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3D Numerical Simulation of Scouring Around Bridge Piers (Case Study: Bridge 524 crosses the Tanana River)

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Abstract—Due to the three- dimensional flow pattern interacting with bed material, the process of local scour around bridge piers is complex. Modeling 3D flow field and scour hole evolution around a bridge pier is more feasible nowadays because the computational cost and computational time have significantly decreased.

In order to evaluate local flow and scouring around a bridge pier, a completely three-dimensional numerical model, SSIIM program, was used. The model solves 3-D Navier-Stokes equations and a bed load conservation equation. The model was applied to simulate local flow and scouring around a bridge pier in a large natural river with four piers. Computation for 1 day of flood condition was carried out to predict the maximum local scour depth. The results show that the SSIIM program can be used efficiently for simulating the scouring in natural rivers. The results also showed that among the various turbulence models, the k-ω model gives more reasonable results.

Keywords**—**Bridge piers, Flood, Numerical simulation, SSIIM.

I. Introduction

THE evaluation of the maximum local scour depth around bridge piers is a typical topic in river engineering.

Local scouring around bridge piers can be a sever problem, especially when a high flow occurs in the river. When this undesirable event occurs, a scour hole appears around bridge piers. The local scour depth develops in high flows and if it is not predicted correctly the bottom level of local scour hole will exceed the original level of the pier foundation. In this case the safety and stability of the bridge will be in danger. Bridge collapse during a flood raises many direct and indirect economic and social costs [1].

The three-dimensional flow field around a pier is extremely complex due to separation and generation of multiple vortices. The complexity of the flow field is further magnified due to the dynamic interaction between the flow and the moveable boundary during the development of a scour hole [2]. Accurate prediction of scour pattern around bridge piers strongly depends on resolving the flow structure and the mechanism of sediment movement in and out of the scour hole [3].

Streambed scour is the leading cause of bridge failure in the United States [5]. The costs associated with restoring damaged structures are substantial, but are less than five times the indirect costs associated with the disruption of traffic [6]. These costs and societal repercussions are even greater in Alaska, where alternate ground transportation routes between many cities do not exist [7]. The Federal Highway administration (FHWA) has established a requirement that all state highway agencies evaluate the bridges on the Federal Aid System for susceptibility to scour-related failure. In 1994 the U.S. Geological Survey (USGS), in cooperation with the Alaska Department of Transportation and Public Facilities (ADOT & PF), began a cooperative study of bridge scour in Alaska [8].

However, most of the experiments have been carried out in flumes under idealized conditions, such as steady flow, uniform sediment, simplified geometry, etc. Therefore, their applications to field situations may still be problematic and may produce questionable results. A more satisfactory approach for further applications in field situations is to simulate accurately the flow field and scouring processes using a 3D numerical model. Modeling 3D flow field and scour hole evolution around a bridge pier is more feasible nowadays because the computational cost and computational time have significantly decreased [9].

In recent years, several numerical models have been constructed for simulating the 3D flow field and bed variations around circular piers. Reference [10] shows an application of 3D transient model to compute the flow field around a pier within a given fixed scour hole. The scouring phenomena was simulated by solving the 3D Navier-Stokes equations with the κ- ε (turbulent kinetic energy and dissipation rate) model for the Reynolds stresses, and the advection diffusion equation for sediment transport [11]. Reference [12] used a finite element method to solve the 3D Navier-Stokes equations along with a stochastic turbulence-closure model and proposed a function called the sediment transport capacity for local scouring to express the effects of downflow, vortex strength and turbulent intensity in the sediment transport part. Transport capacity for local scouring need to be determined.

Reference [13] investigated numerically the 3D turbulent flow field around square and circular piers. Their results show

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that the simulated velocity and shear stress around the square pier were significantly higher than those around the circular pier.

In this study, the local scouring around bridge piers in large natural river was simulated by using SSIIM program. This program is being used in river, environmental, hydraulic and sedimentation engineering. SSIIM is an abbreviation for sediment simulation in water intakes with multiblock option. This 3D CFD model was based on the finite volume method to solve the Navier-Stokes equations using the various turbulence models [14].

II. The Numerical Model

The SSIIM program solves the Navier-Stokes equations of three dimensional and general non-orthogonal. These equations are discretized with a control volume approach. The SIMPLE method is also used for the pressure coupling. Additionally SIMPLEC method can be invoked. An implicit solver is used, producing the velocity field in geometry. The velocities are used when solving the convection-diffusion equations for different sediment sizes. The three dimensional model is solved by the equations reported below [14]. The Navier-Stokes equations for non-compressible and constant density flow can be modeled as:

$$\frac{\partial u_i}{\partial t} + U_j \frac{\partial u_i}{\partial x_j} = \frac{1}{\rho}\frac{\partial}{\partial x_j}(-p\,\delta_{ij} - \rho\overline{u_i u_j}) \qquad (1)$$

The left term on the left side of the 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 second term on the right side of the equation is the Reynolds stress term. In order to evaluate this term, a turbulence model is required. SSIIM program can use different turbulence model that is determined by user, but the default turbulence model is k-ε.

The free surface is computed using a fixed-lid approach, with zero gradients for all variables. The location of the fixed lid and its movement as a function of time and the water flow field are computed by different algorithms. 1D backwater computation is default algorithm and it is invoked automatically. It is possible to use other algorithms by user.

In this 3D CFD program, the suspended load can be calculated with the convection-diffusion equation for the sediment concentration. In particular the following expression was used:

$$\frac{\partial c}{\partial t} + u_j \frac{\partial c}{\partial x_j} + w\frac{\partial c}{\partial z} = \frac{\partial}{\partial x_j}(\Gamma_T \frac{\partial c}{\partial x_j}) \qquad (2)$$

Where w is the fall velocity of sediment particles (m/s) and Γ_T is the diffusion coefficient and can be expressed in the following way:

$$\Gamma_T = \frac{\nu_T}{Sc} \qquad (3)$$

Where Sc is the Schmidt number, set to 1.0 as default. For calculating the suspended load, SSIIM program uses the formula that was developed by Van Rijn (1987) for computing the equilibrium sediment concentration close to the bed. The concentration equation has the following expression:

$$C_{bed} = 0.015\frac{d^{0.3}}{a}\frac{\left[\frac{\tau-\tau_c}{\tau_c}\right]^{1.5}}{\left[\frac{(\rho_s-\rho_w)g}{\rho_w \nu^2}\right]^{0.1}} \qquad (4)$$

Where, C_{bed} is the sediment concentration (kg/kg), d is the sediment particle diameter (m), a is a 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 and ρ_S are the density of water and sediment (kg/m^3) respectively, ν is the viscosity of the water (Pa.s) and g is the acceleration due to gravity (m/s^2). In addition, the bed load discharge (q_b) can be calculated by Van Rijen's formula as follows:

$$\frac{q_b}{D_{50}^{1.5}\sqrt{\frac{(\rho_s-\rho_w)g}{\rho_w}}} = 0.053\frac{\left[\frac{\tau-\tau_c}{\tau_c}\right]^{1.5}(1)}{D_{50}^{0.3}\left[\left(\frac{(\rho_s-\rho_w)g}{\rho_w \nu^2}\right)\right]^{0.1}} \qquad (5)$$

, where D_{50} is the mean size of sediment (m).

The velocity gradient towards the wall is often very steep, thus it is assumed that the velocity profile follows a certain empirical function called a wall law. The default wall law in SSIIM is described below:

$$\frac{U}{u_x} = \frac{1}{\kappa}ln\left(\frac{30y}{k_s}\right) \qquad (6)$$

The shear velocity is denoted u_x (m/s), κ is a constant equal to 4.0, y is the distance to the wall (m) and k_s is the roughness equivalent to a diameter of particles on the bed (m).

III. Description of The Case Study

The case study bridge named bridge 524 crosses the Tanana River, a major tributary of the Yukon River, on the Richardson Highway in USA. The location of bridge is shown in Fig. 1. The Tanana River is a glacier-fed river that carries large sediment loads. The basin area upstream of the bridge is 34,965 (Km^2) with an average elevation of 1048.5 (m). Six percent of the basin is glaciated, two percent is lakes, ponds, and swamps; and fifty percent is forest [15].

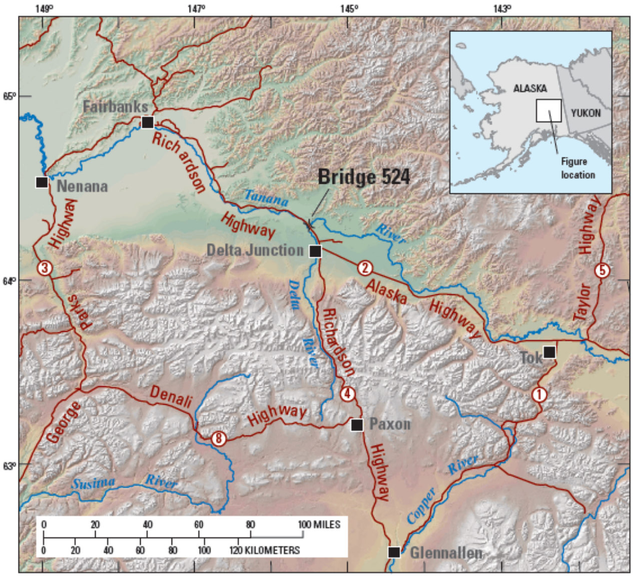

Fig. 1 Location of the Tanana River and case study bridge [15].

Bridge 524 was constructed in 1966. It consists of 5 spans with a equal length except one span. The piers are not aligned directly across the flow; therefore the river strikes them at an angle. This attack angle of the flow to the piers has the potential to increase the local scour at the piers significantly. In the spring of 1996, the right (north) bank of the river began to erode substantially. About 3 meters of the bank had sloughed into the river by mid-April 1996, and the concern was that the further erosion could affect the highway bridge and the pipeline crossing. Bathymetric and hydraulic data were collected during August 26-28, 1996, by the USGS as a cooperative effort with ADOT & PF [15].

The USGS initially identified a potential streambed scour problem at bridge 524 in 1975 [15]. Reference [16] shows that the condition of this site at high flows has been observed and the angle of attack was determined 35 degrees. D_{50} varied between 0.014 to 0.03 (m) in this site.

A scour monitoring system that can provide the cross section profile has been installed at this bridge site. Thus the bed change around bridge piers is available, especially after a high flow occurs in the river. The surveyed cross section upstream of the bridge and the soundings that were made in 2007 and 2006, are shown in Fig. 2.

Geometric data show that length and width of pier 2 is larger than the other piers. Pier 3, 4 and 5 has the same size.

The Delta River follows into the Tanana River immediately downstream the bridge. Backwater on the Tanana River from the confluence with the Delta River can influence the river hydraulics especially at bridge site.

The quality and quantity of these influences depends on the discharge in Tanana and Delta River. Thus different scenarios can be assumed.

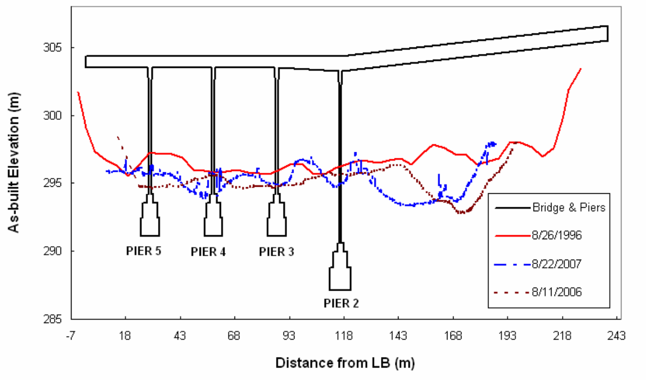

Fig. 2 Surveyed upstream cross section and pier soundings at bridge 524, Tanana River at Big Delta, Alaska.

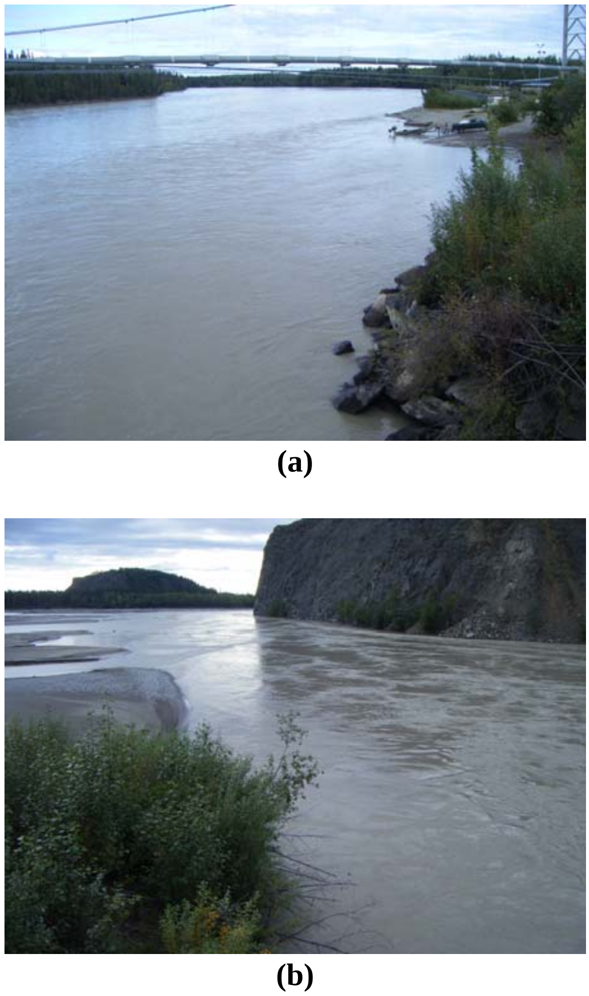

Fig. 3 (a) upstream and (b) downstream view of the bridge 524.

The most conservative scenario will be obtained when no flow entering from Delta to Tanana River. This scenario results in the lowest water surface and highest velocities at the piers of bridge. The corresponding model for this scenario will be considered in this study.

IV. Model Geometry And Properties

Making an appropriate grid is the most time-consuming process in the preparation of input data for SSIIM program. The size and alignment of the cells will strongly influence accuracy, convergence and computational time [14].

According to the contraction at downstream of the bridge the natural geometry of study case is complex. The Surveyed cross sections in August 1996 are used to make a grid for numerical simulations. Fig. 4 shows the computational grid which is used for numerical modeling.

As was mentioned, the right bank of the river was eroded in April 1996, and further erosion could affect the bridge. Thus, hydraulic data must be prepared and scour computations were needed to design a protective structure on the north bank. However the former studies concluded that the local scour depth around bridge piers is considerable and consequently more attention must be paid to this site.

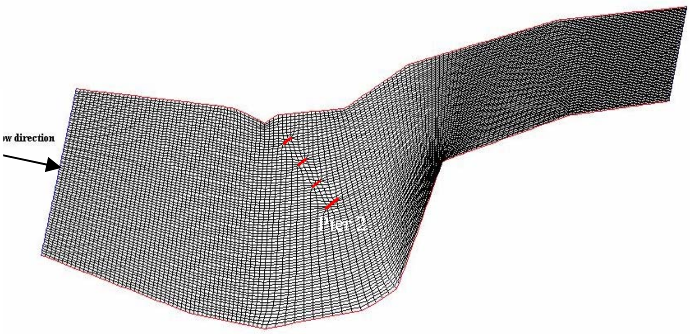

Fig. 4 Calculation grid used for the 3D hydrodynamic modeling by SSIIM program.

V. Numerical Simulations

A. Model Calibration

The first step in running the numerical code is model calibration. In order to calibrate the numerical model the boundary condition of a high flow that occurred in August 2007 was used. Computation of 1 day for a flood of about 1121.35 (m^3/s) was carried out to predict the maximum local scouring depth.

After the calibration, time step and roughness were obtained 20s and 0.085m, respectively. In this stage the calculated equilibrium scour depths for pier 2, 3, 4 and 5 are 1.5 m, 1.8m, 2.15m and 1.3m, respectively. And the corresponding measured scour depths are equal to 1.42 (m), 0.98m, 2.07m and 1.34 m, respectively. The measured depths have been obtained by comparing the pier soundings of scour monitoring system with the surveyed cross section upstream of the piers in August 1996. It is shown that the k-ω model gives more reasonable results than the other various models of turbulence.

B. Results

After the model calibration, the numerical software was applied for another event occurred in August 2006. The boundary condition was assigned in terms of water level and spatial distribution of the input discharge. The discharge of high flow in August 2006 was 914.63 (m^3/s).

The simulated cross section immediately upstream of bridge piers and surveyed cross section in the same position are presented in Fig. 5. It can be seen that there is a good agreement between computed and measured scour depth.

Fig. 6 shows the simulated bed changes around the bridge piers. There is a considerable scouring in the region close to right bank.

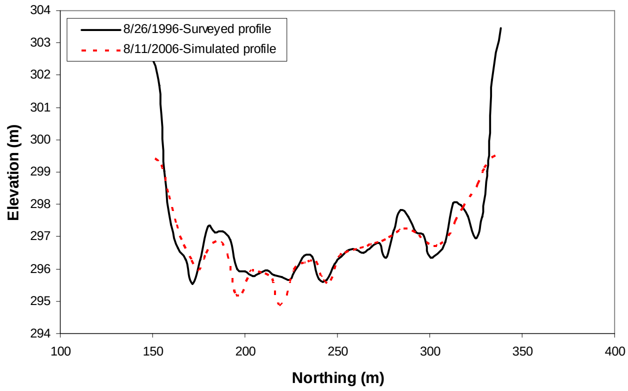

Fig. 5 Simulated and surveyed cross sections in the immediately upstream side of bridge piers.

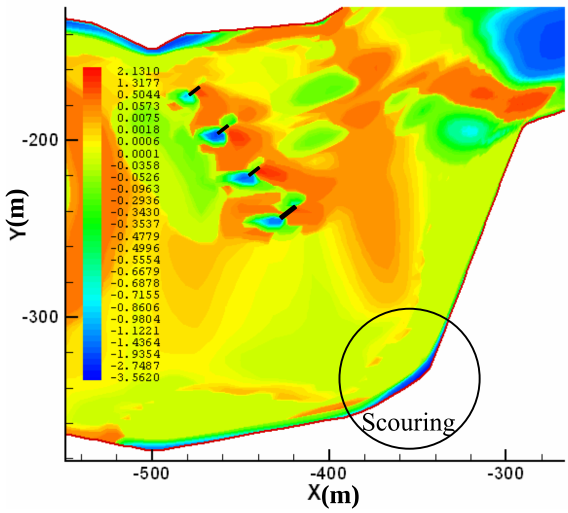

Fig. 6 Bed changes and the consequent scouring around bridge piers.

For comparison, the computed values of scour depth around each bridge pier against the measured values are presented in Table I.

Figs. 7 and 8 show the velocity and bed shear stress field around the bridge piers, respectively. The shear stress increases locally around the flow separation points aling the pier edges.

TABLE I
COMPARISON BETWEEN SIMULATED AND OBSERVED SCOUR DEPTH IN THE VICINITY OF BRIDGE PIERS.

Date	Discharge (m ^{3} /s)
8/11/2006	914.63
Pier 2	Simulated scour depth=1.55m Observed scour depth=0.91m
Pier 3	Simulated scour depth=1.6m Observed scour depth=1.4m
Pier 4	Simulated scour depth=2m Observed scour depth=0.7m
Pier 5	Simulated scour depth=1.08m Observed scour depth=2.05m

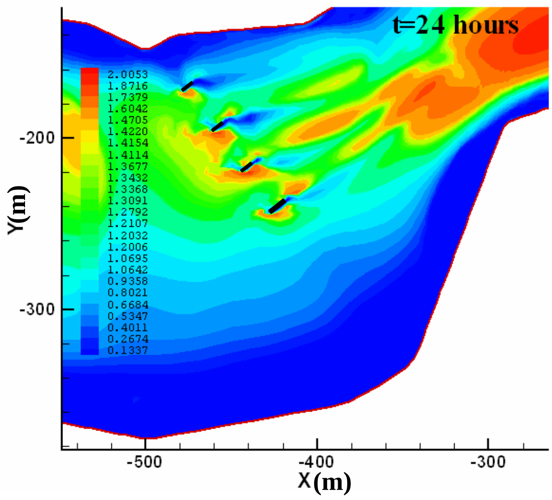

Fig. 7 Flow velocity field around the bridge piers for Q= 914.63 m^3/s.

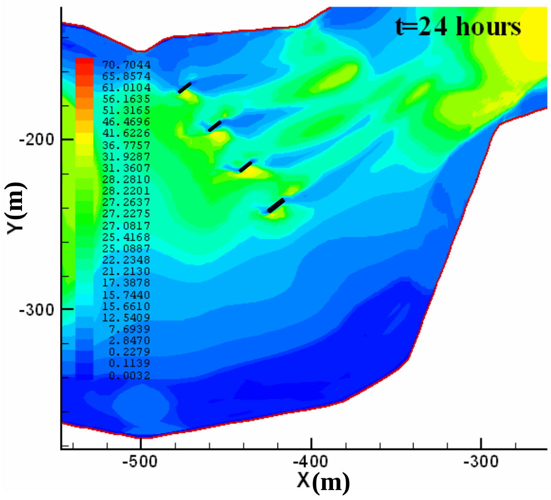

Fig. 8 Shear stress field around the bridge piers for Q= 914.63 m^3/s.

VI. CONCLUSIONS

The following results are obtained from this study:

- Numerical models are useful instruments that can supply some useful results such as scouring depths, evaluation of the scour holes shape and reproduction of temporal evolution of scour process.

-As for turbulence models for simulation, the k-ω model gives most reasonable results among others.

- Numerical codes that can solve the three dimensional flow and sediment, like SSIIM program, are more adaptable for the real condition. The SSIIM program can be used for time dependent calculations and simulation of sediment transport with movable bed in complex geometry. Therefore, it is a powerful instrument in river engineering field.

- The value of bed shear stress near the bank of the Tanana River is significantly large, and the right of the river starts to be eroded.

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