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Analysis of an open source quadtree grid shallow water flow solver for flood simulation

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ABSTRACT

The shallow water flow solver within Gerris Flow Solver implements second-order accurate Gudunov type numerical schemes, with preserving the balance of source and flux terms on quadtree cut cell grids. The solver provides flexible grid generation, with using adaptive quadtree grids and the cut cell method, which can improve computational efficiency in 2D simulations. The solver, however, cannot implicitly discretize nonlinear friction without linearization since the current version of Gerris supports the implicit discretization only for linear friction. We compare implicit treatment for Manning's friction to the linearization. Simulation results using a benchmark test show the difference between two methods is only significant when the roughness coefficient is unrealistically high. Two real flood events, Malpasset dam break in France and Baeksan levee failure in Korea, are simulated using the quadtree grid based shallow water model, with adaptively refining meshes near water fronts and river boundaries. Comparison of simulation results with observations and measurements demonstrates that the grid adaptation can save approximately 85%–95% of the computational cost while preserving the accuracy. The research result shows that the linearized friction using the current version of Gerris can be applied for flood simulation and multiple inflow boundaries can be treated as source terms.

1. Introduction

Numerical modeling of shallow water flow is an important research topic for flood risk management. The simulation results play a significant role in national decision-making on flood prevention and control. One-dimensional shallow water models are quite often preferred in the field of engineering (e.g., FLUCOMP; Fread, 1993; Ervine and MacLeod, 1999; HEC-RAS; ISIS; MIKE11), mostly due to the fast computation (Syme, 2011). The rapid development in computer technologies, however, makes two-dimensional shallow water flow models acceptable in practice. A number of 2D models have been developed (i.e., Bates and De Roo, 2000; Yoon and Kang, 2004; Mignot et al., 2006; George, 2011; Kim and Cho, 2011). In general, the 2D models are more accurate and reliable than 1D models for complex flow simulation given that the water is allowed to move only in the longitudinal direction in 1D models. 2D modeling is, however, still computationally heavy to engineers despite the advances in computing technologies, particularly for flood risk assessment or real time flood forecasting, which forces engineers to choose 1D models over 2D, giving up accuracy.

One of the solutions to improve computational efficiency in 2D modeling is the implementation of adaptive mesh refinement (AMR), in which grid resolution is adjusted with following flow features. Generally, the finer grid resolution is achieved along wave fronts or complex geometry than within inundated area. The optimal grid resolution is time varying given that flows change with time. The method of adaptive meshing makes numerical simulations much more efficient (Berger and Oliger, 1984; Berger and Colella, 1989; Borthwick et al., 2001), and its adoption for numerical simulations becomes practice in engineering and science, including shallow water flow modeling. George and LeVeque (2008) used block-structured AMR for tsunami modelling. Their AMR algorithms allow nesting of rectangular subgrids of multiple levels and the subgrids evolve spatially and temporally. George (2011) applied the same model to simulate dam break flow and showed

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that the shallow water model with AMR is efficient and suitable for flood simulation. Alternatively, Liang et al. (2007) and Liang (2010) simulated inundation scenarios on adaptive quadtree grids. The adaptive quadtree grid is a way to carry out AMR and uses a quadtree and hierarchical data structure. Liang (2010) compared the performance of their model with the commercial code and showed that the shallow water model on adaptive quadtree grids is highly efficient while preserving accuracy. Popinet (2011, 2012) developed a quadtree adaptive tsunami model to solve shallow water equations within the Gerris Flow Solver framework (Popinet, 2003). Lee et al. (2011) presented a dynamically adaptive quadtree grid generation system for the solution of a two-dimensional two-layer shallow water model in order to improve computational efficiency.

Gerris Flow Solver has the capability of adaptive quadtree grid generation. The Gerris solver was initially designed to solve the incompressible Euler equation, and then has been extended to multiphase incompressible Navier–Stokes equations (Popinet, 2009), spectral wave models (Popinet et al., 2010), and shallow water equations to simulate tsunami propagation (Popinet, 2011, 2012). Recently, An and Yu (2012) applied the cut cell method to the shallow water flow solver of Gerris, which provides the model with more flexibility. In addition, the Gerris Flow Solver is open source software, and users can see the internal structure and even modify the codes for better representation. Moreover, the Gerris Flow Solver is well equipped with auxiliary programs such as GfsView for visualization, which most open source software are lack of as Chien (2008) mentioned. Gerris supports a variety of file formats such as Cartesian Grid Data (CGD), ESRI ASCII grid, xyz files to treat initial and boundary conditions, which facilitates specifying a time varying boundary condition. Gerris can produce outputs as text, image, MPG video, or KMZ files for Google Earth as well as GfsView files. Lee et al. (2013) compared the simple pre- and post-processing in Gerris to those in FLUMEN (FLUvial Modeling Engine), and verified the computational efficiency of quadtree grids over triangular grids.

The objective of this paper is to analyze the performance of the shallow water flow solver within Gerris Flow Solver for flood simulation in 2D through real flood cases. The motivation of this paper is the fact that there are few researches with applying the quadtree grid shallow water model to real flood events. Liang et al. (2007) and Liang (2010) simulated flood scenarios using a quadtree model for flood risk assessment. Their simulation results are in good agreement with those obtained by using a commercial model, called TUFLOW. In addition, Kesserwani and Liang (2012) simulated the Malpasset dam break event using the dynamically adaptive grid based shallow water model. The shallow water flow solver of Gerris has been intensively verified through real tsunami cases (Popinet, 2011, 2012) as well as a number of benchmark tests (Popinet et al., 2010; An and Yu, 2012). However, it is still informative to analyze the model performance on real flood events for potential Gerris users because Gerris has several favorable features as stated above. In addition, Gerris has several options to treat inflow boundaries as well as friction, and allows choosing mass conservation or lake-at-rest equilibrium when the dynamic adaptive mesh refinement is applied for flood simulations. The effects of those options are investigated through a benchmark test and real flood simulations in this paper.

2. Numerical model

2.1. Governing equation

Two-dimensional depth-integrated shallow water equations are used for flood event simulation. They have performed well for a broad range of flood simulations in practice. A hyperbolic conservation form of the equations is written as follows:

$$\frac{\partial \mathbf{q}}{\partial t}+\frac{\partial \mathbf{f}}{\partial x}+\frac{\partial \mathbf{g}}{\partial y}=\mathbf{s}, \tag{1}$$

where t denotes time, x and y are Cartesian coordinates, and $\mathbf{q}$, $\mathbf{f}$, $\mathbf{g}$, and $\mathbf{s}$ are vectors representing conserved variables, fluxes in the x- and y-direction, and source terms, respectively. By neglecting the friction term, the vectors can be written as:

$$\mathbf{q}=\begin{pmatrix} h \\ hu \\ hv \end{pmatrix}, \quad \mathbf{f}=\begin{pmatrix} hu \\ hu^2+gh^2/2 \\ huv \end{pmatrix}, \quad \mathbf{g}=\begin{pmatrix} hv \\ huv \\ hu^2+gh^2/2 \end{pmatrix}, \quad \mathbf{s}=\begin{pmatrix} 0 \\ -hgz_x \\ -hgz_y \end{pmatrix}, \tag{2}$$

where h is water depth, u and v are depth-averaged velocity components in the x and y-direction, g is the acceleration of gravity, and $z_x(=\partial z/\partial x)$ and $z_y(=\partial z/\partial y)$ are bed slopes in the x and y-direction. The friction term will be added to $\mathbf{s}$ in Eq. (2) for completeness, without changing the fundamental structure of the equations in Section 2.3.

2.2. Spatial and temporal discretization

Recently, a number of well-balanced numerical schemes have been proposed for shallow water flow equations (e.g., Audusse et al., 2004; Audusse and Bristeanu, 2005; Caleffi et al., 2006; Kim et al., 2008; Caleffi and Valiani, 2009) given that the gradient of water depths and the bed slope terms are often imbalanced in a discretized domain in case of irregular beds. The imbalance may cause unphysical perturbations when dry–wet transitions occur or flows reach a steady state condition, which significantly affects the accuracy of flood prediction. In order to solve the problem of imbalance, Gerris implements the hydrostatic reconstruction technique proposed by Audusse et al. (2004), whose satisfactory performance has been verified in Popinet (2011) and An and Yu (2012). Following An and Yu (2012), the second-order accurate discretization on a two dimensional quadtree cut cell grid is written as:

$$\frac{A_{i,j}}{\Delta t}\left(\mathbf{q}_{i,j}^{n+1}-\mathbf{q}_{i,j}^{n}\right)+\boldsymbol{F}_{i,j}=\boldsymbol{S}_{i,j}+\boldsymbol{Sc}_{i,j} \tag{3}$$

where $A_{i,j}$ is the area of the cell (i,j), $\boldsymbol{Sc}_{i,j}$ is an additional source term to balance in the presence of a source, and $\boldsymbol{F}_{i,j}$ is the numerical flux. A MUSCL-type unsplit discretisation is combined with a predictor-corrector time-stepping scheme to construct a second-order accurate Godunov type scheme (Popinet, 2011). The predicator step computes a temporary cell-center value over the half time step $\Delta t/2$:

$$A_{i,j}\mathbf{q}_{i,j}^{n+1/2}=A_{i,j}\mathbf{q}_{i,j}^{n}-\frac{\Delta t}{2}\left(\boldsymbol{F}_{i,j}^{n}-\boldsymbol{S}_{i,j}^{n}-\boldsymbol{Sc}_{i,j}^{n}\right), \tag{4}$$

The corrector step updates the conservative values over a time step Δt as:

$$A_{i,j}\mathbf{q}_{i,j}^{n+1}=A_{i,j}\mathbf{q}_{i,j}^{n}-\Delta t\left(\boldsymbol{F}_{i,j}^{n+1/2}-\boldsymbol{S}_{i,j}^{n+1/2}-\boldsymbol{Sc}_{i,j}^{n+1/2}\right). \tag{5}$$

The above scheme is second-order accurate in space and time, and the details of discretization and the well-balanced scheme are described in An and Yu (2012).