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Research paper

Numerical modeling of flow and scouring around a cofferdam

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Abstract

When planning river hydraulic structures, the analysis of the hydrodynamic and bed elevation change is of great importance, particularly the assessment of the scour depth around a cofferdam. In this study, the flow field variation and the corresponding scour depth was simulated using two-dimensional hydrodynamic analysis and a bed-load transport model. The hydrodynamic model used the streamlined upwind Petrov–Galerkin (SUPG) finite element scheme to solve the Reynolds-averaged turbulent flow equations. Based on the results of flow field analysis, the bed-load transport model was able to simulate the scour hole development, where it was shown that velocity gradients dramatically increase due to the existence of hydraulic structures. The applicability of the model was tested by simulating the velocity field and bed elevation changes around the cofferdam constructed during the Lock and Dam No. 26 replacement project in the Mississippi River. The model created in this study is able to estimate the maximum scour depth, determine the configuration of the cofferdam to suggest changes to reduce any local scour, and suggest if protection materials around the cofferdam are needed.

Keywords: Finite element method; Cofferdam; Mathematical modeling; Groin; Bed-load; Scour

1. Introduction

Hydraulic structures, such as spur dikes and groins, redirect flow, protect riverbanks from erosion, create stable pools for aquatic habitat, and trap sediment in backwater zones (Duan, 2009). These types of hydraulic structures reduce the flow area and alter the flow patterns, which increase the local velocities, shear stresses, vortices, and turbulence and result in significant changes in the bed elevation (Molinas et al., 1998). Thus, understanding the flow fields and removing channel bed material when scour holes are developed around bridge abutments, spur dikes, and groins are of great importance not only for assessing the safety of the hydraulic structures but also for improving the ecosystem of the river.

Experiments have been conducted that identified the mean flow field and the local scouring, including the bed evolution around spur dikes, abutments, and thin walls, that are due to the existence of spur dikes and groins (Rajaratnam and Nwachukwu, 1983a, 1983b; Kuhnle et al., 1999). The three-dimensional (3D) turbulent flow field around a short vertical wall abutment has been identified using acoustic Doppler velocimetry (ADV) (Dey and Barbhuiya, 2005). Duan (2009) investigated the mean flow and turbulence around a spur dike in a laboratory flume using ADV and found that local scouring occurred in the zone where there was a high bed-shear stress near the dike, where the bed-shear stress at the dike tip was approximately two to three times greater than the bed-shear stress of the approaching flow.

In addition to experimental studies, many numerical simulations of two-dimensional (2D) and 3D hydrodynamic models around hydraulic structures have been created. Tingsanchali and Maheswaran (1990) incorporated a streamline curvature for shear stress computations near the tips of groins of a depth-averaged 2D hydrodynamic simulation. Mayerle et al. (1995) compared reattachment lengths by applying different degrees of eddy viscosity closures in a 3D

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finite element model and found that the results from turbulent viscosity approach, based on the mixing-length configuration and such assumptions as local equilibrium of the kinetic energy produced by the wake length, agreed closely with the actual measurements. Ouillon and Dartus (1997) investigated flow and shear stress distributions around groins using a 3D $k-\varepsilon$ turbulent model and the porosity method to track the free surface and compared the results with those of the rigid-lid model. There was no discrepancy between the rigid-lid and free surface model near the nose region of the groin where significant local scour was expected. Molinas and Hafez (2000) derived the velocity amplification factor using a 2D finite element surface flow model based on the protrusion ratio of short abutments. Duan and Nanda (2006) reported the development and application of a depth-averaged hydrodynamic model to simulate the concentration of suspended sediment around groins.

Nagata et al. (2005) developed a numerical model to simulate the flow and bed deformation around spur dikes and bridge piers using the 3D Reynolds-averaged Navier–Stokes equations, which required 10 days of simulation time to compute the channel bed deformation. Huang et al. (2009) created a computational fluid dynamics model of the flow and scouring around bridge piers using the FLUENT software package and found that perfect results were difficult to obtain even with complex 3D numerical modeling. Hung et al. (2009) developed a 2D unsteady depth-averaged model for non-uniform sediment transport in alluvial channels and noted that even though many 3D numerical models of sediment transport processes had recently been reported, hydraulic engineers often use the 2D depth-averaged model in practice because of its efficiency and reasonable accuracy. The scouring and sedimentation process is generally a full 3D process because the vertical velocity in the depth direction results in an eddy zone in the vertical plane, resulting in a spiral flow in the horizontal plane. However, the 2D approach is still valid when simulating bed elevation changes if the shear stress on the channel bottom is obtained from a flow solver. The sediment continuity equation that solves the change in the bed elevation is a 2D equation, despite the bed being in 3D space (Liu and Garcia, 2008).

This study focused on determining the flow field distribution and the corresponding bed elevation changes around hydraulic structures, such as bridge abutments and cofferdams. In particular, when a cofferdam is constructed on alluvial streams, a considerable amount of scour is expected in the constricted channel cross-section at the flood stage. By solving the 2D Reynolds-averaged Navier–Stokes equations using the upwind finite element method scheme and the bed-load transport equation to estimate the scour depth hole development, the models proposed in this study were tested using laboratory data and used to estimate the scour depth during Phase I of the Lock and Dam No. 26 replacement project on the Mississippi River. The model proposed in this study estimates the maximum scour depth and can suggest changes to the configuration of the cofferdam to reduce any local scour.

2. Model description

2.1. Hydrodynamic model

The hydrodynamic model solves the following depth-averaged continuity and momentum equations with turbulent eddy viscosity. The time-averaged Navier–Stokes equations (Reynolds-averaged equations) for the mean turbulent flow under steady and incompressible conditions constitute the hydrodynamic simulation model. The governing continuity and momentum equations are

$$\frac{\partial hu}{\partial x}+\frac{\partial hv}{\partial y}=0 \tag{1}$$

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=-\frac{\partial}{\partial x}\left(\frac{P}{\rho}\right)+\frac{\partial}{\partial x}\left(2\nu_{\mathrm{T}}\frac{\partial u}{\partial x}\right)+\frac{\partial}{\partial y}\left[\nu_{\mathrm{T}}\left(\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x}\right)\right]+\left[\frac{\partial}{\partial z}\left(\frac{\tau_{\mathrm{s}}}{\rho}\right)\right]_{z=h}+F_x \tag{2}$$

$$u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}=-\frac{\partial}{\partial y}\left(\frac{P}{\rho}\right)+\frac{\partial}{\partial x}\left[\nu_{\mathrm{T}}\left(\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x}\right)\right]+\frac{\partial}{\partial y}\left(2\nu_{\mathrm{T}}\frac{\partial v}{\partial y}\right)+\left[\frac{\partial}{\partial z}\left(\frac{\tau_{\mathrm{n}}}{\rho}\right)\right]_{z=h}+F_y \tag{3}$$

where u is the depth-averaged flow velocity in the x-direction (longitudinal); v is the depth-averaged flow velocity in the y-direction (transverse); P is the mean pressure; ν_{T} is the turbulent viscosity; F_x and F_y are the gravitational body forces in the longitudinal and transverse direction, respectively; z is the vertical distance from the channel bed; h is the flow depth; ρ is the density of water; and τ_{s} and τ_{n} are the longitudinal and transverse turbulent shear stresses, respectively.

The two shear stress terms in Eqs. (2) and (3) are evaluated at the water surface. These stress terms can be expressed in terms of the depth-averaged velocities, u and v, the Darcy–Weisbach friction factor, f and the von Karman constant, κ. It is possible to express the longitudinal and transverse turbulent shear stresses with turbulent viscosity.

$$\frac{\tau_{\mathrm{s}}(z)}{\rho}=\nu_{\mathrm{T}}\frac{\partial u(z)}{\partial z};\frac{\tau_{\mathrm{n}}(z)}{\rho}=\nu_{\mathrm{T}}\frac{\partial v(z)}{\partial z} \tag{4}$$

Assuming a power law variation of the longitudinal velocity in the vertical direction, a general relationship can be described as

$$\frac{u(z)}{U_{\mathrm{av}}}=C_1\left(\frac{z}{h}\right)^{C_2} \tag{5}$$

where C_1 and C_2 are experimental coefficients that describe the vertical velocity distributions; $u(z)$ is the longitudinal local velocity as a function of the vertical distance from the bed; and U_{av} is the depth-averaged longitudinal velocity. In the past, for large rivers, C_1 and C_2 values were found to be 1.143 and