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Wu, Weiming; Wang, Sam S.

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PREDICTION OF LOCAL SCOUR OF NON-COHESIVE SEDIMENT AROUND BRIDGE PIERS USING FVM-BASED CCHE2D MODEL

By

Weiming Wu[1] and Sam S.Y. Wang[2]

ABSTRACT

The FVM-based CCHE2D model is a depth-averaged 2-D numerical model for flow and sediment transport in open channels. It is enhanced to simulate the local scour around hydraulic structures after modifying Wu et al's (2000) sediment transport capacity formulas to account for the influences of pressure gradient and turbulence intensity on sediment movement. Preliminary tests using 34 sets of experimental data from bridge piers and spur dikes show that the measured and simulated maximum scour depths are in good agreement. The FVM-based CCHE2D model is applied to simulate the local scour around bridge piers in ICSF-1 test cases 1 and 2. The predicted maximum scour depths are 0.182m and 0.205m, respectively, with a margin of about ±20% errors.

INTRODUCTION

The local scour around hydraulic structures is a very complicated three-dimensional phenomenon, and the prediction of the scouring process is very challenging. Many empirical formulas have been established by using experimental measurements. These formulas usually are limited to providing some lumped information on the maximum scour depth, the scour volume, etc., under constant flow conditions. In order to provide more detailed information on the local scour process in more general situations, numerical modeling has been applied to this field recently. Because of the complexity of flow and sediment transport in the vicinity of hydraulic structures, a three-dimensional numerical model is usually required. However, the cost of three-dimensional modeling is still very high. Recently, we are trying to establish the local scour prediction capability in the depth-averaged 2-D numerical model, FVM-based CCHE2D. Some promising progress has been achieved. The FVM-based CCHE2D is applied to simulate the test cases proposed by the First International Conference on Scour of Foundation (ICSF-1). Introduced in this paper are the modeling techniques, model calibration and prediction results.

BRIEF DESCRIPTION OF THE FVM-BASED CCHE2D MODEL

The FVM-based CCHE2D flow model is a depth-averaged 2-D model for open-channel flows. It solves the two-dimensional depth-averaged shallow water equations by using the finite volume

[1] Research Assistant Professor, National Center for Computational Hydroscience and Engineering, The University of Mississippi, MS 38677, USA, (wuwm@ncche.olemiss.edu)
[2] F.A.P. Barnard Distinguished Professor and Director, National Center for Computational Hydroscience and Engineering, The University of Mississippi, MS 38677, (wang@ncche.olemiss.edu)

method on a non-staggered (collocated) curvilinear grid system. The SIMPLE and SIMPLEC algorithms in conjunction with Rhie and Chow's (1983) momentum interpolation technique are used to solve the pressure-velocity coupling problem. The convection terms in the governing equations can be discretized by four numerical schemes: hybrid upwind/central scheme, exponential scheme, QUICK scheme and HLPA scheme. The turbulence stresses can be determined by five turbulence models, including the depth-averaged parabolic model, mixing length model, "sub-grid" model, standard k-ε turbulence model and RNG k-ε turbulence model. The FVM-based CCHE2D flow model can simulate steady and unsteady flows in rivers and estuaries.

The FVM-based CCHE2D sediment transport model (Wu and Wang, 2002) simulates the non-equilibrium transport of nonuniform total-load sediment. The bed load and suspended load are calculated separately or jointly according to sediment transport modes. The non-cohesive sediment transport capacity is determined by four formulas: Wu et al's (2000) formula, the SEDTRA module, the modified Ackers and White's formula and the modified Engelund and Hansen's formula. The governing equations are discretized by the finite volume method in curvilinear grid, which is the same as that used in the flow model. The model has been tested in many experimental and field cases of general sediment transport under gradually-varying flow conditions.

However, the above-mentioned FVM-based CCHE2D model, which was designed for general sediment transport modeling, cannot be applied to local scour simulation. For this purpose, certain enhancements must be made. For simulating the local scour due to jet impingement and headcut migration using a three-dimensional numerical model, Wu et al's (1999) modified van Rijn's (1989) sediment transport formulas by introducing several correction factors to take into consideration the influences of the dynamic pressure gradient, downward flow, bed slope and turbulent intensity on sediment movement. Following Wu et al's approach, we modified the Wu et al's (2000) sediment transport capacity formulas implemented in the FVM-based CCHE2D model. Due to the fact that the downward flow and the vertical pressure gradient cannot be determined by a depth-averaged 2-D model, the correction factors for these two flow attributes have to be dropped. The pressure gradient in stream-wise direction is replaced by the water elevation gradient. The critical shear stress, τ_c, for the incipient motion of uniform sediment in the modified formulas is given as 0.045, which is 1.5 times of the value used in the original Wu et al's (2000) formulas. The same change can be found in other stochastic formulas, such as that proposed by van Rijn (1989).

After considering the influences of the stream-wise pressure gradient and the turbulence intensity, the effective tractive force τ_e used in the modified Wu et al's sediment transport capacity formulas is determined by

$$\tau_e = \alpha_t \max\left(\tau_b, -\frac{\pi}{6} f d \rho g \frac{\partial z_s}{\partial s}\right) \tag{1}$$

where τ_b is the bed shear stress; d is the diameter of sediment particles; g is the gravitational acceleration; z_s is the water elevation; s is along the stream-wise direction; ρ is the flow density; and f is a empirical coefficient relating to the sediment particle shape, pier shape, flow conditions, etc. The coefficient f is preliminarily calibrated as

$$f = \begin{cases} 3.4 D_*^{-0.3} f_s & D_* < 50 \\ 52.5 D_*^{-1} f_s & D_* \geq 50 \end{cases} \tag{2}$$

where $D_* = d\left[g(\rho_s/\rho - 1)/\nu^2\right]^{1/3}$; ρ_s is the sediment density; ν is the dynamic viscosity of flow; f_s is the shape factor of sediment particles, $c/\sqrt{ab}$, with *a*, *b* and *c* being the longest, the medium and the shortest diameters of sediment particles.

α_t is the correction factor to consider the influence of turbulence intensity. Assuming the instantaneous tractive force to have a normal distribution, time-averaging the instantaneous sediment transport rate and taking the ratio of the time-averaged sediment transport rates in the rapidly-varying flow and normal flow, one can obtain

$$\alpha_t = \left(\frac{\sigma}{\sigma_0}\right)\left[\int_0^\infty x^m e^{-0.5(x-p)^2} dx\right]^{1/m} \Bigg/ \left[\int_0^\infty x^m e^{-0.5(x-p_0)^2} dx\right]^{1/m} \tag{3}$$

where *m* is the power index of $\tau_e/\tau_c - 1$ in Wu et al's (2000) formulas, and hence $m = 2.2$ for the bed-load transport rate, and *m* is approximated as 2.6 for the suspended-load transport rate; $x = (\hat{\tau}_e - \tau_c)/\sigma$, $p = (\overline{\tau}_e - \tau_c)/\sigma$, and $p_0 = (\overline{\tau}_{e0} - \tau_c)/\sigma_0$. $\hat{\tau}_e$ is the instantaneous tractive force. $\overline{\tau}_e$ is the mean value of $\hat{\tau}_e$. $\overline{\tau}_{e0}$ is the bed shear stress in the approach normal flow. σ and σ_0 are the deviations of the tractive force at the rapidly-varying flow and normal uniform flow respectively. $\sigma = 0.4\rho c_{\Gamma\varepsilon} c_\mu \overline{k}$, in which $\overline{k}$ is the turbulent energy. c_μ and $c_{\Gamma\varepsilon}$ are coefficients in the k-ε turbulence model (Rodi, 1993). σ_0 is the value of σ at the upstream approach reach.

If the slope angle is larger than the submerged repose angle of sediment, a loose bed will collapse due to the gravity. This physical phenomenon has been considered in the calculation by adjusting the steeper bed slopes to the submerged repose angle of sediment according to mass conservation.

TEST OF THE FVM-BASED CCHE2D MODEL FOR LOCAL SCOUR

The FVM-based CCHE2D model with the newly modified Wu et al's sediment transport capacity formulas is tested using several groups of laboratory flume experiments, including the experiments on local scour at cylindrical piers conducted by Ettema (1980), near cylindrical piers by Ahmed (1995), around cylindrical and square piers by Yanmaz and Altinbilek (1991), and near spur dikes by Rajaratnan and Nwachukwu (1983). The total number of experimental runs simulated here is 34, including 6 on spur-dikes, 3 on square piers and 25 on cylindrical piers. The approach flow depths are in the range of 0.1m-0.6m, the approach flow velocities are in 0.2m/s-0.48m/s, and the diameters of piers or the lengths of spur dikes are in 0.057m-0.24m. The sediment is almost uniform, with size ranging 0.24mm-7.8mm. Fig. 1 shows the comparison between the measured and simulated maximum scour depths. The agreement between measurement and simulation is very good. The errors in most of the tested cases are in the range of ±20%. The development process and the final shape of the scour hole are simulated reasonably well. Those results are not shown here unfortunately because of the limit of paper length.

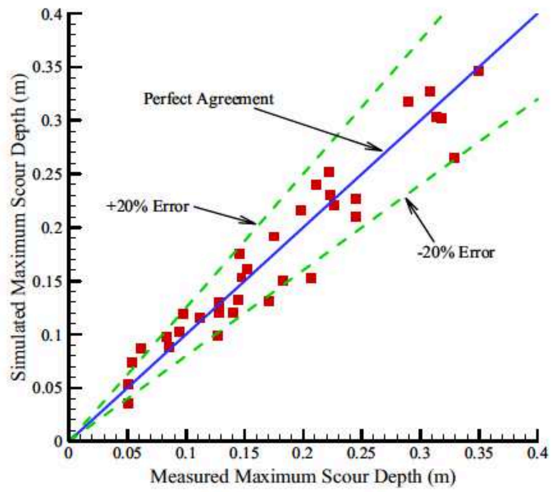

Fig. 1 Measured vs. Simulated Maximum Scour Depths around Bridge Piers and Spur Dikes

PREDICTION RESULTS FOR THE ICSF-1 TEST CASES

Because the modified Wu et al's sediment transport capacity formulas are only for non-cohesive sediment, the prediction is just made for the flume cases 1 and 2. In case 1, the diameter of the cylindrical pier is 160mm, and the width of the flume is 1.5m. The medium size of sediment particles is 0.3mm. The approach flow velocity and depth are constant during the 1-day experimental period, with values of 0.35m/s and 0.375m, respectively. In case 2, the pier diameter, the flume width and the sediment size are the same as in case 1. The experiment in case 2 lasts 4 days. The approach velocity is 0.25m/s in the first day and 0.35m/s in the second day, and then each of the two velocities repeats once in the third and forth days.

Table 1 shows the prediction results using the FVM-based CCHE2D model. The predicted maximum scour depths in cases 1 and 2 are 0.182m and 0.205m, respectively. As shown in Fig. 1, the prediction by the FVM-based CCHE2D may have about ±20% errors, which may apply to the values of the predicted maximum scour depth shown in Table 1.

Table 1 Flume Test Prediction by FVM-Based CCHE2D Model

Test description	**Maximum depth of scour hole when the flume test stops**
Flume case 1: 160 mm diameter circular pier placed in clean sand deposit and subjected to a constant velocity over a period of one day.	0.182 m
Flume case 2: 160 mm diameter circular pier placed in clean sand deposit and subjected to a multi-velocity hydrograph over a period of 4 days.	0.205 m

CONCLUSION

The FVM-based CCHE2D model, which is a depth-averaged 2-D numerical model for flow and sediment transport in open channels, is capable of simulating the local scour of non-cohesive sediment near hydraulic structures after modifying the Wu et al's (2000) sediment transport capacity formulas to take into consideration the influences of the pressure gradient and the turbulence intensity on sediment movement. Preliminary tests using 34 sets of flume experimental data of local scour around bridge piers and spur dikes show that the simulated maximum scour depth is very close to the measurements. The FVM-based CCHE2D model is applied to simulate the local scour around bridge piers in ICSF-1 test cases 1 and 2. The predicted maximum scour depths are 0.182m and 0.205m, respectively. According to the model calibration, the prediction using the FVM-based CCHE2D model may have about ±20% errors, which may apply to the values reported here.

The FVM-based CCHE2D model is under development, and it will be tested using a wider range of experimental and field data. It will also be enhanced to simulate the local scour of cohesive sediment near hydraulic structures.

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