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A dike–groyne algorithm in a terrain-following coordinate ocean model (FVCOM): Development, validation and application

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ABSTRACT

A dike–groyne module is developed and implemented into the unstructured-grid, three-dimensional primitive equation finite-volume coastal ocean model (FVCOM) for the study of the hydrodynamics around human-made construction in the coastal area. The unstructured-grid finite-volume flux discrete algorithm makes this module capable of realistically including narrow-width dikes and groynes with free exchange in the upper column and solid blocking in the lower column in a terrain-following coordinate system. This algorithm used in the module is validated for idealized cases with emerged and/or submerged dikes and a coastal seawall where either analytical solutions or laboratory experiments are available for comparison. As an example, this module is applied to the Changjiang Estuary where a dike–groyne structure was constructed in the Deep Waterway channel in the inner shelf of the East China Sea (ECS). Driven by the same forcing under given initial and boundary conditions, a comparison was made for model-predicted flow and salinity via observations between dike–groyne and bed-conforming slope algorithms. The results show that with realistic resolution of water transport above and below the dike–groyne structures, the new method provides more accurate results. FVCOM with this MPI-architecture parallelized dike–groyne module provides a new tool for ocean engineering and inundation applications in coastal regions with dike, seawall and/or dam structures.

1. Introduction

It is a challenge for a terrain-following coordinate coastal ocean model to simulate the flow field in an estuarine or coastal system with dikes and groynes. The constructions are usually submerged during high tide but may be fully exposed during low tide. If they are treated as submerged vertical walls, the terrain-following coordinate transformation cannot be directly applied. Adding a slope on the surface of a dike or groyne could make the topographic coordinate transformation work (e.g. Qi, 2003; Du, 2007), but it changes the hydrodynamics. Instead of solid blocking (no flux towards the wall) in the lower column with the dike or groyne and free exchange in the upper column above the construction, that type of construction makes the water tend to flow along the submerged part under the dynamical constraints of the sloping bottom boundary layer. As a result, this approach can overestimate vertical and lateral mixing and thus produce unrealistic circulation around the construction.

Recently, inundation has received intense attention for model applications to coastal and estuarine problems. It is defined as coastal flooding of normally dry land caused by heavy rains, high river discharge, tides, storm surge, tsunami processes, or some combination thereof. In many coastal regions, dams are built around the area where the height of land is lower or close to the mean sea level to protect the land from flooding (Pullen et al., 2007, 2008, 2009; Lhomme et al., 2008; Allsop et al., 2009). An coastal inundation forecast system is aimed at (1) making warming of coastal flooding on an event timescale in order to facilitate evacuation and other emergency measures to protect human life and property and (2) estimating accurate statistics of coastal inundation in order to enable rational planning regarding sustainable land-use practices in the coastal zone. A model used for this application must produce accurate, real-time forecasts of water level at high spatial resolution in the coastal zone and have the capability to resolve the overtopping process of dams and similar structures. These dams are like a solid wall boundary when the water level is lower than it, but become submerged constructions like dikes when flooding occurs. The existing wet/dry treatment technology available in current terrain-following coordinate system models (e.g. Lynch and Gray, 1980; Johns et al., 1982; Zheng et al., 2003; Chen et al., 2007; Zhao et al., 2010) is capable of resolving coastal

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flooding in many situations but not those with vertical seawalls in the computational domain. It is imperative that we implement a dike–groyne treatment module in a terrain-following coordinate unstructured-grid coastal ocean numerical model if we are to apply this type of model to accurately simulate the complex flow fields found in coastal and estuarine regions with submerged dikes and groynes.

There have been many efforts on examining the fluid flow features in the dike and groyne systems and developing discrete algorithms to resolve these features in real applications (Ouillon and Dartus, 1997; Muto et al., 2002; Uijttewaal, 2005; Yossef, 2005; McCoy et al., 2006, 2007, 2008; Tang et al., 2006; Kurzke et al., 2002; Yeo and Kang, 2008; Uijttewaal et al., 2001; Yossef and Vriend, 2011; Delft3D-FLOW User Manual, 2009). Recent laboratory experiments revealed that the flow field between dikes is characterized by various types of eddies with significantly different spatial scales and fluctuations under conditions of submerged and emerged dikes (Yossef and Vriend, 2011). The fluid dynamics that control eddy formation and evolution were examined using Large Eddy Simulation (LES) (McCoy et al., 2006, 2007, 2008; Tang et al., 2006; Ouillon and Dartus, 1997). A Computational Fluid Dynamics (CFD) program (named FLOW-3D) was developed to simulate the flow structures around a submerged groyne (Yeo and Kang, 2008). This program, however, is designed for the CFD scale without consideration of the earth's rotation. In order to apply this program to realistic ocean situations, the program must be couple with an ocean model. The Delft3D-FLOW (Delft3D-FLOW User Manual, 2009) is the current commercial consulting software that is widely used for coastal and estuarine engineering. This model includes a dam treatment algorithm, which treats a dam as an infinitely thin object on a grid line. On this line, no water exchange between two computational cells connected to that line is allowed. This algorithm works well for Delft3D-FLOW, but the structured grids used in this model limits its application to resolve complex and irregular geometry of coastal ocean and estuaries.

A joint research team of the University of Massachusetts Dartmouth (UMassD) and Woods Hole Oceanographic Institution (WHOI) has developed the unstructured-grid, three-dimensional, primitive equations finite-volume coastal ocean model (FVCOM) (Chen et al., 2003, 2006a,b, 2007; Huang et al., 2008). FVCOM uses a non-overlapped triangular mesh in the horizontal and a terrain-following coordinate in the vertical. The triangular mesh used in FVCOM can resolve the geometry of dikes-groynes. With the wet/dry point treatment in this model, FVCOM is capable of predicting the water exchange over a dam on land. As with all other terrain-following coordinate models, however, FVCOM has an issue with including the correct kinematics for the case with submarine dikes-groynes.

In this paper, we have introduced an unstructured-grid algorithm to calculate the water velocity and tracer concentration in a dike–groyne system. This algorithm has been coded into FVCOM with MPI parallelization (Chen et al., 2006a; Cowles, 2008) and validated for idealized channel cases with dike–groyne construction where analytical solutions and laboratory experiment results are available for comparison and an idealized estuary with dike–groyne features. As an example of an application, we applied this algorithm to the Changjiang River (CR) for the simulation of the tidal and residual flows inside and outside of the dike–groyne system constructed there in the last decade.

The rest of the paper is organized as follows. In Section 2, an unstructured-grid discrete algorithm for the dike–groyne treatment is described. In Section 3, three idealized cases were selected to validate the dike–groyne module code under physical conditions driven by river discharge and tides and the overtopping process of a seawall. In Section 4, FVCOM with this new dike–groyne module is applied to the CR and validated with field measurement data, the simulation results are presented, and the computational efficiency of the method is discussed. Conclusions are then summarized in Section 5.

2. An unstructured-grid dike–groyne algorithm

Three types of dike and groyne are considered: (a) "straight," (b) "joint" and (c) "cross" (Fig. 1). In plan view, the first is constructed by a straight line running along edges of triangles. The second consists of two lines, with the end point of one line connecting to the other line. The third is composed of two lines, with one crossing the other. In the vertical, we consider three different cases. In the first case, the tops of the structures are always below sea level. For this case, the water column connected to the structure is characterized by two layers: an upper layer in which the water can flow freely across the structure, and a lower layer in which flow is blocked (with no flux into the wall). In a free-surface model, due to the temporal variation of the surface elevation, the top of a dike or a groyne is probably contained within a terrain-following layer. For simplification, we define the interface of free and blocked layers either at the upper level (when a portion of the length of the structure is longer than half the thickness of the terrain-following layer) or at the lower level (when a portion of the length of the structure is shorter than half the thickness of the terrain-following layer). In the second case, the dikes and groynes are always above sea level. This is the simplest case in which the dikes and groynes can be easily treated as solid lateral boundaries. In the third case, the dikes and groynes are sometimes above and sometimes below sea level. For this case, the approaches used for the first and second cases are combined.

In general, the width of a dike or groyne is on the order of 2–5 m. For a numerical simulation with a horizontal resolution of > 20–100 m, these dikes or groynes can be treated as lines without width. Under this assumption, we can construct the triangular grid along dikes and groynes, with a single control volume above the structure and two separate control volumes beneath it (Fig. 2). The algorithm of the dike–groyne treatment is described as follows. An example is given for the algorithm used for a single dike or groyne, and this approach is simply extended for the case of multiple dikes and groynes.

2.1. Free-surface elevation

In the Cartesian coordinate system, the vertically integrated continuity equation can be written in the form of

$$\frac{\partial \zeta}{\partial t} = -\frac{1}{\Omega}\left[\oint_{l_\Omega}(\bar{u}D)\,dy - \oint_{l_\Omega}(\bar{v}D)\,dx\right] \tag{1}$$

where ζ is the free-surface elevation, u and v are the x- and y-components of the horizontal velocity, D is the total water depth defined

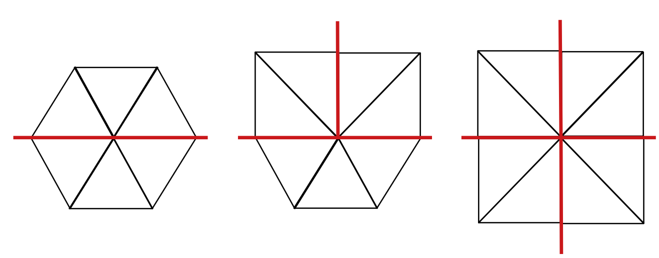

Fig. 1. Three types of dike and groyne construction. Type 1: a straight dike (left panel). Type 2: a groyne joined at its end with a dike (middle panel). Type 3: a groyne crossed through a dike (right panel). A horizontal red line indicates a dike and a vertical red line represents a groyne. The black lines are the triangle's edges. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)