Ocean Engineering 36 (2009) 810–820

Contents lists available at ScienceDirect

Ocean Engineering

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

Implementation of baroclinic terms in a three-dimensional hydrodynamic model and its application to Anzali Port, Iran

Ali Khosh Kholgh *, Peyman Badiei

School of Civil Engineering, University College of Engineering, University of Tehran, Enghelab Avenue, 11155-4563 Tehran, Iran

A R T I C L E I N F O

Article history:
Received 23 July 2008
Accepted 26 April 2009
Available online 9 May 2009

Keywords:
3D hydrodynamic model
Baroclinic terms
Barotropic terms
Symmetric splitting method
Advection–diffusion
Anzali Port
Salt intrusion

A B S T R A C T

Baroclinic terms have been implemented in a three-dimensional fully hydrodynamic model developed by Badiei et al. [2008. A three-dimensional non-hydrostatic boundary fitted model for free surface flows. International Journal for Numerical Methods in Fluids, 56(6), 607–627] modifying its momentum equations to account for density gradients and utilizing the scalar (salinity, temperature, etc.) conservation equation (SCE) and a state equation for the calculation of density. In the solution of advection–diffusion terms of the governing Navier–Stokes equations (NSE) and SCE, a symmetric splitting method was applied to ensure the long-term stability of simulations. Correction terms proposed by Ruddic et al. (1995) were applied to SCE to ensure the conservation of the scalar quantity. In the presence of baroclinic terms, the zero gradient pressure in the vertical direction in the vicinity of surface and bottom boundaries assumed by Badiei et al. [2008. A three-dimensional non-hydrostatic boundary fitted model for free surface flows. International Journal for Numerical Methods in Fluids, 56(6), 607–627] created spurious currents. This problem was solved by assuming a hydrostatic pressure variation at those boundaries. The ability of extended model was validated by comparing its results with an experimental test case. The simulation of hydrodynamic and salt intrusion at Anzali Port located at the southern coasts of Caspian Sea in Iran was carried out by the model with both barotropic and baroclinic modes. The simulated results with baroclinic mode show a better agreement with measured data as compared to the results of barotropic mode that clearly demonstrate the significance of baroclinic terms in the simulation of cyclic intrusion of salt wedge into the Port Basin.

1. Introduction

Estuaries are valuable bodies of water that serve both mankind and its environment. An estuary, as an environmental eco-system, poses challenging planning and management problems to engineers and scientists. Efficient management of estuaries requires a thorough understanding of the complex physical processes encountered, including the hydrodynamic behavior and current circulation patterns. Circulation in estuaries is mainly affected by inland water discharge, tidal and atmospheric forcing.

Numerical models have been successfully applied to simulation of hydrodynamic characteristics of estuaries. Depending on the significance and treatment of density gradient in the governing equations, these models are classified as barotropic or baroclinic.

Application of 1DV models (e.g. Nunes Vaz and Simpson, 1994; Monismith and Fong, 1996), which are mainly based on simplified assumptions of Hansen and Rattray (1965) and Chatwin (1976), is the simplest approaches for simulation of dynamic features of estuaries. However, these simplifications (e.g. constant horizontal gradient of salinity in vertical direction) limit the realism of the results. The analysis by Kranenburg (1986) demonstrated large temporal variability of salinity gradient due to variations in runoff. Similarly, MacCready (1999) and Hetland and Geyer (2004) used numerical models to indicate the variations of salinity gradient with tidal amplitude. Their studies suggested that the salinity gradient should be included as a dependent variable in the problem, thus limiting the prognostic ability of 1DV models in area with important lateral processes. Warner et al. (2005) also stated that the results of 1DV models are reasonable, only if the longitudinal salinity structure could be properly determined and there were not any important lateral processes.

The problem of specifying salinity gradient can be overcome by using 2DV or three-dimensional (3D) baroclinic models, wherein the salinity gradient becomes dependent variable. Over past decades 2D and 3D baroclinic models have been widely developed (Casulli and Cheng, 1992; Casulli and Stelling, 1998; Casulli, 1999; Stelling and Busnelli, 2001; Namin et al., 2001; Kanarska and Maderich, 2002; Pandoe and Edge, 2003; Choi and Wu, 2006; Zhong and Li, 2006; Chih-Chieh et al., 2007).

The scope of this paper is to implement baroclinic terms in a three-dimensional fully hydrodynamic model developed by Badiei et al. (2008) so that it could be applied to the simulation of natural

* Corresponding author. Tel.: +98 9126208073; fax: +98 66944869.
E-mail address: khosh@ut.ac.ir (A. Khosh Kholgh).

0029-8018/$ - see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.oceaneng.2009.04.008

estuarine configuration. A description of the modifications to the governing equations and their numerical solution that were applied to enable the 3D model to simulate density currents are discussed in Section 2. The results of applying the model to an experimental test case of lock-exchange problem are given in Section 3 and the application of the extended model for the simulation of hydrodynamic and salt intrusion studies for a real-life case at Anzali Port with both barotropic and baroclinic modes are reported in Section 4. Main conclusions are drawn up in Section 5.

2. Model description

2.1. Modification of governing equations

The full three-dimensional Navier–Stokes equations (NSE) reads as:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0 \tag{1}$$

$$\frac{\partial v}{\partial t}+\frac{\partial}{\partial x}(u^2)+\frac{\partial}{\partial y}(vu)+\frac{\partial}{\partial z}(wu)+\frac{1}{\rho}\frac{\partial P}{\partial x}$$
$$=\frac{\partial}{\partial x}\left(\nu_{tx}\frac{\partial u}{\partial x}\right)+\frac{\partial}{\partial y}\left(\nu_{ty}\frac{\partial u}{\partial y}\right)+\frac{\partial}{\partial z}\left(\nu_{tz}\frac{\partial u}{\partial z}\right) \tag{2}$$

$$\frac{\partial v}{\partial t}+\frac{\partial}{\partial x}(uv)+\frac{\partial}{\partial y}(v^2)+\frac{\partial}{\partial z}(wv)+\frac{1}{\rho}\frac{\partial P}{\partial y}$$
$$=\frac{\partial}{\partial x}\left(\nu_{tx}\frac{\partial v}{\partial x}\right)+\frac{\partial}{\partial y}\left(\nu_{ty}\frac{\partial v}{\partial y}\right)+\frac{\partial}{\partial z}\left(\nu_{tz}\frac{\partial v}{\partial z}\right) \tag{3}$$

$$\frac{\partial w}{\partial t}+\frac{\partial}{\partial x}(uw)+\frac{\partial}{\partial y}(vw)+\frac{\partial}{\partial z}(w^2)+\frac{1}{\rho}\frac{\partial P}{\partial z}$$
$$=\frac{\partial}{\partial x}\left(\nu_{tx}\frac{\partial w}{\partial x}\right)+\frac{\partial}{\partial y}\left(\nu_{ty}\frac{\partial w}{\partial y}\right)+\frac{\partial}{\partial z}\left(\nu_{tz}\frac{\partial w}{\partial z}\right)-g \tag{4}$$

where u, v and w are, respectively, the velocity components in x, y and z directions. P is the total pressure, ρ the density and ν_{tx_i} eddy viscosity in x_i direction.

Decomposing the pressure into two parts; the 'hydrostatic' ($\rho_0 gz$) and 'access' pressure ($\rho_0 P^*$):

$$P=\rho_0 gz+\rho_0 P^* \tag{5}$$

so that

$$\frac{\partial P}{\partial x}=\rho_0\frac{\partial P^*}{\partial x} \tag{6}$$

$$\frac{\partial P}{\partial y}=\rho_0\frac{\partial P^*}{\partial y} \tag{7}$$

$$\frac{\partial P}{\partial z}=-\rho_0 g+\rho_0\frac{\partial P^*}{\partial z} \tag{8}$$

and substituting the pressure derivatives of Eqs. (6)–(8) into (2)–(4), the momentum equations could be rewritten as follows:

$$\frac{\partial u}{\partial t}+\frac{\partial}{\partial x}(u^2)+\frac{\partial}{\partial y}(vu)+\frac{\partial}{\partial z}(wu)+\frac{\rho_0}{\rho}\frac{\partial P^*}{\partial x}$$
$$=\frac{\partial}{\partial x}\left(\nu_{tx}\frac{\partial u}{\partial x}\right)+\frac{\partial}{\partial y}\left(\nu_{ty}\frac{\partial u}{\partial y}\right)+\frac{\partial}{\partial z}\left(\nu_{tz}\frac{\partial u}{\partial z}\right) \tag{9}$$

$$\frac{\partial v}{\partial t}+\frac{\partial}{\partial x}(uv)+\frac{\partial}{\partial y}(v^2)+\frac{\partial}{\partial z}(wv)+\frac{\rho_0}{\rho}\frac{\partial P^*}{\partial y}$$
$$=\frac{\partial}{\partial x}\left(\nu_{tx}\frac{\partial v}{\partial x}\right)+\frac{\partial}{\partial y}\left(\nu_{ty}\frac{\partial v}{\partial y}\right)+\frac{\partial}{\partial z}\left(\nu_{tz}\frac{\partial v}{\partial z}\right) \tag{10}$$

$$\frac{\partial w}{\partial t}+\frac{\partial}{\partial x}(uw)+\frac{\partial}{\partial y}(vw)+\frac{\partial}{\partial z}(w^2)+\frac{\rho_0}{\rho}\frac{\partial P^*}{\partial z}$$
$$=\frac{\partial}{\partial x}\left(\nu_{tx}\frac{\partial w}{\partial x}\right)+\frac{\partial}{\partial y}\left(\nu_{ty}\frac{\partial w}{\partial y}\right)+\frac{\partial}{\partial z}\left(\nu_{tz}\frac{\partial w}{\partial z}\right)-\frac{\rho-\rho_0}{\rho}g \tag{11}$$

Badiei et al. (2008) solved the above system by assuming $\rho=\rho_0$, which is only valid for barotropic simulations.

In addition to above equations, an advection–diffusion equation for any scalar quantity (e.g. salinity and temperature) is added to the governing equations:

$$\frac{\partial \phi}{\partial t}+\frac{\partial}{\partial x}(u\phi)+\frac{\partial}{\partial y}(v\phi)+\frac{\partial}{\partial z}(w\phi)$$
$$=\frac{\partial}{\partial x}\left(\lambda_{tx}\frac{\partial \phi}{\partial x}\right)+\frac{\partial}{\partial y}\left(\lambda_{ty}\frac{\partial \phi}{\partial y}\right)+\frac{\partial}{\partial z}\left(\lambda_{tz}\frac{\partial \phi}{\partial z}\right) \tag{12}$$

where ϕ is a scalar quantity and λ_{tx_i} eddy diffusivity in x_i direction.

Finally, the density is calculated through the international equation of state of seawater defined by the Joint Panel on Oceanographic Tables and Standards (UNESCO, 1981).

2.2. Numerical methods

A finite volume approximation has been used to solve the set of governing equations in Cartesian coordinate system. As shown in Fig. 1, staggered grid with rectangular mesh in horizontal planes and boundary fitted grids with equal numbered cells in vertical direction are used to discretise the computational domain. Thus, pressure and scalar variables are defined at the center of each cell and velocities are specified at the center of corresponding faces.

The solution algorithm is comprised of three stages

First, using the time-splitting method, the advected and diffused velocities are computed from the advection–diffusion terms of Eqs. (9)–(11).

Then by coupling the continuity and momentum equations without advection–diffusion terms, a tri-diagonal block system of equations in terms of access pressure for each 2D vertical plane is derived. The values of velocity in x, y and z directions are determined from momentum equations using computed access pressures. An iterative algorithm is used to convergency of results.

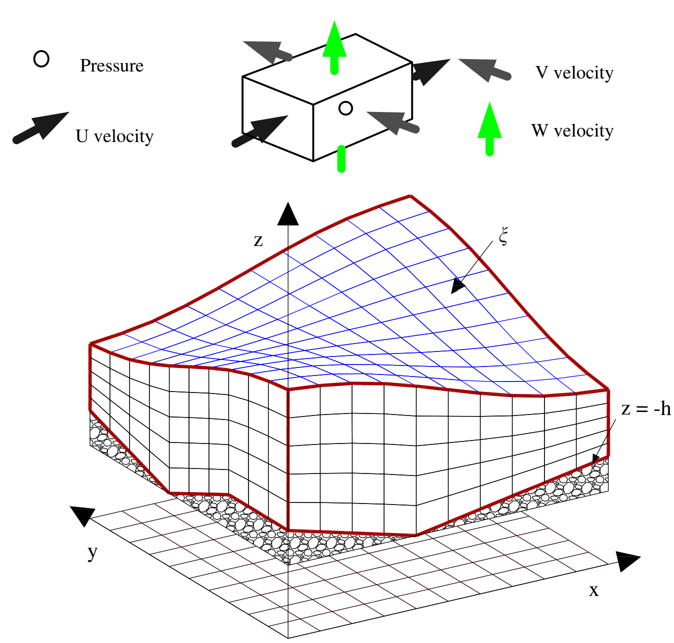

Fig. 1. 3D mesh with rectangular grids in horizontal plane and boundary fitted grids with equal numbered cells in vertical direction.