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Numerical Simulation of Local Scouring around a Cylindrical Pier

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Abstract:

This paper reports the findings of a numerical modeling study for simulating the time-dependent scour hole development around a cylindrical pier standing on a loose bed on an open channel. In order to be able to obtain the realistic flow characteristics such as the downwash motion in front of the pier, the horseshoe vortex around pier, the vortex shadings behind the pier, etc., the CCHE3D model, developed, verified and validated by the scientists of the National Center for Computational Hydroscience and Engineering at the University of Mississippi was applied. Special features for accounting the effects of downwash, vortices and fluctuating turbulence intensity on the sediment entrainment and transport capacity have been added to the transport model. In addition, the non-equilibrium sediment transport equation has been used to further enhance the accuracy. The resulting three-dimensional turbulent flow and the enhanced sediment transport model has been applied to the simulation of the bridge pier scour development study. After calibration of the so-called site-specific parameters using physical model and field data, a validation procedure was conducted based on additional physical measurement having not been used in the calibration process. The calibrated and validated CCHE3D is then, used to perform a prediction of the maximum scour hole depth for the Case No. 1 specified by the Organization of the Prediction Event of the First International Conference on Scour of Foundations (ICSF-1). The maximum depth and geometry of the scour hole at the end of prediction time are included.

Introduction

It has been observed that in the free surface flow around an obstruction, such as a bridge pier, downwash motions, horseshoe vortices, an vortex shading are formed and the turbulence is intensified in front, around and behind the piers. In addition, a uniquely shaped scour hole on the loose bed around a pier is seen. Experimental studies have found that both the flow and the sediment transport processes during the scour hole development are highly complex.

Many measurements from physical models have shown that the depth of the scouring hole is closely related to the approaching flow condition, sediment property and the dimension of the pier (Melville, 1975 and 1984, Ettema, 1980, Knight, 1975, Kothyari, 1988, Shen and Schneider, 1969, Ahmed and Rajaratnam, 1998 and Eckerle and Langston, 1987). Some empirical functions based on fitting laboratory and field data have been derived to determinate the maximum scour depth around cylindrical piers.

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Some progresses of using numerical simulation to study the flow around a pier and scouring process have been made in recent years. Rizzetta (1993) and Richardson and Panchang (1998) computed flow fields around a bridge pier with a flat bed and in a scour hole using three-dimensional flow models. Zaghloul and McCorquodale (1975) simulated scour hole near a spur dike, vorticity and turbulence energy were introduced to add additional information and enhance sediment transport simulation in the scour hole. Olsen and Melaaen (1993) predicted local scour developing processes using a three-dimensional flow and sediment transport model. The limitation of their simulation was that the sediment transport capacity was only related to frictional shear stress, and the predicted local scour appeared only on the sides of the pier. By introducing vorticity and turbulence energy into the sediment transport capacity, Jia and Wang (1996) simulated local scouring around a spur dike. Accounted for downwash flow, vorticity and turbulence energy, Dou, et al, (1996) introduced a sediment transport capacity formula into three dimensional numerical simulation, and successfully simulated scouring around structures such as cylindrical pier, square pier and bridge abutments. Good agreements between numerical simulation and physical model measurement have been obtained.

This paper presents numerical predications of the maximum depth and the development process of the scour hole near a cylindrical pier. A modified van Rijn's formula relating the sediment transport rate to bottom shear stress and downwash flow was introduced to simulate the scour hole development and it is validated using experiment data.

Mathematic Model

Flow Model

CCHE3D is a three-dimensional numerical model for simulating turbulent free surface flows and sediemnt transport using finite element method (Wang and Hu, 1992 and Jia and Wang, 1998). The momentum and continuity equations were solved:

$$u_{i,t} + u_i u_{i,j} + \frac{p_{,i}}{\rho} - (-\overline{u_i u_j})_j + f_i = 0 \qquad (1)$$

$$u_{i,i} = 0 \qquad (2)$$

where u_i is velocity component in the i-direction ($i = 1,2,3$ for x, y, z of the Cartesian coordinate). f_i is the forcing term in the ith direction. $-\rho\overline{u_i u_j}$ are the Reynolds Stresses, ρ is the density of water. p is pressure. Free surface kinematical equation was used to determine the free surface elevation, η:

$$\eta_{,t} + u_\eta \eta_{,x} + v_\eta \eta_{,y} - w_\eta = 0 \qquad (3)$$

A velocity correction method is used for solving the pressure to enforce mass conservation. The turbulent stresses, $-\rho\overline{u_i u_j}$, are calculated using the mean flow gradients through Boussinesq's eddy viscosity concept:

$$-\overline{u_i u_j} == \nu_t\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_x}\right) - \frac{2}{3}k\delta_{ij} \qquad (4)$$

where ν_t is the turbulence eddy viscosity,

$$\nu_t = C_\mu \frac{k^2}{\varepsilon} \tag{5}$$

k and ε are the turbulent kinetic energy per unit mass and its dissipation rate, governed by transport equations:

$$k_{,t} + u_i k_{,i} = (\frac{\nu_t}{\sigma_k} k_{,i})_{,i} + P - \varepsilon \tag{6}$$

$$\varepsilon_{,t} + u_i \varepsilon_{,i} = (\frac{\nu_t}{\sigma_\varepsilon} \varepsilon_{,i})_{,i} + c_{1\varepsilon} \frac{\varepsilon}{k} P - c_{2\varepsilon} \frac{\varepsilon^2}{k} \tag{7}$$

$$P = -\overline{u'_i u'_j} u_{ij} \tag{8}$$

The modification made by Speziale and Thangam (1992) to the standard k-ε model, RNG k-ε model, is adopted which requires C_μ=0.085, σ_k=0.7179, σ_ε=0.7179, $C_{2\varepsilon}$=1.68 and

$$C_{1\varepsilon} = 1.42 - \frac{\eta(1-\eta/4.38)}{1+0.015\eta^3} \tag{9}$$

Sediment Transport Model

In sediemnt transport simulation, bed load is considered to be dominant in the studied cases. Because the local scouring affected by the turbulent 3D flow, bed load transport is the non-equilibrium transport process governed by

$$\frac{\partial q_{bx}}{\partial y} + \frac{\partial q_{by}}{\partial y} + \frac{1}{L_s}(q_b - q_{*b}) = 0 \tag{10}$$

The local scour deformation around the cylindrical pier is governed by the sediment mass balance equation:

$$(1-p')\frac{\partial z_b}{\partial t} + \frac{\partial q_{bx}}{\partial y} + \frac{\partial q_{by}}{\partial y} = 0 \tag{11}$$

where z_b is bed elevation, q_{bx} and q_{by} are the sediment transport rate in x and y direction, respectively, and $q_b = \sqrt{q_{bx} + q_{by}}$, q_{b*} is sediment transport capacity under equilibrium transport condition. p' is porosity of the bed material. L_s is the so called adaptation length, related to local flow conditions and mesh size.

Sediment transport capacity is determined by modified van Rijn's formula:

$$q_{*b} = 0.053(\frac{\rho_s - \rho}{\rho} g)^{0.5} \frac{d^{1.5}}{D_*} T^{2.1} \tag{12}$$

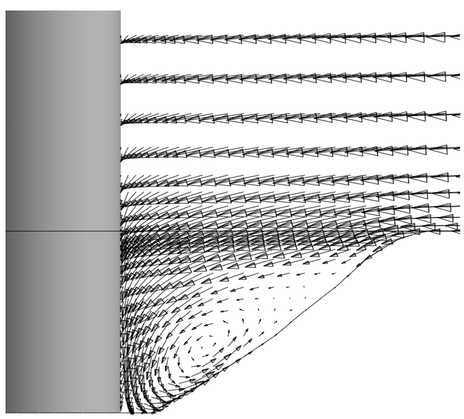
where, ρ_s and ρ are sediments and fluid density, d is the sediment size and $D_* = d_{50}\{\frac{\rho_s - \rho}{\rho}\frac{g}{\nu^2}\}^{1/3}$. T is sediment mobility parameter:

$$T = \frac{[C_s \tau_d (u_\perp / u_{\perp,\max}) + \tau] - \tau_{cr}}{\tau_{cr}} = \frac{C_s \tau_d (u_\perp / u_{\perp,\max})}{\tau_{cr}} + \frac{\tau}{\tau_{cr}} - 1 \tag{13}$$

The first term is introduced in this study for handling local scouring process. $u_{\perp}$ is the near bed velocity component normal to bed surface. τ_d is the mean frictional shear stress around the cylinder and C_s is an empirical coefficient. It can be seen that the impact of vertical velocity or the "downwash" flow has been taken as the most significant factor for scouring. τ_d serves as a reference measuring the strength of the turbulent flow near the bed of the scouring hole. The term of $\tau / \tau_{cr} - 1$ is the same as the sediment mobility defined by van Rijn (1986). The critical shear stress, τ_{cr}, has included the effect of bed slope and the near bed flow direction.

Validation of the Flow and Sediment Transport Models

The CCHE3D model has been verified and validated by using several analytic methods, physical model and field data. Figure 1 shows the simulated flow field in a preformed scouring hole (Jia and Wang, 1999). The flow conditions of the test case were from the flume experiment of Melville and Raudkivi (1977). The figure indicates that the flow structure (horseshoe vortex) and the near bed velocity are computed realistically.



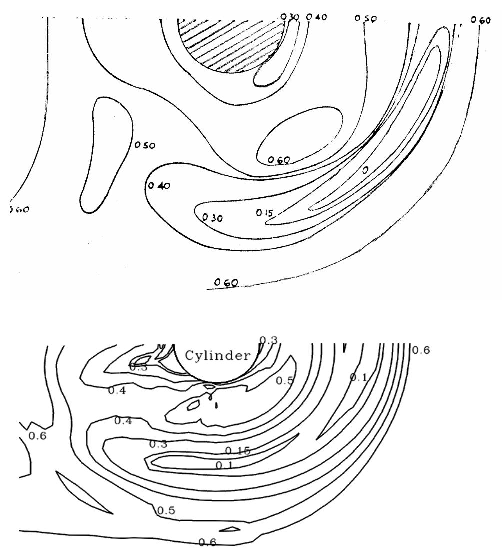


Figure 1. Simulated flow in front of a cylindrical pier and the near bed velocity in a preformed scour hole.

The aforementioned model has been tested using physical model data measured by Ettema (1980). The test cases selected have similar flow condition, cylindrical pier size and sediment size (0.38mm and 0.24mm). The case was clear water scouring with U_*/U_{*cr}=0.9. In these tests, the adaptation length L_s (=5.0) and the coefficient for entraining sediment due to the pier, C_s (=3.0) were determined.

Simulation Results

The CCHE3D model was applied to predict the flow fields and the local scouring around a cylindrical pier under clear water and live-bed scour conditions with sand bed material.

A non-uniform, body fitted mesh with 48x121 nodes were used for the domain discretization. The grid close to the pier has much higher density than those away from it. Grid spacing increases gradually in the radial direction from the pier center. The vertical grid consists of 21 levels with fine grid size near the bed and coarser one near the free surface. The vertical grid was gradually stretched as the scour hole developing. Because the bed change rate is low, the grid velocity was neglected in the computation. The hydrodynamics and the sediment transport computation were not coupled, the flow field was considered as a quasi-steady and updated as bed elevation changes.

The Case 1 of the ICSF-1 (First International Conference on Scour of Foundations) test cases was selected for simulation. The test flume is 1.5m wide with flat bed and vertical walls. A single pier was located in the middle of a straight flume. The flow and sediment conditions used in the numerical simulation are listed in Table 1.

Table 1. Flow conditions of the simulated local scouring cases.

Case	Soil type	y_1 (m)	b (m)	U (m/s)	$R_b = \frac{Ub}{\upsilon}$	$F_r = \frac{U}{\sqrt{gy_1}}$	D_{50} (m)	D_{90} (m)
1	Sand	0.375	0.16	0.35	56,000	0.1825	0.0003	0.0006

y_1 = water depth, b = diameter of the pier, U = approaching mean velocity

The erosion started from the two sides of the pier where the bed surface has the maximum bottom shear stress. The two small scouring holes gradually migrated upstream around the pier and met at the front of the pier. The two scouring holes merged into a bigger one, and its depth and size grew around the front of the pier due to the strong downwash flow. The deepening and widening of the scouring hole stimulated the downwash flow and the vortex in the hole that in turn further accelerated the scouring.

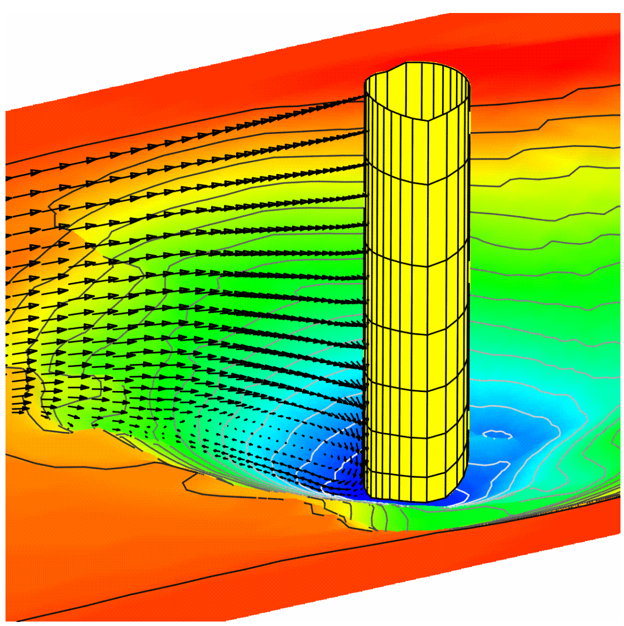


Figure 2. An oblique view: the simulated scouring hole and the three-dimensional flow structure. Case 1.

The simulation started from the flat bed and the scouring depth was recorded from time to time. Figure 2 displays the geometry of the scour hole at the scouring time approaching to 24 hours. The simulation results show that the scour hole depth was asymptotically approaching to 0.323m, when the simulation time reached to 24 hours approximately.

Conclusions

This paper presents the simulation results of local scour around a cylindrical pier, the prediction case proposed by ICSF-1, using CCHE3D model, a numerical model for simulating unsteady three-dimensional hydrodynamic, sediment transport and scour hole formation processes. The modified van Rijn's formula for predicting sediment transport capacity was introduced and validated using experimental data. The predicted maximum depth of the local scour hole for the test Case 1 was 0.323m after 1 day of scouring.

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