Woodrow Wilson Bridge Replacement Scour Study: Using a 3-D Numerical Model

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Abstract

A new bridge is currently being designed to replace the Woodrow Wilson Bridge and span the Potomac River, connecting suburban Virginia and Maryland. The bridge piers are supported by piles designed to support the structure under various loading scenarios and extreme event scour conditions. The cost estimate to drive hundreds of piles to a stable depth to withstand initial scour depth estimates was extremely expensive. This prompted the 3-D scour modeling study described in this paper.

Introduction

GKY & Associates, Inc. used a three-dimensional hydrodynamic and sediment transport numerical model to simulate local scour at the foundations of the existing and proposed Woodrow Wilson Bridge. The model adopted in this project is an enhanced version of CCHE3D modified by Dr. Xibing Dou for turbulence closure modeling and sediment transport in order to perform local scour simulation. The original code of CCHE3D was developed by the Center for Computational Hydroscience and Engineering at the University of Mississippi.

The results are summarized in Table 1, and indicate the following:

- The full-scale simulation for Scenario 1 shows slightly deeper scour at the dolphin than at pier M1 with the existing bridge piers removed.
- With the existing bridge piers in place (Scenario 2), the scour at pier M1 and at the dolphin is deeper than without the existing bridge piers. In other words, the existing bridge will exacerbate scour at the proposed bridge.
- The tidal surge scour is approximately 80% less severe than the non-tidal scour.
- In comparing Scenarios 1 and 3, the model results show that the presence of dolphins increases scour at pier M1 due to additional contraction between dolphins and pier M1.

In order to demonstrate the accuracy of the model, two sets of simulation have been performed to repeat the small-scale (1:100 and 1:40 scale) physical modeling studies for Woodrow Wilson Bridge performed at the FHWA Turner Fairbank Hydraulics Research Laboratory. The numerical model results show good agreement with those from the physical model simulation.

Three-Dimensional Numerical Model Simulation for Local Scour

This modeling was funded by Maryland State Highway Administration (MSHA) to improve upon commonly used 1-dimensional hydraulic modeling for estimating scour depth. The Wilson Bridge

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replacement will include hundreds of piles and the cost of driving these piles for scour safety can be exorbitant. This 3-dimensional modeling may be used to justify cost savings through shallower pile driving.

Model Description. The 3-D model consists of both hydrodynamic and sediment transport algorithms. A stochastic turbulence closure-model, which predicts anisotropic turbulence stresses, is used. The governing equations are solved using Efficient Element Method developed by the Center for Computational Hydroscience and Engineering. A sediment transport function, which includes the dominant factors to local scour such as the downflow, vortices and turbulence intensity, has been adopted in the model for calculating sediment transport for local scour.

Table 1. Summary of Full-Scale Numerical Modeling Results

3D Scour Simulation (Full Scale)	Locations	Max. Scour for Q100 (ft)	Max. Scour for Q500 (ft)	Max. Scour of Tidal Surge for Q100 (ft)	Max. Scour of Tidal Surge for Q500 (ft)
Scenario 1 M1 w/78' Cap and Three 45' Dolphins	At M1	25.76	33.23		
	At Dolphin	28.41	39.35		
Scenario 2 M1 w/78' Capand Three 45' Dolphins & E1	At M1	28.89	36.32	5.76	7.64
	At Dolphin	35.60	42.79	7.64	12.43
	At E1	21.05	26.83	3.18	1.67
Scenario 3 M1 w/78' Cap and without Dolphin	At M1	19.72	30.58		

Physical Description. The reader is directed to design drawings for the precise location of the proposed bridge crossing the Potomac River. This model simulates the proposed M1 pier at the main channel of the river. The width of the pile cap is 78 feet. The piles are 3 feet in diameter, but were aggregated into one large pile for each pier in the model.

Model Assumptions and Boundary Conditions. Hydrostatic pressure is used in the model. The free surface is obtained based on the kinematic condition. The pressure under the cap is linearly interpolated by the free surface just upstream and downstream of the cap. The Law of Wall is used to calculate the shear stress and force the boundary conditions. The discharge per unit width at the upstream boundary was provided by the 1-dimensional HEC-RAS model. The surface elevation from the FEMA flood study was adopted to specify the downstream water surface elevation

Model Results. The reader is referred to Table 1 for a summary of model results. Figure 1 is a bed elevation contour line plot for the full-scale simulation of M1 with E1 for Q100 flood. The plot shows that after simulation for 40 hours the deepest scour hole of about 8 feet occurs at one of the two upstream dolphins. Due to the presence of the existing pier E1, the scour hole at the other upstream dolphin does not reach the maximum. Its value is about the same as that near the pile cap.

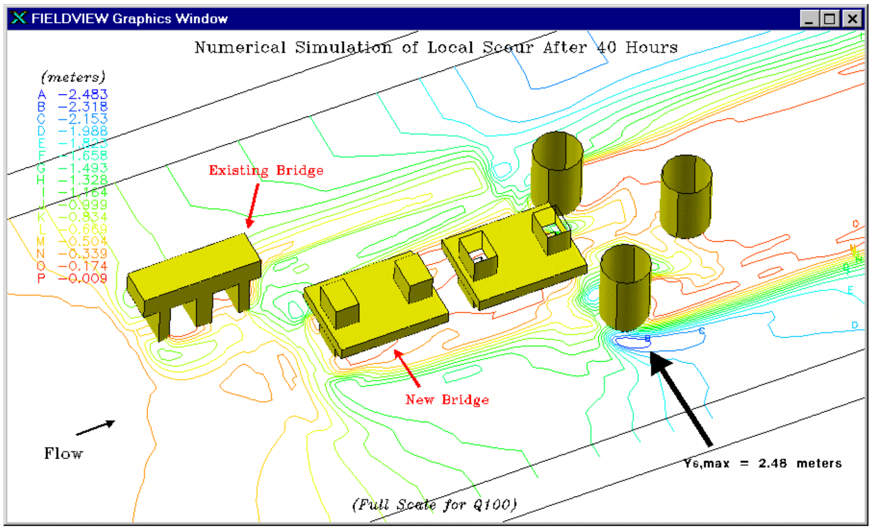

Figure 1. Bed-elevation contour line plot (see text).

Shear Stress and Stream Power Studies

Shear stress is one of the most important factors in sediment transport. Many sediment transport formulas have been developed based on shear stress. In this 3-D model study, it has been found that the shear stress in a scour hole decreases with the increase of the depth of the scour hole. In order to help the researchers who prefer to use shear stress to analyze sediment transport yield for local scour, the shear stress at the maximum scour depth at pier M1 for Q500 flood is provided and shown in Figure 2. In this figure, the shear stress normalized by the shear stress of the approach flow is plotted against the changes of the maximum scour depth. However, it has been recognized that the shear stress is not the exclusive factor that causes local scour. There are many other factors involving in local scour processes. Annandale (1993) found that in flowing water the fluctuating turbulent pressure, which is the primary cause of erosion, is strongly related to the rate of energy dissipation. Therefore, it is might be a better approach to use stream power (SP), a flow parameter which represents the rate of energy dissipation, to estimate sediment transport rate for local scour. In this study the stream power varying with time at the maximum scour depth near pier M1 has been investigated. It has been found that stream power decays with the increase of scour depth. Because SP is the function of U^3 and SS is the function of U^2, the relation between SP and SS can be determined by SP = f ($SS^{3/2}$). In the above figure, the ratio between the stream power at bed (SP_{bed}) at the maximum scour depth near pier M1 and the stream power at bed of the approach flow ($SP_{bed,app}$) is plotted.

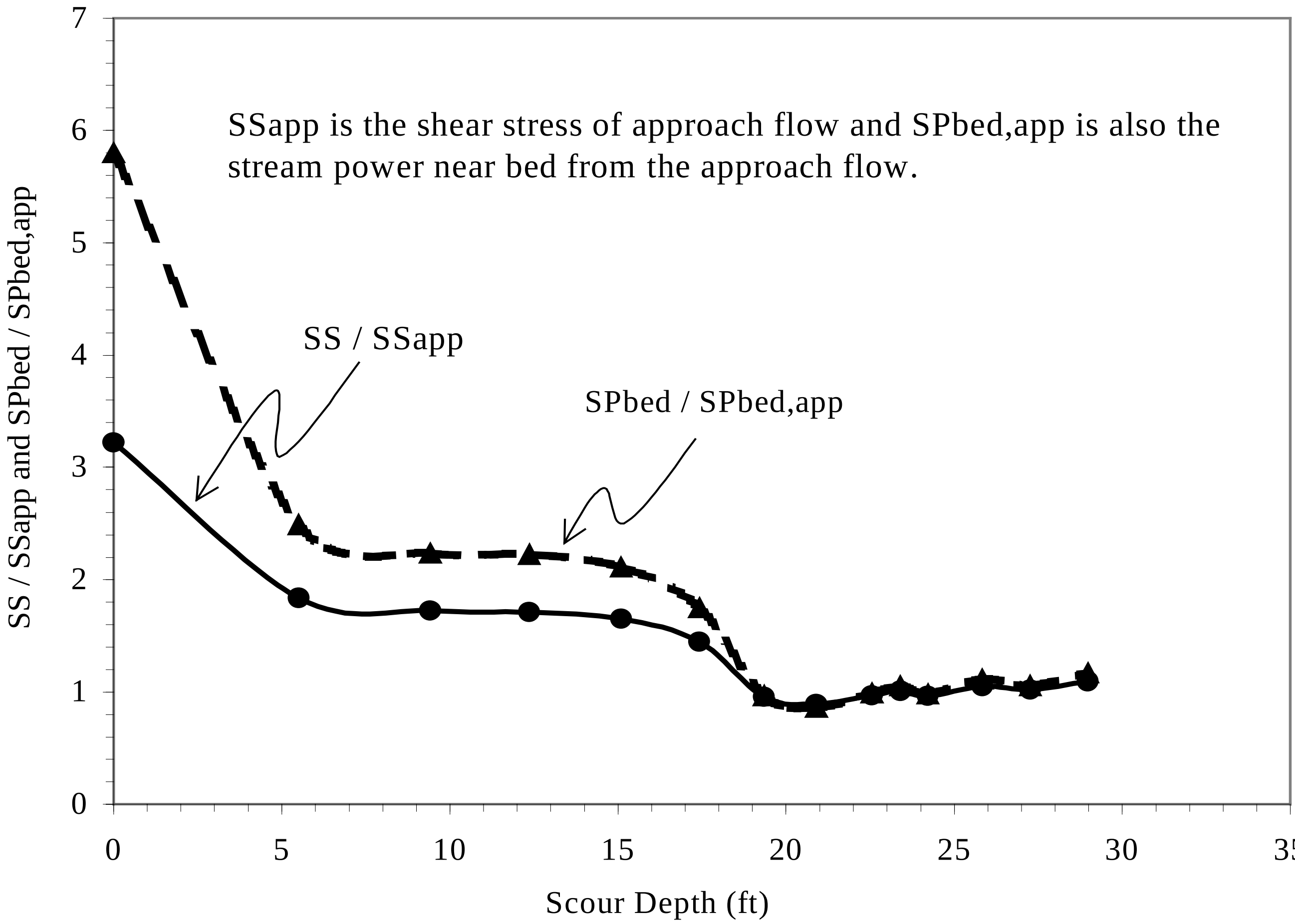

Figure 2. Shear stress (SS), stream power near bed (SS_{bed}) vs scour depth.

Sediment Transport Capacity

Stream power can also be determined using sediment transport capacity (Dou, 1997) that is equated to the Unit Stream Power or the stream power per unit weight proposed by Yang (1973). To perform sediment transport calculation for local scour, Dou (1997) proposed an **effective** sediment transport capacity formula by adding the traditional formula with the terms that consist of the dominant factors in local scour process, such as downflow, vortices and turbulence intensity. In the 3-D model studies, local scour at pier M1 is simulated using the effective sediment transport capacity. Figure 3 shows that the depth-averaged effective stream power, which directly calculated based on the effective sediment transport capacity, changes with the scour depth at the location where the maximum scour occurs. Similar to SP_{bed} and SS, the depth-averaged effective stream power (SP_{av}) decays rapidly started from the flat bed to the scour depth that is about 15 ft. After 15 ft, the decrease of the effective stream power slows down. The scour hole reaches equilibrium when the maximum scour depth is about 30 ft. At this time, the remaining effective stream power is about a quarter of its original value a flow possessed with a flat bed. The depth-averaged effective stream power at the maximum scour hole near pier M1 is normalized by the value from the approach flow.

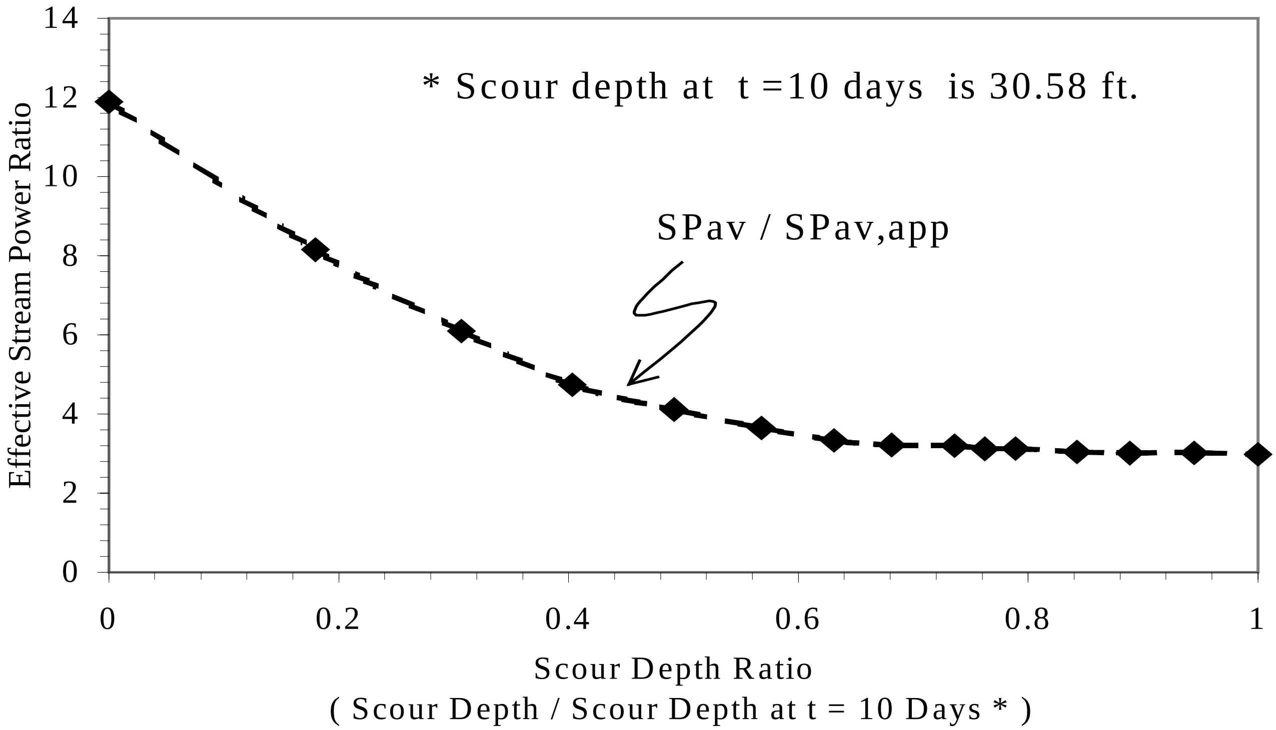

Figure 3. Non-dimentional depth-averaged effective stream power curve.

Conclusions and Suggestions

The 3-D model has been applied to a full-scale simulation. The sediment transport simulation involves live-bed scour process. Three scenarios of pier and dolphin setups with three different flood discharges (Q100, Q500 and Tidal Surge) have been tested. Some complex 3-D mesh systems for describing dolphins and pile caps have been generated. Comparing this to the other studies, the 3-D model shows a strong capability to deal with the complicated coupled hydrodynamic and sediment transport issues. The computed results qualitatively match the phenomenon of local scour. The results also show that in full-scale simulation, this 3-dimensional model typically yields less scour than traditional 1-D approaches. It may imply that the viscous effects cause a higher resistance to flow in the small-scale models, which results in a deeper scour hole.

In this study, uniform sand (0.1 mm) is used as the bed material in full-scale simulation, which is different from the cohesive bed materials in the field. The model needs to be improved to have the ability to deal with cohesive materials and the material gradation. Because the model uses an explicit method to solve the governing equations, the time step is limited by the Courant condition, which greatly affects the computation time. Also, the time step for sediment transport should be carefully selected. It seems that a larger time step for sediment transport can cause a smaller scour depth. Therefore, sufficient time for correcting the flow field after computing sediment transport is very important to the accuracy of scour simulation.

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