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Drying–wetting approach for 3D finite element sigma coordinate model for estuaries with large tidal flats

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Abstract

An approach to represent drying and wetting processes in a three-dimensional finite element sigma coordinate model is described. This approach makes use of capillaries in dry areas, which can connect to the nearby wet areas. The time marching of the mass conservation equation is modified by introducing a "size factor" coefficient and a water level diffusion term. Therefore, the fictitious water level of the dry nodes can fluctuate with the adjacent wet nodes. This eliminates the artificial pressure gradient appearing in some drying and wetting approaches in the partially wet (transition) elements. This approach results in a null momentum computation at the dry areas, which can guarantee numerical stability and satisfy the mass and momentum conservation. The approach has been applied in a hypothetical case and a real case in Xiamen Estuary, China, with satisfactory results.

Keywords: Drying and wetting; Finite element; Three-dimension; Sigma coordinate; Estuary

1. Introduction

Most of the tidal flats in estuaries are wetland. Wetland plays a very important role in the ecosystem and its productivity is maintained mainly by the periodic drying and wetting processes. At the same time, salt water and freshwater mixing is mostly a three-dimensional (3D) phenomenon. So it is necessary for an estuary numerical model to have a practical approach that not only can simulate drying and wetting processes accurately, but also can maintain stability to carry long-term 3D studies. Reviews of several drying and wetting approaches were made by Leclerc et al. [1], Ip et al. [2], etc. The approaches to the drying and wetting processes can be broadly classified to two categories: (1) moving mesh approach and (2) fixed mesh approach. The first approach is based on spatially deforming computational meshes. The nodes on the boundary are front-tracking; thus the coordinates of the nodes vary with time. This means that models equipped with this approach include two parts of computations, the hydrodynamic computation and the computation for new mesh generation. This approach is rather expensive because the mesh shall be re-generated with the moving boundary in every time step. Although this moving mesh is proved to be the most precise approach [3,4]; the application can not be extended to a domain with complex boundary, e.g., an estuary with large tidal flats, because the continuous mesh adjustment and re-generation are significant burdens to the model performance.

The fixed mesh technique can be divided into two sub-categories as well. The first sub-category can be referred as the earlier approach suggested by Leendertse [5] in his two-dimensional (2D) model using an alternating direction implicit (ADI) finite difference algorithm. This type of approach "turns off/turns on" the model elements when the water level drops below/above a

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Nomenclature

$\widetilde{H}$	water depth considering the water volume in capillary
$\widetilde{V}$	water volume including the water in capillary
a	coefficient controlling the decreasing rate of the capillary width
B	Width scale of the capillary
B_s	the minimum width scale of the capillary
f	Coriolis parameter
H	actual water depth $H = \zeta + h$
h	water depth relative to the minimum water level
P_i^*	baroclinic force with Boussinesq assumption
t	time
u, v, ω	velocity components in the x, y, z directions in σ coordinate
U_i	depth averaged velocity components
w	vertical velocity in Cartesian coordinate
x_1, x_2, x_3	spatial coordinates with σ transformation
z_0	elevation of capillary bottom
Z_b	bed elevation, which is equal to $-h$
Δt	time step
ε_x, ε_y, ε_z	eddy viscosity coefficients for water
ζ	water level from the minimum water level
τ^b	bottom shear stress
Ω	area of the element
Γ	boundary of the element

threshold water depth, imposes a null value to the velocity components at dry elements, and sets the water level to the bed elevation at the drying process. When it comes to the wetting process the water level at the moving boundary is determined by extrapolating the water level values at the neighboring wet elements (see Fig. 1a). In this type of approach, an artificial slope of the free surface, which generates an extra artificial pressure gradient term, will be formed in the dry area because the water level is arbitrarily fixed at the bed elevation. Leclerc et al. [1] used this approach in a finite element model with the Newton–Raphson solver, and the elements were classified to three types: the dry element, the partially wet (transition) element and the wet element. The treatment of the dry element and wet element was similar to the idea proposed by Leendertse [5]. But for the transition element, in order to eliminate the artificial pressure gradient term, the pressure gradient force and bottom shear stress were dropped out to form a "reduced" momentum equation. Cheng and Smith [6], and Lin and Falconer [7] used a refined algorithm of this type of approach in their 3D layer-integrated models with fixed grids in the vertical direction. In the refined algorithm, there are four steps to check the dry element and three steps for wetting element checking. Although this refined approach is robust, the strict diagnostic tests are necessary to treat different drying and wetting patterns in the transition elements.

Another approach is based on modifying the hydrodynamic equations to include a cell or an element "size factor" as a function of water depth, e.g., the "marsh porosity method" [2]. In this approach, all the dry and wet areas are computed by assuming that there is water flow in the porous layer below the bed, and the water level can fall below the assigned bed elevation (Fig. 1b). The advantage of this approach is that there are no artificial pressure gradients in the dry elements and there is no need to impose any assumed value on the water elevation and velocity. However, the mass and momentum are not conserved because there are artificial water flows between the dry and wet areas. Some methods have been proposed to reduce this fictitious transport, e.g., Flather and Hubbert [8] and Ip et al. [2] modified the momentum equation by adding a hydraulic conductivity in the porous medium; Heniche et al. [9] increased the bottom shear stress by assuming that Manning coefficient is a function of negative water depth. The main purpose of these methods is to restrain the velocity components, but the mass and conservation can not be satisfied completely unless the velocity components are imposed as zero, which unfortunately will once again lead to the artificial pressure gradient problem.

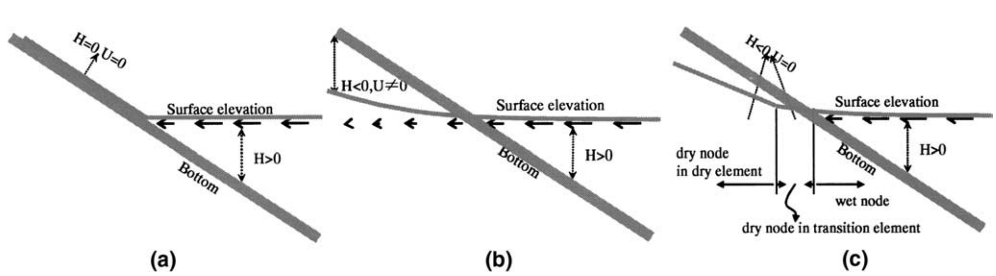

Fig. 1. The hydraulic patterns for approaches: (a) the classical approach (mass conservation); (b) the marsh porosity approach (without artificial slope of the free water surface); (c) the present approach (mass conservation, without artificial slope of the free water surface).