with density interfaces. However, the Z-grid is not boundary-fitted in the vertical direction so bed is represented using staircase approximation. The zig-zag representation was found to lead to high inaccuracies in computing bed shear stress and horizontal advection near beds (Bijvelds 2001; Cornelissen 2004).

In this study, a new mesh system is proposed: an unstructured and physical-coordinate (UPC) mesh. A UPC mesh adopts unstructured arbitrarily shaped cells in the horizontal plane and an equal number of physical-coordinate mesh points in the vertical direction. Key differences of the UPC mesh from the traditional sigma-mesh include: