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Validation of 3D Numerical Model SSIIM to Simulate and Predict Local Scour around Bridge Abutments

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Abstract: Scour may occur because of the natural changes of flow in the channel or because of man-made activities. A precise numerical model that can simulate local scour around bridge abutments and predict maximum or equilibrium scour depths is an important issue for engineers and researchers. This paper investigates the validation of a numerical model to simulate andpredict local scour at bridge abutments. The numerical model that will be used in this paper is Sediment-Simulation-In-Intakes-with-Multiblock-option "SSIIM". The default k–ε turbulence model will be used for calculating the turbulent shear stress as a simpler turbulence model. Also, the SIMPLE method is used for pressure corrections. The main objective of this paper is to build and validate a numerical model that cansimulate and predict local scour around bridge abutment with high accuracy and can be used for any further studies and experiments that are not easily done in the laboratory.

Keywords: Local scour; Bridge Abutment; Numerical model; CFD; SSIIM

1. INTRODUCTION

The flow in an open channel with a live bed is always accompanied by the transport of sediments. Scour is a natural phenomenon that has been caused by the flow of water over an erodible boundary.Scour may occur because of the natural changes of flow in the channel or because of man-made activities, such as the construction of structures in the channel or dredging of material from the bed. Also, it can be occurred due to the presence of structures encroaching on the channel.

Several statistical studies have shown that the most common cause of bridge failures has resulted from the removal of bed material around bridge foundations [1].Many researchers have tried to calculate the maximum scour depth at bridge piers and abutments foundations, where many studies have been carried out using physical models under different conditions. Few studies have used numerical models to simulate the scour. However, many mathematical models have been developed to simulate and predict the flow near the vertical obstructions. Fewer models were developed to simulate sediment transport through waterways and around structures. These models have enabled many researchers to predict the effects of changing flow characteristics, which are not easily accomplished during laboratory experiments [1].

This study aims to validate the application of the numerical models to simulate and predict local scour at bridge abutments.

2.MODEL THEORETICAL BASIS

In this paper, the employed program is called Sediment-Simulation-In-Intakes-with-Multiblock-option "SSIIM", which is used in river, environmental, hydraulic, sedimentation engineering. SSIIM was developed by Olsen [2] and is taken under consideration more powerful than other Computational Fluid Dynamics "CFD" programs, thanks to its capability to model sediment transport with a moveable bed in exceedingly 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 an impact volume discretization approach together with the power-law scheme or the second-order upwind scheme.

The SIMPLE method is employed for calculating the pressure coupling. An implicit solver is employed to provide the rate field within the geometry. Consequently, these velocities are used when solving the convection-diffusion equations for various sediment sizes. The equations employed within the three-dimensional model are as follows [2]:

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:

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

Where: Ui is the local velocity, xj is space dimension, δij is Kronecker delta; ρ is the fluid density, P is pressure, and ui is the average velocity.

The first term on the left-hand side in 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 next 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.

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

$$-\overline{u_i u_j}=v_T\left(\frac{\partial U_j}{\partial X_i}+\frac{\partial U_i}{\partial X_j}\right)+\frac{2}{3}k\delta_{ij} \quad (2)$$

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. To calculate the eddy viscosity using a k-ε turbulence model, the following equation is used:

$$v_T=C_\mu\frac{k}{\varepsilon^2} \quad (3)$$

Where: k is turbulent kinetic energy and defined by:

$$k\equiv\frac{1}{2}\overline{u_i u_j} \quad (4)$$

Where: k is modeled as:

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

Where: Pkis given by:

$$P_k=v_T\frac{\partial U_j}{\partial x_j}\left(\frac{\partial U_j}{\partial X_i}+\frac{\partial U_i}{\partial X_j}\right) \quad (6)$$

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

$$\frac{\partial\varepsilon}{\partial t}+U_j\frac{\partial\varepsilon}{\partial x_j}=\frac{\partial}{\partial x_j}\left(\frac{\nu_T}{\sigma_k}\frac{\partial k}{\partial x_j}\right)+C_{\varepsilon1}\frac{\varepsilon}{k}P_k+C_{\varepsilon2}\frac{\varepsilon^2}{k} \quad (7)$$

Where: $C_{\varepsilon1}$ and $C_{\varepsilon2}$ are constant and hardcoded 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 [2].

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

$$\frac{U}{u_x}=\frac{1}{k}\ln\left(\frac{30y}{k_s}\right) \quad (8)$$

Where: ux 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:

$$\frac{\partial c}{\partial t}+U_j\frac{\partial c}{\partial x_j}+w\frac{\partial c}{\partial z}=\frac{\partial}{\partial x_j}\left(\Gamma_T\frac{\partial c}{\partial x_j}\right) \quad (9)$$

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:

$$\Gamma=\frac{v_T}{S_c} \quad (10)$$

Where: Sc is the Schmidt number, which is assumed to be unity in this study.

To calculate the suspended load, the SSIIM program uses the developed formula by Van Rijn [3] for computing the equilibrium sediment concentration close to the bed. Equation (11) represents the concentration equation:

$$c_{bed}=0.015\frac{d^{0.3}}{a}\frac{\left[\frac{\tau-\tau_c}{\tau_c}\right]^{1.5}}{\left[\frac{(\rho_S-\rho_W)g}{\rho_W v^2}\right]^{0.1}} \quad (11)$$

Where: 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:

$$\frac{q_b}{D_{50}^{1.5}\sqrt{\frac{(\rho_s-\rho_w)g}{\rho_w}}}=0.053\,\frac{\left[\frac{\tau-\tau_c}{\tau_c}\right]^{2.1}}{D_{50}^{0.3}\left[\frac{(\rho_s-\rho_w)g}{\rho_w v^2}\right]^{0.1}} \qquad (12)$$

3.NUMERICAL MODEL

Two experimental models were established to investigate local scour around bridge abutment in a sandy soil channel [4][5]. The numerical model developed in this paper will be validated using the results of these two experimental models, which were called model A [4]and model B[5].

The firstexperimental model A (24 run cases) used a rectangular flume of a width of 1.0 m [4]. This flume was 5.0 m long, 1.0 m wide, 0.5 m deep, and the water depth ranging from 115 mm to 124 mm.

The second experimental model B (27 run cases) used a rectangular flume of a width of 1.5 m [5]. This flume was 30.0 m long, 1.5 m in wide, 0.5 m deep, and the water depth ranged from 100 mm to 140 mm.

3.1 Meshing Preparation

After many trials of meshing generation using several tools, the most suitable three-dimensional structured grid was achieved as shown in Figures 1 and 2 and as described below:

3.1.1 Meshing Preparation for Model A [4] (1.0 m Wide)

The structured grid used in the developed SSIIM model consisted of 192 elements in X-direction, 90 elements in Y-direction, and 16 elements in Z-direction.

***X-direction elements**:* The mesh was divided into 7 cells with 25.0 cm, 5 cells with 5.0 cm, 10 cells with 2.5 cm, 25 cells with 1.0 cm, 100 cells with 0.5 cm, 25 cells with 1.0 cm, 10 cells with 2.5 cm, 5 cells with 5.0 cm and 5 cells with 25.0 cm respectively.

***Y-direction elements**:* The mesh was divided into 5 cells with 5.0 cm, 10 cells with 2.5 cm, 25 cells with 1.0 cm, and 50 cells with 0.5 cm respectively.

***Z-direction elements**:* The mesh was divided as a percentage of water depth to 5 cells with 2%, 4 cells with 5%, and 7 cells with 10% from bed to water-free surface respectively.

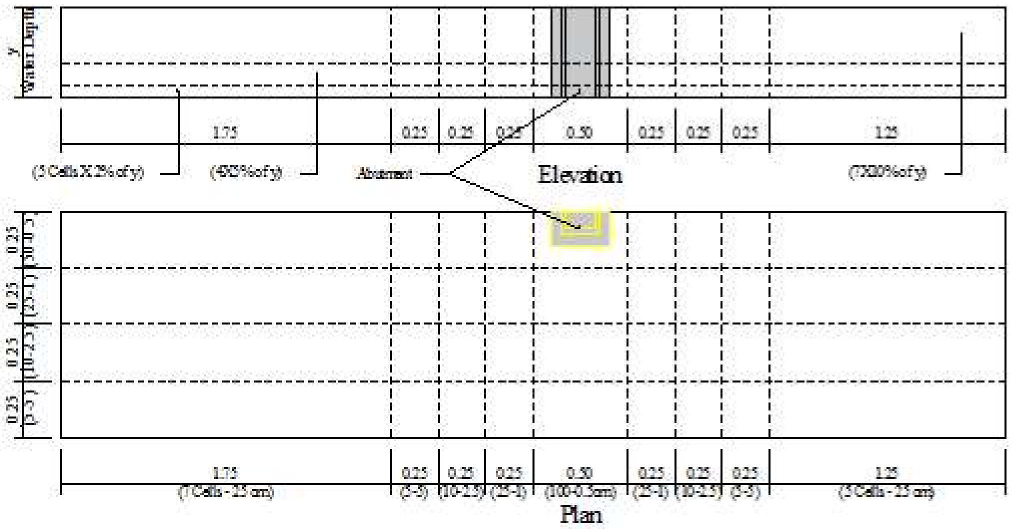

FIG 1. Mesh Layout for Model A

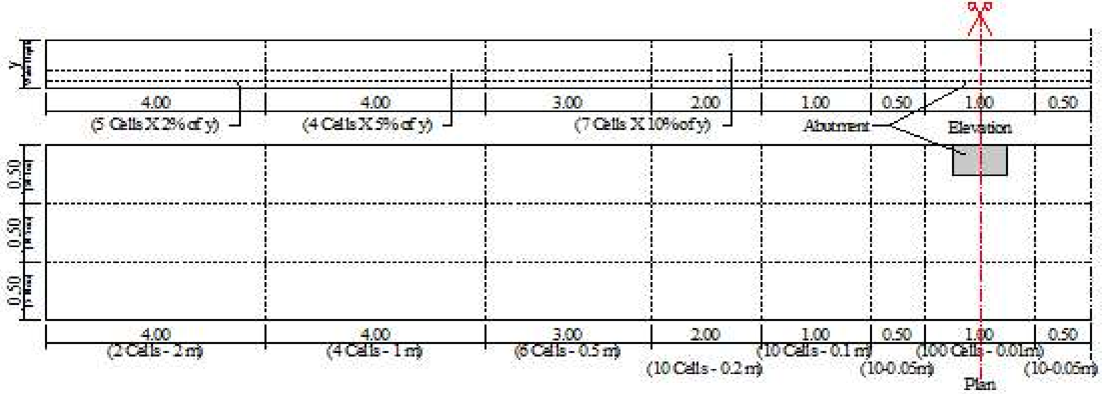

FIG 2. Mesh Layout for Model B

3.1.2 Meshing Preparation for Model B [5] (1.5 m Wide)

The structured grid used in the developed SSIIM model consisted of 185 elements in X-direction, 66 elements in Y-direction, and 16 elements in Z-direction.

***X-direction elements**:* The mesh was divided into 2 cells with 2.0 m, 4 cells with 1.0 m, 6 cells with 0.5 m, 10 cells with 0.2 m, 10 cells with 10 cm, 10 cells with 5 cm, 100 cells with 1 cm, 10 cells with 5 cm, 10 cells with 10 cm, 10 cells with 0.2 m, 6 cells with 0.5 m, 4 cells with 1.0 m, and 2 cells with 2.0 m respectively.

***Y-direction elements**:* The mesh was divided into 5 cells with 10 cm, 10 cells with 5 cm, and 50 cells with 1 cm respectively.

***Z-direction elements**:* The mesh was divided as a percentage of water depth to 5 cells with 2%, 4 cells with 5%, and 7 cells with 10% from bed to water-free surface respectively.

3.2 Run Case Properties

The run case properties and boundary conditions that were specified included 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 was considered to prevent instabilities, which means that the water discharges at the downstream boundary were not specified. All run case properties were applied as specified in the two studied models A[4] and B [5].

However, every run of the experimental models A (24 run cases) and B (27 run cases) was simulated as the main three-run cases mentioned in the next section. All these steps were applied to get the best agreement with the observed experimental results.

4.NUMERICAL MODEL CALIBRATION

To calibrate the numerical model, the boundary conditions from the two experimental models A and B have been assigned through the Control files. The abutment size and the flow condition were chosen to simulate and predict the maximum local scouring depth. The following steps have been followed to get better results for the developed numerical model:

4.1Time Step Trails

After too many trials, 30 seconds for each time step was the most suitable for the model.

4.2 Roughness Trails

After many trials, 0.000380 and 0.000475 roughness coefficients were the most suitable for the model A and B respectively.

4.3Other Important Parameters

Sediment size, angle of response, relaxation factor, and other factors were also affecting the results.

5.MATHEMATICAL MODEL VERIFICATION

5.1 First Stage of Verification Process

To verify the developed numerical model, too many runs were carried out and the obtained simulated results are shown in Table 1 and Figure 3.

The model showed acceptable results where the run (MS-07.50-05) for the equilibrium scours was overestimated by 7.5%, run (MS-10.00-15) was underestimated by 1%, and run (MS-15.00-21) was overestimated by 1.6%. The overall results are accepted and the model can be used.

TABLE 1. Comparisons between Observed [4] and Simulated Maximum and Equilibrium Scour Depths for Model A

Run ID	Observed [4]		Simulated	
	Maximum Scour Depth after 12 Hrs (m)	Equilibrium Scour Depth after 84 Hrs (m)	Maximum Scour Depth after 12 Hrs (m)	Equilibrium Scour Depth after 84 Hrs (m)
MS-07.50-05	0.1150	0.1270	0.1225	0.1365
MS-10.00-15	0.1150	0.1320	0.1054	0.1307
MS-15.00-21	0.0980	0.1190	0.1035	0.1209

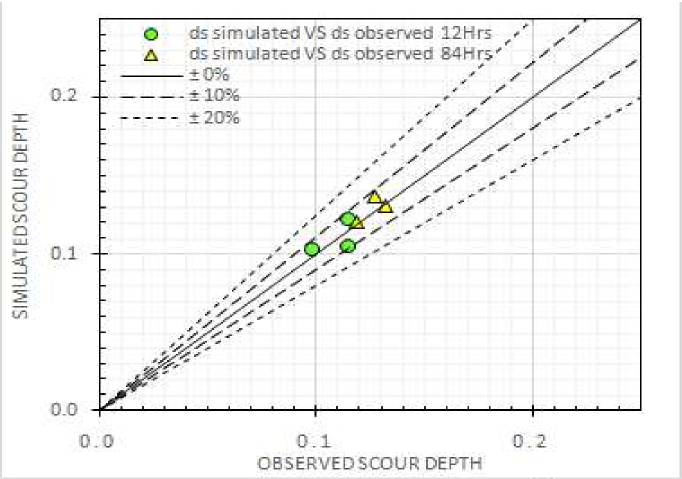

FIG 3. Comparisons between Observed [4] and Simulated Maximum and Equilibrium Scour Depths for Model A

5.2 Second Stage of Verification Process

The twenty-four runs carried out experimentally for model A [4] (observed) were simulated employing the developed numerical model, as shown in Table 2. The scour depths were recorded after time 12 Hrs.

The comparisons between observed and simulated scour depths for model A for time 12 Hrsare presented in Figure 4. The graph showed a good agreement between the observed and the simulated data. Common comparisons were above the perfect line ± 0% with +10% and overall results did not exceed +20%. On the other hand, the remaining results were below the perfect line ± 0% with -10% and overall results did not exceed -20%.

So, the numerical model of the experimental model A has been verified and is valid to be applied to a research study.

TABLE 2. Comparisons between Observed [4] and Simulated Scour Depths for Model A

Run ID*	Observed [4] Scour Depth after 12 Hrs (m)	Simulated Scour Depth after 12 Hrs (m)
MS-01.00-07.50-15.00-120-0.0131	0.0160	0.0183
MS-01.00-07.50-15.00-120-0.0168	0.0310	0.0255
MS-01.00-07.50-15.00-120-0.0218	0.0570	0.0592
MS-01.00-07.50-15.00-119-0.0250	0.0680	0.0721
MS-01.00-07.50-15.00-120-0.0292**	0.1150	0.1225
MS-01.00-07.50-15.00-120-0.0354	0.1700	0.1525
MS-01.00-10.00-20.00-115-0.0126	0.0330	0.0254
MS-01.00-10.00-20.00-119-0.0167	0.0400	0.0433
MS-01.00-10.00-20.00-120-0.0183	0.0530	0.0613
MS-01.00-10.00-20.00-119-0.0189	0.0560	0.0602
MS-01.00-10.00-20.00-120-0.0211	0.0640	0.0634
MS-01.00-10.00-20.00-122-0.0231	0.0700	0.0821
MS-01.00-10.00-20.00-119-0.0240	0.1000	0.1023
MS-01.00-10.00-20.00-121-0.0252	0.1110	0.1153
MS-01.00-10.00-20.00-122-0.0268**	0.1150	0.1054
MS-01.00-10.00-20.00-121-0.0290	0.1250	0.1321
MS-01.00-10.00-20.00-115-0.0304	0.1620	0.1828
MS-01.00-10.00-20.00-119-0.0356	0.1920	0.1898
MS-01.00-15.00-30.00-124-0.0131	0.0400	0.0460
MS-01.00-15.00-30.00-118-0.0188	0.0700	0.0898
MS-01.00-15.00-30.00-121-0.0229**	0.0980	0.1035
MS-01.00-15.00-30.00-121-0.0251	0.1220	0.1494
MS-01.00-15.00-30.00-119-0.0309	0.1720	0.1812
MS-01.00-15.00-30.00-120-0.0354	0.1980	0.2212

Run ID*: Example to read Run ID (Same as mentioned for Table 3)

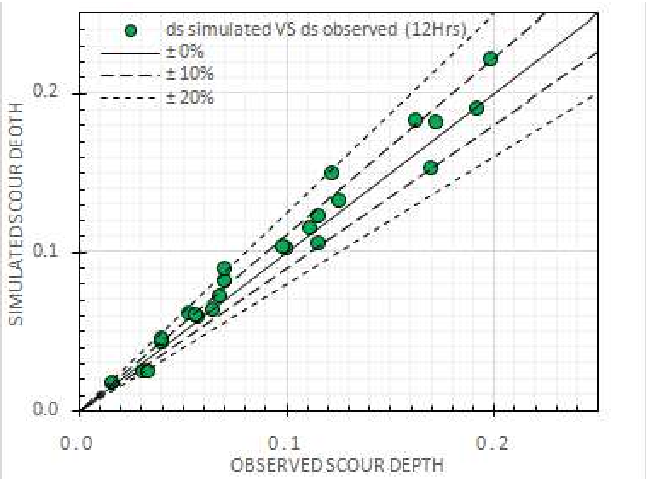

FIG 4. Comparisons between Observed and Simulated Scour Depths for Model A

The twenty-seven runs carried out experimentally for model B [5] (observed) were simulated employing the developed numerical model. The observed scour depth (d_{smax}) was recorded after time 12 Hrs. The properties of each case described in the run ID name as illustrated in table 2.

TABLE 3.Comparisons between Observed [5] and Simulated Scour Depths for Model B

Run ID*	Observed [5] Scour Depth after 12 Hrs (m)	Simulated Scour Depth after 12 Hrs (m)
MS-01.50-10-05-100-0.050	0.0955	0.0905
MS-01.50-10-05-120-0.050	0.0518	0.0595
MS-01.50-10-05-140-0.050	0.0220	0.0221
MS-01.50-15-05-100-0.050	0.1288	0.1340
MS-01.50-15-05-120-0.050	0.0785	0.0901
MS-01.50-15-05-140-0.050	0.0403	0.0450
MS-01.50-20-05-100-0.050	0.1640	0.1480
MS-01.50-20-05-120-0.050	0.0995	0.0984
MS-01.50-20-05-140-0.050	0.0645	0.0736
MS-01.50-25-05-100-0.050	0.1885	0.1653
MS-01.50-25-05-120-0.050	0.1155	0.1155
MS-01.50-25-05-140-0.050	0.0750	0.0814
MS-01.50-25-10-100-0.050	0.1621	0.1550
MS-01.50-25-10-120-0.050	0.1004	0.1129
MS-01.50-25-10-140-0.050	0.0606	0.0625
MS-01.50-25-20-100-0.050	0.1540	0.1364
MS-01.50-25-20-120-0.050	0.0861	0.0791
MS-01.50-25-20-140-0.050	0.0548	0.0619
MS-01.50-25-30-100-0.050	0.1488	0.1530
MS-01.50-25-30-120-0.050	0.0792	0.0808
MS-01.50-25-30-140-0.050	0.0599	0.0536
MS-01.50-25-40-100-0.050	0.1500	0.1488
MS-01.50-25-40-120-0.050	0.0817	0.0905
MS-01.50-25-40-140-0.050	0.0643	0.0719
MS-01.50-25-50-100-0.050	0.1453	0.1291
MS-01.50-25-50-120-0.050	0.0845	0.0809
MS-01.50-25-50-140-0.050	0.0606	0.0732

Run ID* Example to read Run ID “MS-01.50-25-50-140-0.050”: MS is for Model of Scour, 01.50: Flume Width (m), 25: Abutment Width perpendicular to flow direction (cm), 50: Abutment Length (cm), 140: Water Depth (mm), 0.050: the discharge in (m^3/s).

The comparisons between observed and simulated scour depths for model B for time 12 Hrsare presented in Figure 5. The graph showed a good agreement between the observed and the simulated data. Common comparisons were above the perfect line ± 0% with +10% and overall results did not exceed +20%. On the other hand, the remaining results were below the perfect line ± 0% with -10% and overall results did not exceed -20%.

So, the numerical model of the experimental model B has been verified and is valid to be applied to a research study.

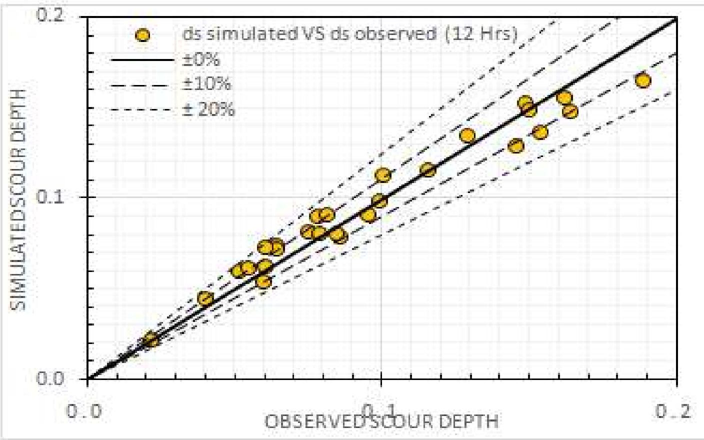

FIG 5. Comparisons between Observed [5]and Simulated Scour Depths for Model B

The equilibrium scours pattern of model A[4] for the experiment with run ID (MS-10-15) is shown in Figure 6. The left picture was a real isometric for the scour hole after 84 hrs, while the right figure was a contour map. It showed that the equilibrium scour was about -12 cm from the channel bed level.

The simulated equilibrium scours hole was much similar to the real equilibrium scour hole for model A [4], as shown in Figure 7.

Figure 8 illustrated the contour map for the flume 1.0 m of the simulated experiment using the numerical model. The equilibrium scours depth is 12 cm, which was similar to the real scour obtained in the contour map of model A [4] (Figure 6).

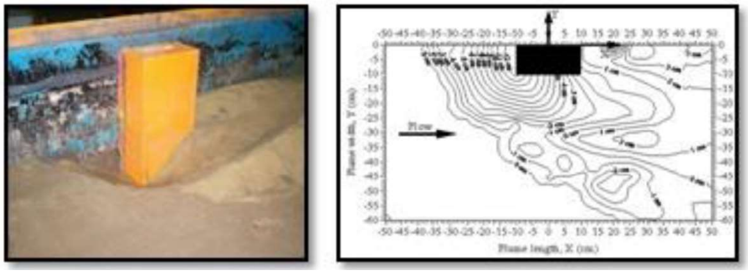

FIG 6. Equilibrium Scour Pattern of Experiment MS-10-15 of Model A[4]

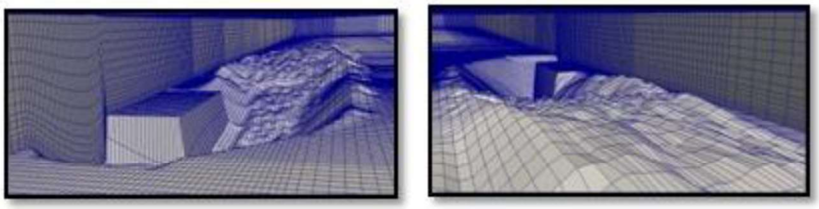

FIG 7. Isometric view of 3D Simulated Scour hole of MS-10-15 of Model A

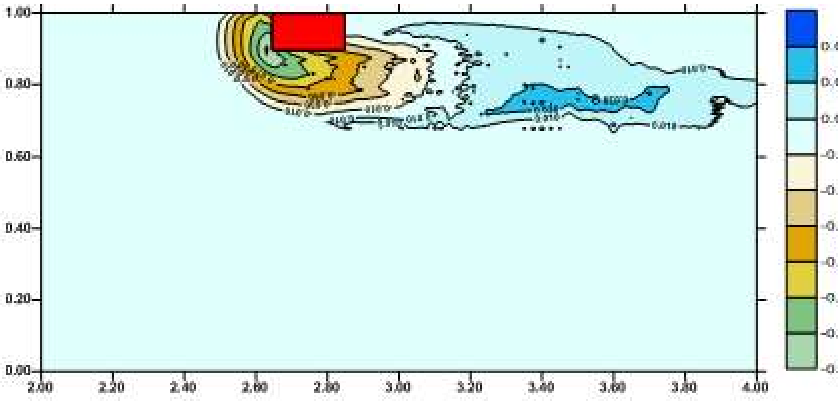

FIG 8. Equilibrium Scour Pattern of Simulated Case MS-10-15 employing the developed Numerical Model

6.CONCLUSIONS

It is concluded that SSIIM numerical model can be used for time-dependent calculations and simulation of local scour around bridge abutments.

SSIIM can be a valid inexpensive 3-D modeling tool that will assist engineers and researchers to simulate sediment transport and also to predict scour rate and depth around bridge abutments with decent accuracy.

Cost, time, and effort are going to be reduced using SSIIM, as a well-calibrated and verified numerical model compared to more costly physical models.

The obtained results have shown good agreement with the observed results of two experimental models.

Thus, the numerical model is valid to further studies.

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