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Modeling dam-break flows using a 3D mike 3 flow model

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Abstract

Dam-break flows usually propagate along rivers and floodplains. However, the majority of existing three-dimensional (3D) models used to simulate dam-break flows are only applicable to fixed beds. In this model, the common 3D shallow water equations are modified, so that the bed evolution on the flood wave propagation can be considered. These equations are based on the numerical solution of the three-dimensional incompressible Reynolds averaged Navier-Stokes equations invoking the assumptions of Boussinesq and of hydrostatic pressure. Thus, the model consists of continuity, momentum, temperature, salinity and density equations and it is closed by turbulent closure scheme. For this 3D model the free surface is taken into account using a sigma-coordinate transformation approach. The model employs an unstructured finite volume algorithm. A predictor–corrector scheme is used in time stepping, leading to a second-order accurate solution in both time and space. The model was verified against results from existing numerical models and laboratory experiments at the same time it was used to simulate dam-break flows over a fixed bed in the predicted flood wave speed and depth. The results indicate that there is a good correlation between the dam-break flow predictions made over a fixed bed and existing numerical models and laboratory experiments.

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Introduction

Dam-break flows could lead to severe flooding with cata-strophic consequences, such as damage to properties and loss of human life. Therefore, dam-break flows have been the subject of scientific and technical research for many hydraulic scientists and engineers. Earlier studies were primarily based on analytical solutions for idealised conditions. For example, Stoker (Stoker JJ, 1957) developed an analytical solution to predict dam-break flows in an idealised channel, in which the bed slope was assumed to be zero and the friction term was ignored. Chanson (Chanson H, 2005) proposed an analytical solution of dam-break waves with flow resistance, and then it was applied to simulate tsunami surges on dry coastal plains. During the past two decades, numerical models and laboratory experiments have become very popular for investigating dam-break flows (Lin *et al.,* 2003; Zech *et al.*, 2008). Developments in the last years have led to several numerical models aimed at solving the so-called dam-break problem (Glaister, 1988; Alcrudo and Garcia-Navarro, 1993; Zhao *et al.*, 1996). Mathematically, this problem is described by the Saint-Venant shallow-water equations stating mass and momentum conservation. Numerically, those equations can be solved by various techniques such as finite differences, finite elements, and finite volumes, in one or two spatial dimensions. With the advancement of computer technology and numerical solution methods of the shallow water equations hydrodynamic models based on two-dimensional (2D) and three-dimensional (3D) approaches are increasingly being used for predicting dam-break flows. Currently, numerical solutions of the shallow water equations type are one of the most active topics in the field of hydraulics research. Several numerical models pertaining to dam-break flows can be found in the literature, and they have been successfully used to predict flood inundation extent and velocity distributions. However, the majority of these models are only applicable to dam-break flows over fixed beds (Lin *et al.*, 2003; Zhou *et al.*, 2004; Gallegos *et al.*, 2009) . In this study, a three-dimensional finite-volume scheme is used for the numerical simulation of the dam-break flow over fixed beds in the straight channel. The model was verified against results from existing numerical models and experimental data from laboratory tests documented in the literature, and at the same time it was used to simulate dam-break flows over a fixed bed in the predicted flood wave speed and depth. Finally, this study simulated dam-break flows over a fixed bed to examine the differences in the predicted flood wave speed and depth. Those results provide new interesting elements for understanding the physics of the phenomenon and for the validation of numerical models.

Governing equations

The hydrodynamic governing equations used are based on solution of the three-dimensional incompressible Reynolds averaged Navier-Stokes equations, subject to the assumptions of Boussinesq and of hydrostatic pressure (Zhang and Xie, 1993; Xie, 1990). The shallow water governing equations of the 3D hydrodynamic model comprise the mass and momentum conservation equations for the mixture flow. The modified continuity (Eq. (1)) and momentum equations in the x and y-directions (Eq. (2) and (3)) can be expressed in detail as follows:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=S \qquad (1)$$

$$\frac{\partial u}{\partial t}+\frac{\partial u^2}{\partial x}+\frac{\partial uv}{\partial y}+\frac{\partial uw}{\partial z}= fv-g\frac{\partial \eta}{\partial x}-\frac{1}{\rho_0}\frac{\partial P_a}{\partial x}-\frac{g}{\rho}\int_z^{\eta}\frac{\partial \rho}{\partial x}dz- \frac{1}{\rho_0 h}(\frac{\partial s_{xx}}{\partial x}+\frac{\partial s_{xy}}{\partial y})+F_u+\frac{\partial}{\partial z}(v_t\frac{\partial u}{\partial z})+u_s S \qquad (2)$$

$$\frac{\partial v}{\partial t}+\frac{\partial v^2}{\partial x}+\frac{\partial uv}{\partial y}+\frac{\partial vw}{\partial z}=-fu-g\frac{\partial \eta}{\partial y}-\frac{1}{\rho_0}\frac{\partial P_a}{\partial y}-\frac{g}{\rho}\int_z^{\eta}\frac{\partial \rho}{\partial y}dz-\frac{1}{\rho_0 h}\left(\frac{\partial s_{yx}}{\partial x}+\frac{\partial s_{yy}}{\partial y}\right)+F_v+\frac{\partial}{\partial z}\left(v_t\frac{\partial v}{\partial z}\right)+v_s S \quad (3)$$

where t is the time; x, y and z are the Cartesian co-ordinates; η is the surface elevation; d is the still water depth; $h=\eta+d$ is the total water elevation; u,v,w are the velocity components in the x, y and z direction; $f=2\Omega\sin\phi$ is the coriolis parameter (Ω is the angular rate of revolution and ϕ the geographic latitude); g is the gravitational acceleration; ρ is the density of water; $S_{xx}, S_{xy}, S_{yx}, S_{yy}$ are components of the radiation stress tensor; v_t is the vertical turbulent (or eddy) viscosity; P_a is the atmospheric pressure; ρ_0 is the reference density of water; S is the magnitude of the discharge due to point sources and u_s, v_s is the velocity by which the water is discharged into the ambient water. The horizontal stress terms are described using a gradient-stress relation, which is simplified to

$$F_u=\frac{\partial}{\partial x}\left(2A\frac{\partial u}{\partial x}\right)+\frac{\partial}{\partial y}\left(A\left(\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x}\right)\right)$$
$$F_v=\frac{\partial}{\partial y}\left(2A\frac{\partial v}{\partial y}\right)+\frac{\partial}{\partial x}\left(A\left(\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x}\right)\right) \quad (4)$$

Where A is the horizontal eddy viscosity.

In many numerical simulations, small-scale turbulence cannot be resolved with the chosen spatial resolution. This kind of turbulence can be approximated using subgrid scaled models. (Smagorinsky, 1963) proposed the expression of subgrid scale transports by an effective eddy viscosity on a characteristic length scale. The subgrid scale eddy viscosity (A) was calculated by

$$A=c_S^2 l^2\sqrt{2S_{ij}S_{ij}} \quad (5)$$

Where c_S = constant and l = characteristic length. The deformation rate is given by

$$S_{ij}=\frac{1}{2}\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right) \quad (i,j=1,2) \quad (6)$$

In the vertical domain, The eddy viscosity derived from the log-law is calculated by

$$\upsilon_t=U_\tau h\left(c_1\frac{z+d}{h}+c_2\left(\frac{z+d}{h}\right)^2\right) \quad (7)$$

Where $U_\tau=Max(U_{\tau b},U_{\tau s})$ and c_1 and c_2 are two constants. $U_{\tau s}$ and $U_{\tau b}$ are the friction velocities associated with the surface and bottom stresses, c_1=0.41 and c_2= -0.41 give the standard parabolic profile.

Model Description

All simulations were performed using the MIKE 3 hydrodynamic modeling software developed by the Danish Hydraulic Institute (DHI). The MIKE 3 flow model FM is a modeling system based on a flexible mesh approach, developed for oceanographic, coastal, and estuarine environmental applications. Turbulence closure was implemented using the Smagorinsky model in the horizontal and vertical directions , respectively. The free surface was taken into account using a sigma- coordinate transformation approach (DHI, 2008). Spatial discretization of the primitive equations was performed using a cell-centered finite-volume method. The spatial domain was discretized by subdivision of the continuum into non overlapping elements/cells. In the horizontal plane, an unstructured grid was used, whereas in the vertical domain, a sigma-layer approach was used. The elements could be prisms or bricks, whose horizontal faces were triangles and quadrilateral elements, respectively. An approximative Riemann solver (Roe, 1981) was used to compute the convective fluxes, which makes it possible to handle discontinuous solutions. For time integration, a semi-implicit approach was used, where in the horizontal terms were treated explicitly and the vertical terms implicitly.

Model test

(Xia.*et al.*, 2010) modeled rapidly varying flows caused by sudden dam-break by a two-dimensional finite volume numerical method. They used experimental data to verify the numerical model. Imaging technique for acquisition of experimental data was utilized. Test cases of dam-break flows was undertaken a partial dam-breach flow over a fixed bed. The mesh was created using the MIKE Zero Mesh Generator, using the triangular and rectangular unstructured mesh form. Meshes with various numbers of nodes were tried during the mesh creation process. They were tested for simulation time, and the finest mesh with an acceptable run time was selected. The selected mesh consisted of 21181 elements (Fig.1). The maximum element area was about 1500 m². The model domain was composed a 2000 m by 10000 m basin of a fixed bed, with a wall being inserted in the center to partition the basin into two regions. A 40 m wide dam was assumed to be located in the center of the wall. (Fig.2) shows a sketch of the model domain, in which two observation points are also marked. Initially on the left side of the wall the water depth was set to 5 m, and on the right side of the wall it is assumed to be dry. In the vertical domain, the uniformly distributed 10-layer model was chosen for further analyses. For temporal discretization, a time step of 36 s was described, corresponding to the maximum Courant-Friedrichs-Lewis criterion of 0.8.

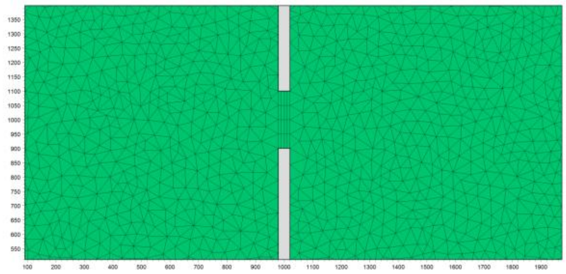

Fig. 1. Overview of computational mesh.

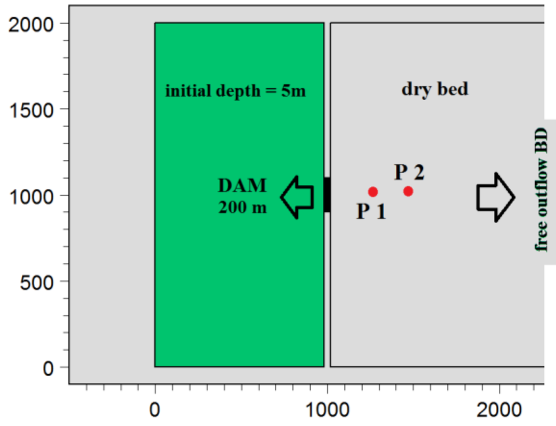

Fig. 1. Sketch of a partial dam-break flow.

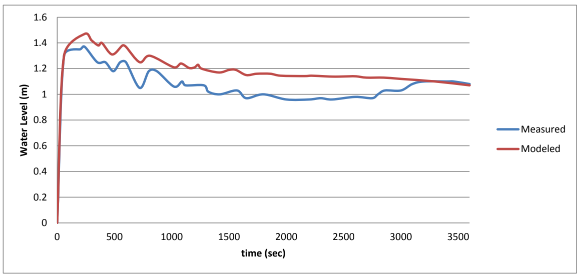

Fig. 2. Water level variations downstream of the dam for P1.

Model results and discussion

After validating the calibrated model, it was run for an hour, and the water level was analyzed. Water level variations downstream of the dam (Fig. 3 and 4) shows the variations of water levels at sites P1 and P2. It can be seen from these two figures that the predicted water levels. Fig. 5, 6 and 7 shows, the contours of current speed every 3 minutes after start dam break respectively. During the routing of the dam-break wave, the flow from the dam-break diffused to-wards the circumference, with the largest velocity occurring at a point along the channel centerline. Fig. 8, 9 and 10 shows a longitude profile of current speed and water level at centerline every 3 minutes after start dam break.

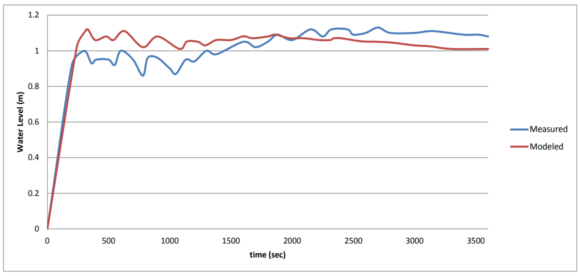

Fig. 3. Water level variations downstream of the dam P2.

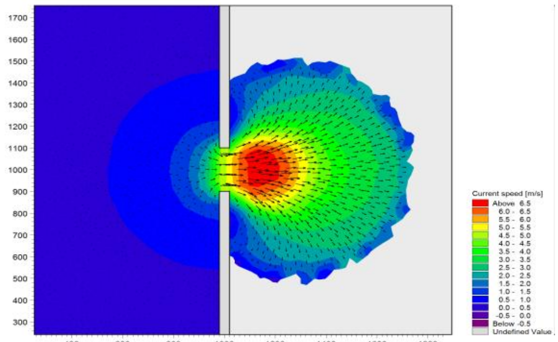

Fig. 4. Contours of current speed after 3 minutes.

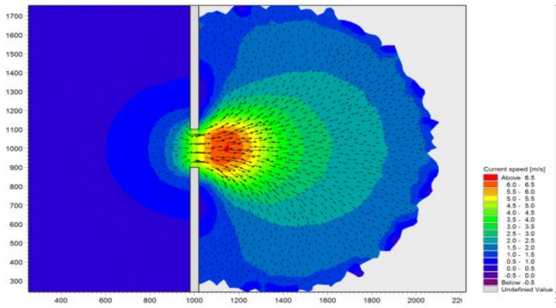

Fig. 5. Contours of current speed after 6 minutes.

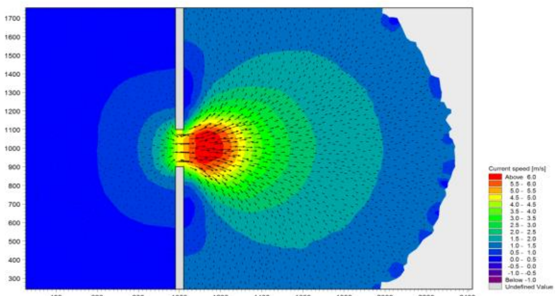

Fig. 6. Contours of current speed after 9 minutes.

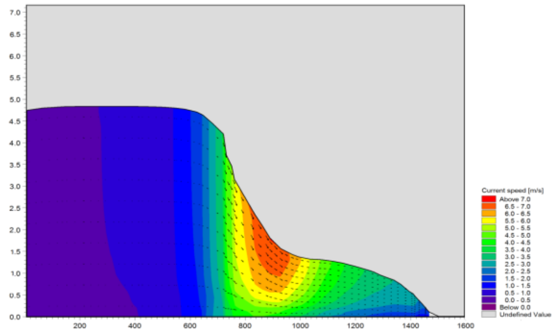

Fig. 7. Contours of current speed and water level at centerline after 3 minutes.

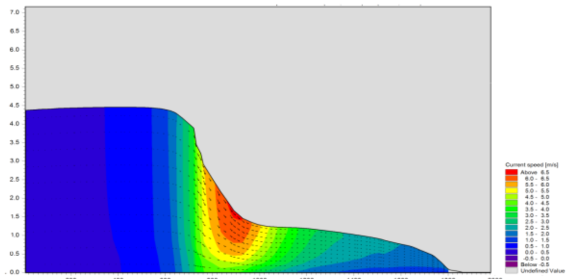

Fig. 8. Contours of current speed and water level at centerline after 6 minutes.

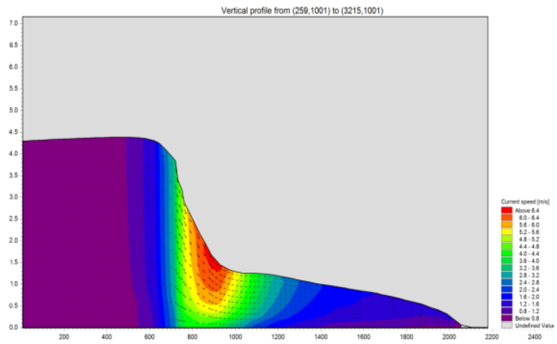

Fig. 9. Contours of current speed and water level at centerline after 9 minutes.

Conclusion

Numerous marine works, especially immersion processes and navigational issues, need to determine moderate flow conditions for operation. To identify moderate flow conditions, models have become essential and unavoidable tools in the modern world of water management. They are used extensively and play an important auxiliary role in fulfilling the core tasks of water management, in policy preparation, and in operational water management. Setting up a model or selecting and calibrating the model parameters are very time-consuming tasks. The model was also validated temporally and spatially. In model calibration, a visible difference was observed between the model results and measurements at water level. From the results of the 1-hour model evaluation, it was observed that the current velocities in the profile and plan at the upper layer were higher than in the lower layer. From the results of the model evaluation, it was observed that the current velocities increased from the surface to the middle layer. The maximum current velocity reached 6.5 m/s at the surface and 7 m/s at the middle layer.

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