VALIDATING SSIIM 3-D NUMERICAL MODEL TO CALCULATE LOCAL SCOUR AROUND BRIDGE PIERS

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ABSTRACT

The aim of this study is to utilize accurate numerical simulations for predicting local scour around bridge piers. The numerical model used in this study is Sediment Simulation In Intakes with Multiblock option “SSIIM” where a *k–ε* and SIMPLE method was used to predict the turbulence and to compute the pressure around the piers. The main objective is to check the validity of using a numerical model in predicting the local scour around a bridge pier.

Key words: Local scour; SSIIM; Numerical model; *k–ε* Turbulence model; CFD

1. INTRODUCTION

During the last few decades, river engineers have tried to calculate the maximum scour depth at bridge piers and abutment foundations, where extensive work has been done using physical models under different conditions, with a few of these studies using numerical models to analyze the scours. Nowadays many mathematical models have been developed to simulate the flow field in the vicinity of vertical obstructions. Even fewer models were developed to simulate the sediment transport through waterways and around structures. These models have enabled researchers to predict the effects of changing flow variables, which could not be accomplished easily during laboratory experiments.

2. MODEL THEORETICAL BASES

The program called Sediment Simulation In Intakes with Multiblock option, or “SSIIM” is used in River/Environmental/Hydraulic/Sedimentation Engineering. SSIIM was developed by Olsen [3] and is considered more powerful than other CFD programs, due to its capability to model sediment transport with a moveable bed in a complex geometry.

The SSIIM program solves the Navier-Stokes equations with the k-ε model on a three-dimensional almost general non-orthogonal grid, then uses a control volume discretization approach together with the power-law scheme or the second order upwind scheme. The SIMPLE method is used when calculating the pressure coupling. An implicit solver is used to produce the velocity field in the geometry. Consequently, these velocities are used when solving the convection-diffusion equations for different sediment sizes. The equations employed in the three dimensional model [3] are as follows:

2.1. Water flow calculation

The turbulent flow equations in a general three-dimensional geometry are solved to obtain the water velocity. The Navier-Stokes equations for non-compressible and constant density flow can be modeled as:

$$\frac{\partial U_i}{\partial t} + Uj\frac{\partial U_i}{\partial x_j} = \frac{1}{\rho}\frac{\partial}{\partial x_j}(-P\delta_{ij} - \rho\overline{u_i u_j}) \qquad (1)$$

Where, U_i is the local velocity; x_j is space dimension; δ_{ij} is Kronecker delta; ρ is fluid density; P is pressure; and u_i is the average velocity.

The left most term in this equation (1) is the transient term. The next term is the convective term. The first term on the right-hand side is the pressure term and the right most term of the equation is the Reynolds stress term. A turbulence model is required to compute this term. SSIIM program can use a different turbulence model that is determined by the user, but the default turbulence model is k-ε.

In order to model the Reynolds stress term, the eddy-viscosity concept as introduced by Boussinesq approximation is used:

$$-\overline{u_i u_j} = \nu_T\left(\frac{\partial U_j}{\partial x_i} + \frac{\partial U_i}{\partial x_j}\right) + \frac{2}{3}k\delta_{ij} \qquad (2)$$

The first term on the right side of equation (2) is the diffusive term in the Navier- Stokes equation. The second term is often neglected and the third term is incorporated into the pressure which is very small, and usually not significant. In order to calculate the eddy viscosity using a k-ε turbulence model, the following equation is used:

$$\nu_T = c_\mu \frac{k}{\varepsilon^2} \qquad (3)$$

Where k is turbulent kinetic energy and defined by equation (3-4):

$$k = \frac{1}{2}\overline{u_i u_j} \tag{4}$$

k is modeled as:

$$\frac{\partial k}{\partial t} + U_j \frac{\partial k}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\frac{\nu_T}{\sigma_k}\frac{\partial k}{\partial x_j}\right) + P_k - \varepsilon \tag{5}$$

Where P_k is given by:

$$P_k = \nu_T \frac{\partial U_j}{\partial x_i}\left(\frac{\partial U_j}{\partial x_i} + \frac{\partial U_i}{\partial x_j}\right) \tag{6}$$

The dissipation of k is denoted ε, and modeled as:

$$\frac{\partial \varepsilon}{\partial t} + U_j \frac{\partial \varepsilon}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\frac{\nu_t}{\sigma_k}\frac{\partial \varepsilon}{\partial x_j}\right) + C_{\varepsilon 1}\frac{\varepsilon}{k}P_k + C_{\varepsilon 2}\frac{\varepsilon^2}{k} \tag{7}$$

Where Cε1 and Cε2 are constant and hard coded by the developer and cannot be changed by the user.

The equations are discretized with a control-volume approach using an implicit solver with a multi-block option. The SIMPLE method is the default method used for pressure- correction [3].

The default wall law in SSIIM is given below and is an empirical formula for rough walls:

$$\frac{U}{u_x} = \frac{1}{\kappa}\left(\frac{30y}{k_s}\right) \tag{8}$$

In this case, u_x is the shear velocity, κ is the von Karmen constant equal to 0.4, y is the distance to the wall, and k_s is the roughness.

2.2. Sediment flow calculation

Sediment transport is traditionally divided into bed load and suspended load. The suspended load can be calculated with the convection-diffusion equation for the sediment concentration, as shown in equation (9):

$$\frac{\partial c}{\partial t} + U_j \frac{\partial c}{\partial x_j} + w\left(\frac{\partial c}{\partial x_z}\right) = \frac{\partial}{\partial x_j}\left(\Gamma \frac{\partial c}{\partial x_j}\right) \tag{9}$$

Where c is the sediment concentration, *w* is fall velocity of sediment particles, and Γ is the diffusion coefficient obtained from the k-ε model:

$$\Gamma = \frac{\nu_T}{S_c} \tag{10}$$

S_c is the Schmidt number which is assumed to be unity in this study.

In order to calculate the suspended load, the SSIIM program uses the developed formula by Van Rijn [7] for computing the equilibrium sediment concentration close to the bed. Equation (11) represents the concentration equation:

$$C_{bed} = 0.015\frac{d^{0.3}}{a}\frac{\left[\frac{\tau - \tau_c}{\tau_c}\right]^{1.5}}{\left[\frac{(\rho_s - \rho_w)g}{\rho_w \nu^2}\right]^{0.1}} \tag{11}$$

C_{bed} is the sediment concentration (kg/kg), d is the sediment particle diameter (m), a is the reference level set equal to the roughness height (m), τ is the bed shear stress (pa), τ_c is the critical bed shear stress for movement of sediment particles according to Shield's curve (Pa), ρ_w is the density of water (kg/m^3), ρ_S is the density of sediment (kg/m^3), ν is the viscosity of the water (Pa.s), and g is the acceleration due to gravity (m/s^2).

In addition to suspended load, the bed load discharge (q_b) can be calculated using Van Rijn's formula as follows:

$$\frac{q_b}{D_{50}^{\ 1.5}\sqrt{\frac{(\rho_s - \rho_w)g}{\rho_w}}} = 0.053\frac{\left[\frac{\tau - \tau_c}{\tau_c}\right]^{1.5}}{D_{50}^{\ 0.3}\left[\frac{(\rho_s - \rho_w)g}{\rho_w \nu^2}\right]^{0.1}} \tag{12}$$

3. NUMERICAL MODEL

Local scour around the bridge pier in a sandy soil channel has been extensively studied by Sharafaddin [6] using a large scale rectangular flume 21.0 m long, 2.0 m wide and 0.9 m deep; the flow measurements area was about 10.0 m long.

3.1. Gride construction

Making an appropriate grid is the most time-consuming process in the input data preparation for the SSIIM program. The size of the cells will strongly influence accuracy, convergence and computational time.

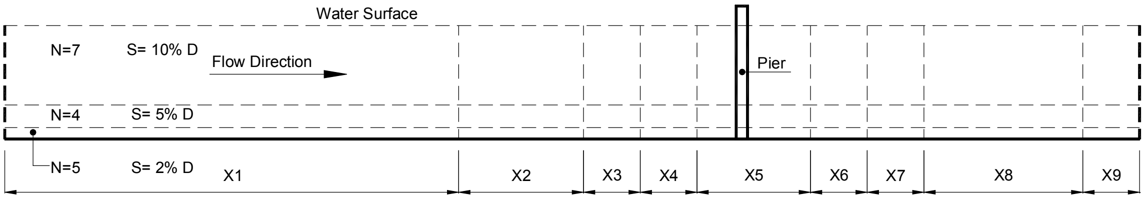
The SSIIM program uses both structured and non-structured grids. In this study it is more convenient to use structured grids, as rectangular piles will be used; the structured grid mesh on the X-Y-Z plane was generated. As shown in Figure (1), a three dimensional grid mesh with 250 elements in the X-direction, 350 elements in the Y-direction and 16 elements in the Z-direction.

An uneven distribution of grids in horizontal and vertical directions was chosen in order to reduce the total number of cells in an acceptable range and to get valuable results in the area around the pier. The used grids are finer at the pile group area, but are coarser at the wall and boundary vicinities. The grid lines have been distributed as follows:

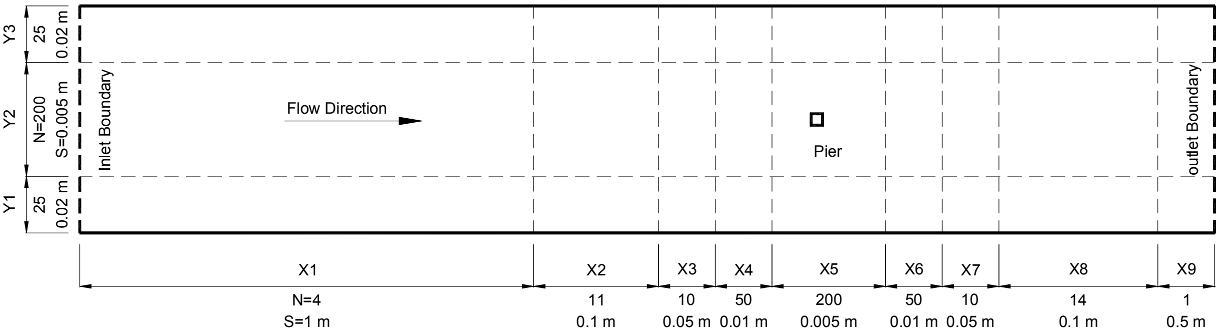
X-direction: the total model length in this direction is 10.0 m. The grids will be distributed at 4 cells with 1 m, 11 cells with 0. 1 m, 10 cells with 0.05 m, 50 cells with 0.01 m, 200 cells with 0.005 m, 50 cells with 0.01 m, 10 cells with 0.05 m, 14 cells with 0. 1 m and 1 cell with 0.5 m respectively.

Y-direction: the total model width in this direction is 2.0 m; the grids will be distributed at 25 cells with 0.02 m, 200 cells with 0.005 m and 25 cells with 0.02 m respectively.

Z-direction: the grid distribution in this direction is represented by a percentage value from the water depth; finer grids exit near the bed and become coarser towards the water's surface. The distribution will be 5 cells with 2% height of the water depth, 4 cells with 5% of the water depth, and 7 cells with 10% of the water depth.



Longitudinal Section



Plan View

***Fig. 1.** Schematic model grids layout*

3.2. Boundary condition

The boundary conditions that were specified are the water discharge, the initial water level, and the sediment size. The upstream boundary condition was given by the discharge amount from the experiments. At the downstream boundary condition, zero gradient had to be given to prevent instabilities, which means that the water discharges at the downstream boundary was not specified. The size of the sediment d_{50} was taken as 0.00052 mm as specified by Sharafaddin [6].

4. MATHEMATICAL MODEL CALIBRATION

In order to calibrate the numerical model, the boundary conditions from the experimental work have been assigned through the Control file. 50 mm square piles have been used in the calibration process, and the flow condition has been chosen to be as presented by Sharafaddin [6] (the discharge of 0.12 m3/sec and water depth of 200 mm) to predict the maximum local scouring depth. The following steps have been followed to better obtain the calibrated model:

4.1. Time step calibration

Many trial runs have been attempted to get the appropriate time step for the 50 mm pile. The time step range was from 1 second to 60 seconds, and it was found that 20 seconds is the most convenient for this model, as it is not affecting the result's accuracy and suitable run time.

4.2. Roughness calibration

After fixing the time step, the bed roughness has been calibrated, and used at this stage, ranging from d_{50} to 10 d_{50}. The most appropriate value of the bed roughness was 0.0053 mm.

4.3. Model calibration results

The predicted maximum scour is in agreement with the observed scour depth by Sharafaddin [6], where the predicted maximum scour depth was 92.4 mm while the observed one was 90.30 mm. This means that the calibrated model overestimates the maximum scour by only 2%.

5. MATHEMATICAL MODEL VERIFICATION

In order to check the ability of the calibrated model in predicting the maximum scour for different cases, two runs have been conducted using 100 mm and 150 mm square piles. Table (1) represents a comparison between the maximum predicted scour depth by the SSIIM model and the maximum observed scour from experimental work by Sharafaddin [6]. The model validation shows that for the 100 mm square pile, the SSIIM underestimates the scour depth by only 3%, while for the 150 mm square pile, it overestimates the scour depth by 11%. The overall average difference value is about 3.33%, which indicates an excellent agreement with experimental results.

Figure (2) represents contour lines for the scour hole around the 100 mm square pile. These contour lines have been drawn by the Surfer program, and relative scour has been drawn in order to specify the scour hole geometry with respect to the pile size.

Table 1. Comparison between predicted and observed relative scour

Pier Size b(mm)	**Sharafaddin, 2003**		**SSIIM**		**Difference**
	ds (mm)	**ds/b**	**ds (mm)**	**ds/b**	
50	90.3	1.81	92.4	1.85	2%
100	167	1.67	162.3	1.62	-3%
150	184	1.23	207.3	1.38	11%

Figure (3) represents a comparison between the predicted maximum scour by the SSIIM model and the most famous equations. Melville; [1] and Melville and Sutherland [2] equations gave highly over-predicted values for all pile sizes, whereas the HEC-18 [4] equation gave excellent agreement.

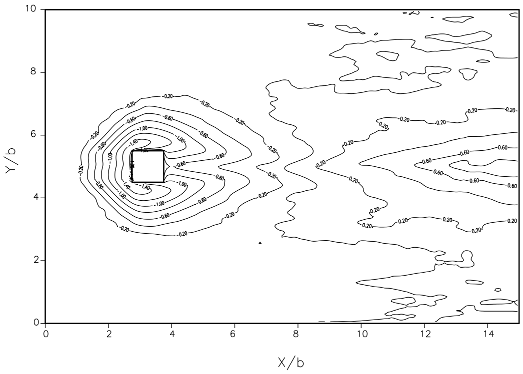


Fig. 2. Scour hole contour lines of 100 mm square pile

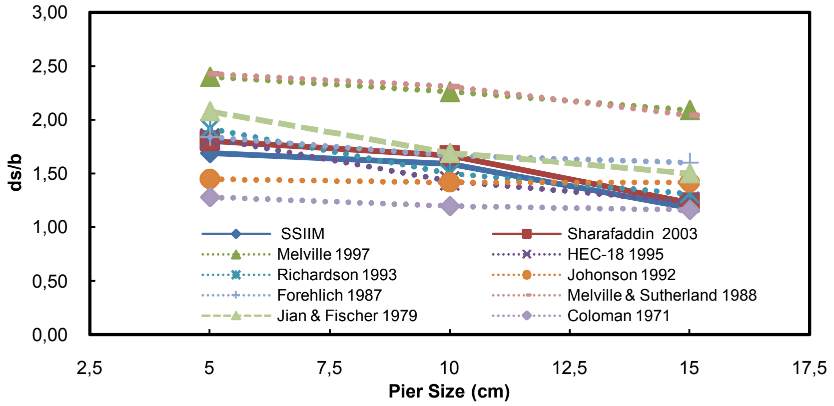


Fig. 3. Comparison between predicted and calculated relative scour

6. CONCLUSION

From the above study, the following may be concluded:

1. The SSIIM numerical model can be used for time dependent calculations and simulation of local scour around pile groups for low Froude.
2. Using pile groups gives smaller scour depth compared to one equivalent pile.
3. The SSIIM is a valid inexpensive 3D tool that may assist engineers and researchers to simulate and predict sediment transport and scour rates around bridge piers with decent accuracy.

4. Both cost and effort can be reduced by using SSIIM, as a well calibrated and verified numerical model compared to more costly physical models.
5. The results have shown good agreement observed by Sharafaddin 2003.

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