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Modeling dam-break flows in channels with 90 degree bend using an alternating-direction implicit based curvilinear hydrodynamic solver

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ABSTRACT

This paper presents a combined numerical and experimental investigation of dam break induced free-surface flows in channels with 90 degree bend. These types of flows are best described by the two-dimensional shallow water equations (SWE) representing the conservations of mass and horizontal momentums. In this study, the governing equations are solved numerically by means of an alternating-direction implicit (ADI) finite-difference scheme in a curvilinear coordinate and contravariant velocity system. This model is tested by simulating for various flow conditions including dam-break flows onto dry beds in a converging–diverging channel and a channel with 45 degree bend. Good fits of the present model predictions with published laboratory measurements are achieved. To further the validation of the model, a series of physical model tests for dam-break flows in a channel with 90 degree bend were conducted. The predicted time-varying water depths downstream of the dam face are shown to have a fairly good agreement with recorded data from model tests. The present ADI solver is found to be capable of capturing the formation and movement of steep wave fronts.

1. Introduction

Throughout history, people have been impacted by flooding due to natural and man-made causes such as dam failures. The potential damage caused by flooding or catastrophic failure of a dam has always been a major concern of the public and engineers alike. This concern has resulted in extensive research on laboratory measurements and numerical simulations of overland flows, especially dam break induced free-surface flows. The ability of modeling these types of flows is of great importance because it enables forecasting the areas may be impacted by flooding from a rainfall event or in the case of a dam failure. The potential impact on a town downstream can be evaluated.

The above mentioned overland flows, including dam-break flows, can be conveniently modeled by solving the two-dimensional shallow water equations (SWE), which are derived from the vertical integration of the Navier–Stokes equations with the use of bottom and water surface boundary conditions. In order to numerically describe those complex types of flows, a model or scheme must be developed, which will perform the simulations while providing good computational results. Usually in flooding simulations, it is important that the model is able to model an advancing wave front over a wet or dry bed. Researchers and modelers frequently performed dam-break simulations on various types of channels using methods among finite-difference (FD), finite-volume (FV), or finite-element (FE). The other considerations would be the selections of the coordinate system and formation of computational grids.

The finite volume (FV) method, which solves the integral form of the SWE on domains with either structured or unstructured grids, has been used to handle the dam-break problems with downstream propagating flood waves. Zoppou and Roberts [36] compared several explicit schemes for one-dimensional dam break problems. Formulations of upwind type FV scheme to solve a Riemann problem at the interfaces between two neighboring elements were presented by Godunov [15]. With the concept of solving the Riemann problem more effectively, Roe [23] introduced approximate Riemann solvers to model flows with shock wave front. Zhao et al. [35] through the test of first-order FV scheme suggested use of limiters to obtain results with higher order accuracy. Extended to higher order accurate scheme, Anastasiou and Chan [1] incorporated slope limiters with the Roe type FV solver to model dam-break flows. Other dam-break flow studies using FV method can be found in Bermudez and Vazquez [8], Rogers et al. [24], Brufau et al. [7], Audusse and Bristeau [2], Valiani and Begnudelli [31], etc.

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Regarding the adoption of the FD method for dam-break flow modeling, one of the commonly selected numerical techniques is the MacCormack scheme ([19]). The MacCormack scheme is an explicit, second-order finite-difference scheme, which has been a popular scheme due to its effectiveness in numerical simulations and capability of modeling shock waves. As indicated by Garcia and Kahawita [14], the MacCormack scheme has an ability to simultaneously handle calculations of slowly varying flows, as well as, rapidly varying flows containing shocks. However, shock capturing algorithms for tracking the evolution of any discontinuity in the solution may introduce unwanted numerically generated oscillations. According to Harten [16], these oscillations not only damage the accuracy of the numerical solution, but can also induce nonlinear instabilities and trigger convergence to non-physical solutions. To resolve these problems, artificial diffusion is typically added or incorporated into the algorithm to remove the spurious oscillations that appear in the computational domain. However, the artificial diffusion terms require fine tuning in order to remove the oscillations without smearing the initial wave front. Due to the numerical oscillations that were observed using the standard MacCormack scheme, the Total Variation Diminishing (TVD) MacCormack scheme [27,28] has been selected to incorporate artificial diffusion into the scheme.

Compared to the MacCormack's explicit scheme, use of the implicit schemes in solving the SWE can improve the stability and accuracy of the FD solutions. The Alternating Direction Implicit (ADI) scheme, which is an implicit scheme, has been applied to simulate various free-surface flow conditions, such as tide-induced flows, in a staggered grid system. However, its application to the dam-break flows is very limited. The advantage the ADI scheme has over most implicit schemes is its ability to solve the governing equations directly without using an iteration procedure for a solution.

One of the first teams of researchers to apply the ADI scheme to fluid dynamics was Wilkes and Churchill [34]. Leendertse and Gritton [17] used the ADI scheme to simulate tide-induced flow and the transport of contaminants into Jamaica Bay in Long Island, New York. Later, Falconer [11] developed an ADI model to simulate tide-induced water levels, depth averaged velocities and nitrogen levels in Poole Basin, Poole Harbour and Holes Bay in Dorset, England. For modeling three-dimensional (3-D) flows and salinity transport in estuaries, Wang [32,33] adopted ADI approach to calculate the vertically integrated velocities that were used in 3-D computations. Molls and Chaudhry [22] used a ADI based model to study a hydraulic jump in a straight channel, flow in a converging channel, flow in a spur dike, and flow in a channel 180° bend. Recently, by using an ADI solver, Liang et al. [18] investigated numerically the problems of a partial dam-break in a square channel and transcritical flow in a frictionless channel with a bump and a dike break.

In terms of experimental studies, the types of experiments vary from dam-breaks in a straight flume, a curved flume or a channel bend, to a dam-break in a channel with an obstruction. Martin and Moyce [20] performed two-dimensional dam-break experiments in a rectangular and semicircular sections and a three-dimensional axial collapse of circular cylinders. The effect of bottom resistance on dam-break flows was examined experimentally by Dressler [10]. A dam-break experiment in a channel with a 180° bend was carried out by Miller and Chaudhry [21], where video cameras and resistance gauges were used to record the data.

Bellos et al. [4] performed a series of two-dimensional dam-break experiments in a converging–diverging channel with different channel slopes and reservoir depths. Three-dimensional dam-break experiments in a rectangular channel were conducted by Fraccarollo and Toro [12]. Capart and Young [9] examined experimentally the scouring of a horizontal granular bed by a dam-break flow. Brufau et al. [7] tested three physical models: a dam-break flow over a triangular obstacle, a non-symmetric dam-break in a pool with a pyramidal obstacle, and the propagation of a flood wave in the Toce River physical model. For dam-break flows occurred in channels with changing flow direction, Frazão and Zech [13] conducted numerical and experimental investigations on dam-break flow in channels with 90° bend. The spatial data rather than the time series data were presented. Their numerical approach was based on the FV method. Two-dimensional and three-dimensional modeling efforts were spent by Biscarini et al. [6] to study dam-break flows in a 90° bend channel.

In this study, a shallow-water equation based two-dimensional free-surface flow solver with the implementation of an ADI finite-difference scheme and coordinate transformation technique has been developed to model dam-break flows of selected cases. The governing equations with variables of contravariant velocities are transferred into the curvilinear coordinate system to allow for a better fit of computational domain to a physical domain, especially a more complex channel configuration. The less stability constrained ADI scheme is applied to formulate FD equations to be solved directly for the water depth and velocity components. Model performance is examined with results compared to other published experimental data for the cases of dam-break flows in a converging–diverging channel and a channel with a 45° bend. Good agreements are obtained. To further the verification of the ADI model, a series of dam-break experiments in a channel with a 90° bend were performed in the hydraulic lab at the University of Houston. The predicted dam-break water depths downstream of the dam face again give reasonable agreement with recorded data from model tests.

2. Governing equations

The governing equations adopted for the development of simulation model are the two-dimensional shallow water equations given as

$$\frac{\partial h}{\partial t}+\frac{\partial(uh)}{\partial x}+\frac{\partial(vh)}{\partial y}=0, \tag{1}$$

$$\frac{\partial(uh)}{\partial t}+\frac{\partial\left(u^2h+\frac{1}{2}gh^2\right)}{\partial x}+\frac{\partial(uvh)}{\partial y}=gh(S_{0x}-S_{fx}),\ \text{and} \tag{2}$$

$$\frac{\partial(vh)}{\partial t}+\frac{\partial(uvh)}{\partial x}+\frac{\partial\left(v^2h+\frac{1}{2}gh^2\right)}{\partial y}=gh(S_{0y}-S_{fy}), \tag{3}$$

where h is water depth, g is the gravitational constant, and u and v are the vertically averaged velocity components along the x- and y-directions respectively. The channel bed slopes, S_{0x} and S_{0y}, are defined as

$$S_{0x}=-\frac{\partial z_f}{\partial x}\ \text{and}\ S_{0y}=-\frac{\partial z_f}{\partial y}, \tag{4a, b}$$

where z_f is the channel bed elevation. The bottom friction slopes S_{fx} and S_{fy} can be calculated according to the Manning's formula as

$$S_{fx}=\frac{n^2u\sqrt{u^2+v^2}}{C_0^2h^{1.33}}\ \text{and}\ S_{fy}=\frac{n^2v\sqrt{u^2+v^2}}{C_0^2h^{1.33}}, \tag{5a, b}$$

where n is the Manning's roughness coefficient, C_0 is 1 for SI units or 1.49 for British units. For the governing equations, Eq. (1) represents the continuity equation while Eqs. (2) and (3) describe the conservation of momentum along the x- and y- directions respectively. Various approaches or methods can be selected to solve Eqs. (1)–(3) numerically. In this study, the finite-difference implicit scheme in a