Continental Shelf Research 146 (2017) 13–27

Contents lists available at ScienceDirect

Continental Shelf Research

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

Development of a finite volume two-dimensional model and its application in a bay with two inlets: Mobile Bay, Alabama

Jun Lee[a], Jungwoo Lee[b,*], Sang-Leen Yun[b], Hye-Cheol Oh[b]

[a] Korea Coastal and Ocean Modeling Solutions, South Korea
[b] Korea Institute of Civil Engineering and Building Technology, South Korea

ARTICLE INFO

Keywords:
Finite Volume Method (FVM)
Unstructured grid
2D shallow water equation
Osher-Solomon scheme
Dam-break problem
Mobile Bay, Exchange flow

ABSTRACT

The purpose of this study was to develop a two-dimensional shallow water flow model using the finite volume method on a combined unstructured triangular and quadrilateral grid system to simulate coastal, estuarine and river flows. The intercell numerical fluxes were calculated using the classical Osher-Solomon's approximate Riemann solver for the governing conservation laws to be able to handle wetting and drying processes and to capture a tidal bore like phenomenon. The developed model was validated with several benchmark test problems including the two-dimensional dam-break problem. The model results were well agreed with results of other models and experimental results in literature. The unstructured triangular and quadrilateral combined grid system was successfully implemented in the model, thus the developed model would be more flexible when applying in an estuarine system, which includes narrow channels. Then, the model was tested in Mobile Bay, Alabama, USA. The developed model reproduced water surface elevation well as having overall Predictive Skill of 0.98. We found that the primary inlet, Main Pass, only covered 35% of the fresh water exchange while it covered 89% of the total water exchange between the ocean and Mobile Bay. There were also discharge phase difference between MP and the secondary inlet, Pass aux Herons, and this phase difference in flows would act as a critical role in substances' exchange between the eastern Mississippi Sound and the northern Gulf of Mexico through Main Pass and Pass aux Herons in Mobile Bay.

1. Introduction

Ocean circulation models with the structured grid system have been dominant in last few decades since it is easy to construct the computational grid system and the matrix of the algebraic equation system has a regular structure. However, this grid system has shortcomings for applications where physical boundaries are complex and thus may require excessively fine grids in order to resolve complex boundaries in the model (Casulli and Walters, 2000). For this reason, unstructured grid ocean circulation models, which are more flexible than structured grids to fit complex boundaries (Shi et al., 2001), have been rapidly taking over structured grid models.

Another main feature which many ocean circulation models have is the Finite Difference Method (FDM). The FDMs are intuitive and easy to implement for simple problems and require less computational effort than the Finite Element Method (FEM) and the Finite Volume Method (FVM). The FDMs, however, are not suitable for the unstructured grid system which mentioned above. Recently, FVM for two-dimensional shallow water equations (SWEs) has been received considerable attention in the numerical computation of fluid dynamics since FVM takes the merits of both FDM and FEM. In some sense, FVM can be considered as FDM applied to the differential conservative form of the conservation laws, written in arbitrary coordinate systems. Hence, FVM can be applied using any structured grids in FDM or unstructured grids in FEM, and generally, FVM needs less computational efforts than FEM (Caleffi et al., 2003; Ng et al., 2006).

The finite volume method is based on the integral form of the conservation equation; therefore, the method can ensure that the basic quantities, such as mass and momentum, remain conserved (Wang and Liu, 2002; Jenny et al., 2003; Chen et al., 2007). Furthermore, the scheme in the conservation form can be constructed to capture shock waves (Zhao et al., 1994; Caleffi et al., 2003; Hirsch, 2007). Because of these advantages of FVM over FDM or FEM, many two-dimensional ocean or riverine circulation models have adapted FVM (e.g., Zhao et al., 1994, 1996; Anastasiou and Chan, 1997; Chippada et al., 1998; Valiani et al., 2002; Skoula et al., 2006; Wu et al., 2014). Even though these models have been developed based on FVM, grid systems and equation solving schemes in these models are different one another.

* Corresponding author.
E-mail addresses: jlee0917@nate.com (J. Lee), jungwoo33@kict.re.kr (J. Lee).

http://dx.doi.org/10.1016/j.csr.2017.08.002
Received 27 November 2016; Received in revised form 30 June 2017; Accepted 4 August 2017
Available online 10 August 2017
0278-4343/

Some models use unstructured triangular meshes only (e.g., Anastasiou and Chan, 1997; Chippada et al., 1998; Skoula et al., 2006; Wu et al., 2014), unstructured quadrilateral meshes only (e.g., Valiani et al., 2002), or combination of either triangular cells or quadrilateral cells (e.g., Zhao et al., 1994, 1996).

Nowadays some dams in South Korea are faced with an unexpected collapse, and one of those dams is located close to an estuary where directly connected to the open sea. Thus, it is required to simulate dam-break scenarios to reduce the impact of a sudden catastrophic dam break. For this reason, we developed a two-dimensional finite volume unstructured grid model in which the well-known Osher-Solomon scheme, which is robust, smooth, and has good ability to solve a tidal bore like system (Zoppou and Roberts, 2003; Castro et al., 2016), is implemented. The model we developed and introduced in this paper is named as a two-dimensional Riverine and Estuarine circulation Model (REM2D), and the term REM2D will be used throughout this paper. We constructed REM2D to be able to use both triangular, which is good for complex geometries, and quadrilateral cells, which is good for a straight narrow channel-like system, to have advantages of both grid systems.

Furthermore, we used the bottom elevation referenced coordinate rather than using mean sea level (MSL) referenced coordinate. Many ocean models, such as the Unstructured Grid Finite Volume Community Ocean Model (FVCOM) and the Regional Ocean Modeling System (ROMS), use their origin at the MSL. These models just require water depth to describe bathymetry, but the information is not sufficient when simulating an estuary connected to a river which is located above the MSL. For this reason, to simulate river flow in such system, a model should use a coordinate system which origin is below the bottom to represent the gravity flow correctly, and the system is what we used in our model (Fig. 1).

First, we tested REM2D comparing with existing dam-break analytical solutions and results of other models for the model verification to show the capability of REM2D for simulation of dam-break problems. Then, we applied REM2D in the Mobile Bay system in Alabama, USA, which has a complex geometry and large river discharge, to validate REM2D in real scale along with classical dam-break tests; unfortunately, there were not enough data to validate REM2D in the provisional target area in South Korea, and that is why we chose Mobile Bay. After validating REM2D we mainly focused on the discharge interaction between two inlets of the Mobile Bay, Main Pass (MP) and Pass-aux-Herons (PaH).

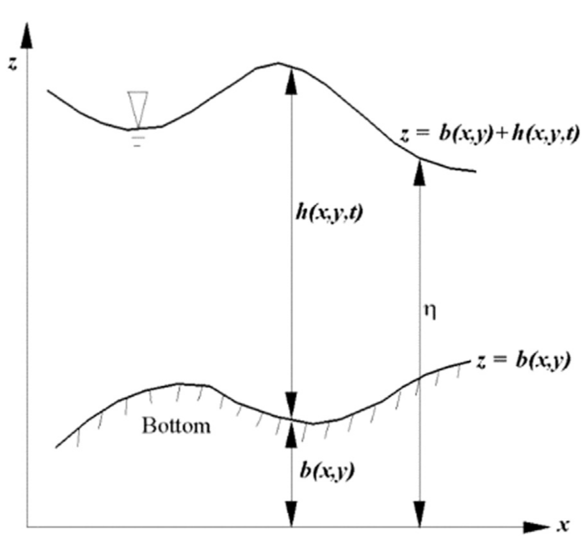

Fig. 1. Schematic diagram of the coordinate system used in the model.

2. Model development

2.1. Governing equations

The two-dimensional (2D) shallow water equations (SWEs) can be traditionally written in a single differential conservative law form with source terms:

$$\frac{\partial(U)}{\partial t} + F(U)_x + G(U)_y = S(U), \tag{1}$$

$$U = \begin{pmatrix} h \\ hu \\ hv \end{pmatrix}, \tag{2}$$

$$F(U) = \begin{pmatrix} hu \\ hu^2 + \frac{1}{2}gh^2 - A_H h\frac{\partial u}{\partial x} \\ huv - A_H h\frac{\partial v}{\partial x} \end{pmatrix}, \quad G(U) = \begin{pmatrix} hv \\ huv - A_H h\frac{\partial u}{\partial y} \\ hv^2 + \frac{1}{2}gh^2 - A_H h\frac{\partial v}{\partial y} \end{pmatrix}, \tag{3}$$

$$S(U) = \begin{pmatrix} 0 \\ -gh\frac{\partial b}{\partial x} + \frac{(\tau_w^x - \tau_b^x)}{\rho} + hfv \\ -gh\frac{\partial b}{\partial y} + \frac{(\tau_w^y - \tau_b^y)}{\rho} - hfu \end{pmatrix}, \tag{4}$$

where U is the vector of conserved physical variables; $F(U)$ and $G(U)$ are the flux vectors in the x and y direction respectively; $S(U)$ is the forcing source or sink term; h represents the total water depth; u and v represent the depth-averaged horizontal velocities in x and y directions; ρ is the density of water; t is time; g is the gravitational acceleration; b is the bottom elevation; A_H represents the horizontal diffusion coefficient; f is the Coriolis parameter. In this equation, τ_b^x and τ_b^y are bottom stresses and can be estimated using empirical formulae such as the Manning's equation or the law of the wall:

$$C_d = \frac{gn^2}{h^{1/3}}, \quad \text{for the Manning equation}$$
$$C_d = \frac{k^2}{\left[\ln(\frac{z}{z_o})\right]^2}, \quad \text{for the log law}$$
$$\tau_b^x = C_d\rho u\sqrt{u^2 + v^2}, \qquad \tau_b^y = C_d\rho v\sqrt{u^2 + v^2} \tag{5}$$

where n is the Manning's roughness coefficient, k is the von Karman constant, z is the water depth above the bottom, z_o is the bottom roughness coefficient. Both Manning's equation and the quadratic friction relation, widely known as the log law, in Eq. (5) are implemented in REM2D, and users can choose one of the given methods for their research purpose.

Similarly τ_w^x and τ_w^y in Eq. (4) are the wind stresses in x and y directions, respectively, at the free surface defined as:

$$\tau_w^x = C_{da}\rho_a u_w\sqrt{u_w^2 + v_w^2}, \; \tau_w^y = C_{da}\rho_a v_w\sqrt{u_w^2 + v_w^2}, \tag{6}$$

where u_w and v_w are the x and y components of wind speed measured at 10 m above the free surface, ρ_a is the density of air, and C_{da} is the drag coefficient. The drag coefficient is normally a function of the roughness of the sea surface and the wind speed at some height above the water surface. In this model, the empirical relationships both developed by Garratt (1977) and Wu (1982) are implemented:

$$C_{da} = 0.001(0.75 + 0.067W_s), \quad \text{Garratt (1977)}$$
$$C_{da} = 0.001(0.80 + 0.065W_s), \quad \text{Wu (1982)} \tag{7}$$

where W_s is the wind speed in meters per second. These two equations are probably the most well-known linear laws for the drag coefficient, and they are implemented in many recognized ocean circulation models. For example, the Garratt's (1977) equation is used in the advanced circulation (ADCIRC) storm surge model (Dietrich et al., 2011),