CFD Analysis of Local Scour at Bridge Piers

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Abstract

Conventional methods for predicting local scour at bridge piers rely on predictive equations developed from physical modeling. These methods may have limited applicability in situations with unique pier shapes or configurations since the complex hydraulic conditions driving the scour processes around piers are inherently three dimensional. This uncertainty may result in excessive conservatism and may even require additional physical modeling to accurately define the local scour depths for unique pier geometry and shapes. Recent advances in computational fluid dynamics (CFD) and computer performance have made 3D modeling a practical approach to evaluate the complex hydraulic conditions driving the local scour processes. Additional progress in sediment transport modeling, has now made it possible for engineers to directly simulate the fully coupled 3D hydraulic and scour processes at complex structures, including bridge piers.

In this study we evaluate the use of a CFD numerical model for predicting the local equilibrium scour depth and deposition around two different pier geometries using a mobile bed 3D sediment transport model. A sensitivity analysis evaluates the range of results based on likely user inputs, and the final numerical predictions are compared to experimental results. This study demonstrates that the results obtained by the numerical model are in good agreement with the results of the physical model.

Introduction

Flood induced scour at bridge abutments and piers is the most common cause of bridge failure in the USA (Ameson et. al, 2012), and underscores the importance of reliable methods for evaluating bridges or other infrastructure at risk for such failure. The hydraulic mechanisms driving scour at bridges are characterized by a complex, 3D horseshoe vortex structure (HSV) (Ameson et. al, 2012). The HSV develops as water flows into the leading edge of the pier, which initiates localized erosion at its base. The intensity of the HSV is diminished as the scour hole grows and an equilibrium scour depth is achieved (Richardson and Richardson, 2008). Factors affecting the scour process include the pier size/shape, approach flow velocity/angle, material size and bed configuration. The most common approaches for evaluating scour potential use empirically derived equations that require inputs derived from 1D/2D hydraulic models. The strong 3D nature of the HSV means that these common methods for evaluating scour may be insufficient to reliably predict the physical processes that are forming scour holes at bridges (Spasojevic and Holly, 2008). In these cases, fully 3D non-hydrostatic simulations may be required to accurately resolve the local detail of the flow field.

Computational Fluid Dynamics (CFD) is a powerful tool for simulating complex hydraulic environments, such as those found near existing bridge infrastructure, and provides a viable
option for addressing some of the uncertainty associated with the standard scour analysis techniques. Coupling the 3D hydraulic simulation results with scour models provides exciting potential for improved methods of predicting scour and deposition processes near critical infrastructure such as bridge piers and abutments.

Several previous studies have been completed to evaluate the use of CFD to analyze bridge hydraulics and fully coupled CFD/sediment transport models. Olsen and Melaan (1993) were some of the first researchers to use a fully coupled sediment transport model within a 3D CFD code to evaluate pier scour. Richardson and Panchang (1998) used FLOW-3D to evaluate hydraulic patterns within an already developed equilibrium scour hole at the base of a bridge pier. Khosranejad (2012) tested a fully coupled 3D CFD and sediment transport model for evaluating scour at three different pier shapes. More recently, Omara et al. (2018) and Zhang et al. (2017) evaluated the sediment transport model in FLOW-3D to predict the equilibrium scour hole development at different shaped bridge piers. They found that FLOW-3D accurately predicted the maximum scour depth and shape for cylindrical pier configurations.

The current study seeks to validate the latest updates to the FLOW-3D sediment transport model for predicting the scour and deposition patterns at bridge piers. Specifically, we will be validating the results of FLOW-3D simulations against physical model measurements of scour at cylindrical and diamond shaped piers reported in Khosranejad (2012). We also test a range of user defined input parameters to determine the sensitivity of the final scour and deposition patterns to common input variables.

**Model Description**

**Hydrodynamic Model**

FLOW-3D is a commonly used general purpose CFD software that solves the fully 3D non-hydrostatic Reynolds-averaged Navier-Stokes equations. Additional capabilities include linkages with other physical phenomena such as air entrainment, chemical reactions, multi-species flows, etc. A full derivation of the governing equations and model capabilities can be found in Flow Science (2019). In all subsequent sections FLOW-3D will be referred to as the “numerical model”.

A key feature of the numerical model is the implementation of the Volume of Fluid (VOF) method for simulating free surfaces (Hirt and Nichols, 1981). The VOF method is a numerical technique used to track the location and movement of complex free surfaces and apply proper dynamic boundary conditions to those free surfaces. The current version of the numerical model incorporates major improvements beyond the original (VOF) method to increase the accuracy of the boundary conditions and interface tracking (Barkhudarov, 2004). The numerical model has been used and validated extensively for a wide range of free surface hydraulic engineering applications (Burnham, 2011).

Another important feature of the numerical model is the use of a structured computational mesh that is composed of rectangular elements defined by a set of planes perpendicular to each of the coordinate axes. The numerical model uses a method called Fractional Area Volume Obstacle Representation (FAVOR) to incorporate the effects of geometry into the conservation equations (Hirt and Sicilian, 1985). This approach calculates the open volume fraction and open area fractions to define obstacles in each cell and offers a simple and accurate method to represent complex surfaces without requiring a body fitted mesh.
Sediment Transport Model

A sediment model was first introduced to the numerical model by Brethour (2003) and has since been updated as described in Wei et al. (2014). The numerical model’s sediment transport module simulates a 3D transient mobile bed. It is fully coupled with the 3D hydrodynamic solver to simulate the morphological changes to an erodible solid boundary composed of non-cohesive sediments. The model is capable of simulating both bedload transport and suspended sediment transport; and allows for the exchange of material between the two transport mechanisms. The model includes the capability to simulate up to 10 different sediment species, where each species defines a unique combination of grain size and material density. A non-uniform grain size distribution or variable sediment density can be simulated by defining multiple sediment species.

In the numerical model, sediment can exist as either a packed bed or as a suspended sediment concentration. A packed bed is an erodible solid object that is represented using FAVOR, the same method used to represent solid objects in the hydrodynamic solver. The morphological change in the packed bed is governed by the conservation of sediment mass, or Exner equation.

\[
\phi \frac{\partial \zeta}{\partial t} = \left( \frac{\partial q_{bx}}{\partial x} + \frac{\partial q_{by}}{\partial y} + D - E \right)
\]

(eq. 1)

\( \zeta \), Bed elevation  
\( q_b \), Volumetric bedload transport rate per unit width  
\( \phi \), Maximum packing fraction  
\( D \), Downward sediment deposition flux  
\( E \), Upward entrainment flux

The physical processes governing the morphological changes are represented numerically on the right side of Equation 1 and illustrated below in Figure 1.

Bedload transport represents the physical process of sediment moving laterally along the channel without being carried into suspension. Entrainment represents the erosion of the packed bed into suspension; and deposition represents suspended grains settling out of suspension onto the packed bed. Together the difference in the entrainment and deposition
rates define the exchange between the packed bed and suspended sediment. Additionally, an angle of repose defines the maximum angle of a stable slope before failure.

The suspended sediment is represented as a scalar concentration in the fluid filled cells. The concentration is assumed to be uniform in a given cell and is coupled with the fluid cell density and viscosity. For each species, the suspended sediment concentration is calculated by solving its own transport equation.

\[
\frac{\partial C_i}{\partial t} + \nabla \cdot (u_{s,i} C_i) = \nabla \cdot (\varepsilon C_i)
\]  
(eq. 2)

\( C_i \), Suspended sediment concentration, species \( i \)  
\( u_{s,i} \), Suspended sediment velocity, species \( i \)  
\( \varepsilon \), Diffusivity

**Bedload Transport:** The bedload transport rate is computed separately for each sediment species. The dimensionless transport rate, \( \Phi_{B,i} \), can be defined by choosing between three available bedload transport functions: Meyer–Peter Müller (1948), Nielsen (1992) and Van Rijn (1984), though additional bedload functions can be added by customizing the source code.

\[
q_{b,i} = \Phi_{B,i} \sqrt{\|g\| \left( \frac{\rho_{s,i} - \rho_f}{\rho_f} \right) d_i^3}
\]  
(eq. 3)

\( q_{b,i} \), Volumetric bedload transport rate per unit width, species \( i \)  
\( \Phi_{B,i} \), Dimensionless bedload transport rate, species \( i \)  
\( \rho_{s,i} \), Density of sediment, species \( i \)  
\( \rho_f \), Density of fluid  
\( g \), Gravitational acceleration  
\( d_i \), Grain size, species \( i \)

To compute the motion of bedload transport in each computational cell, we calculate a bedload layer thickness (eq.4; Van Rijn, 1984) and convert the volumetric bedload transport rate, \( q_{b,i} \), into a bedload velocity (eq. 5):

\[
\frac{\delta_i}{d_i} = 0.3d_i^{0.7} \left( \frac{\tau_{s,i}}{\tau_{c,i}} - 1 \right)^{0.5}
\]  
(eq. 4)

\( \delta_i \), Bedload layer thickness  
\( d_i \), Grain size, species \( i \)  
\( d_{*i} \), Dimensionless grain size, species \( i \)  
\( \tau_{s,i} \), Dimensionless shear stress, species \( i \)  
\( \tau_{c,i} \), Critical dimensionless shear stress, species \( i \)

\[
u_{bed\text{load},i} = \frac{q_{b,i}}{\delta_i c_{b,i} f_b}
\]  
(eq. 5)

\( \nu_{bed\text{load},i} \), Bedload velocity, species, \( i \)  
\( c_{b,i} \), Volume fraction of species, \( i \)  
\( f_b \), Critical packing fraction
**Entrainment and Deposition:** Entrainment and deposition are treated as two opposing micro-processes that take place at the same time. They are combined to determine the net rate of exchange between packed and suspended sediments. For entrainment, the velocity at which the grains leave the packed bed is the lifting velocity and is defined in the numerical model based on Mastbergen and Van Den Berg (2003):

\[
E = \alpha_i n_b d_{*,i}^{0.3} (\tau_{s,i} - \tau_{c,i})^{1.5} \sqrt{gd_i(s_i - 1)} \tag{eq. 6}
\]

- \(E\), Entrainment rate
- \(\alpha_i\), Entrainment rate coefficient, species \(i\) (default value is 0.018),
- \(n_b\), Surface normal vector
- \(d_{*,i}\), Dimensionless grain size, species \(i\)
- \(d_i\), Grain size, species \(i\)
- \(s_i\), Specific gravity, species \(i\)
- \(\tau_{s,i}\), Dimensionless shear stress, species \(i\)
- \(\tau_{c,i}\), Critical dimensionless shear stress, species \(i\)

The deposition or packing rate is defined as the product of the effective settling velocity and near bed suspended sediment concentration. This is the rate at which sediment moves from suspension to the packed bed at the solid boundary:

\[
D = \omega_i c_i \tag{eq.7}
\]

- \(D\), Downward sediment deposition flux
- \(\omega_i\), Settling velocity, species, \(i\)
- \(c_i\), Near bed suspended sediment concentration, species \(i\)

The vertical settling rate is defined from Soulsby (1997), where the settling motion is assumed to be in the direction of gravity:

\[
\omega_i = \frac{\nu_f}{d_i} \left[\left(10.36^2 + 1.049d_{*,i}^{0.5}\right) - 10.36\right] \tag{eq. 8}
\]

- \(\omega_i\), Settling velocity, species \(i\)
- \(\nu_f\), Kinematic viscosity of fluid
- \(d_i\), Grain size, species \(i\)
- \(d_{*,i}\), Dimensionless grain size, species \(i\)

The settling equation accounts for the relative motion of sediment in the fluid. The total vertical velocity of the suspended sediment will be the sum of the settling velocity and the vertical component of the mean fluid-sediment mixture velocity. The settling velocity can be further modified using the Richardson-Zaki correlation to account for concentration effects (Richardson, 1954). Note that additional settling and entrainment equations can be defined through source code customization.
Shear Stress Calculation: Both the bedload transport and entrainment rates are driven by the selected turbulence model. Near-wall boundary conditions are defined for 2-equation turbulence models using the logarithmic law (eq. 9), which provides the shear velocity (and consequently the shear stress) without requiring cells small enough to fully capture the velocity profile in the laminar sub-layer:

\[
\frac{u}{u'} = \frac{1}{\kappa} \ln \left( \frac{y}{c_s d_{50}} \right) + 8.5 \tag{eq. 9}
\]

- \( u \): Near bed fluid velocity
- \( u' \): Shear velocity
- \( y \): Distance from wall
- \( c_s \): Roughness multiplier
- \( \kappa \): Von Karmen constant = 0.41
- \( d_{50} \): Median particle diameter

For hydraulically rough surfaces the form of the wall function is modified to include a variable for the roughness height that defines the Nikuradse sand grain equivalent roughness. The roughness height accounts for additional turbulence at hydraulically rough surfaces and is calculated in the numerical model as \( c_s d_{50} \). The \( d_{50} \) is calculated from the current composition of the sediment species in the packed bed, and \( c_s \) is a multiplier to define the roughness height as a function of the \( d_{50} \). The computed bed shear stress is converted to the dimensionless shear stress value that is used in both the bedload and entrainment equations.

The incipient motion conditions are defined using a critical dimensionless shear stress value \( (\tau_{*c}) \) for each sediment species. Additionally, the \( \tau_{*c} \) value can be modified to account for slope effects (eq. 10; Soulsby, 1997). This modification increases the \( \tau_{*c} \) value for fluid moving upslope and decreases \( \tau_{*c} \) for sediment movement in the downslope direction:

\[
\frac{\tau'_{*c,i}}{\tau_{*c,i}} = \frac{\cos \psi \sin \beta + \sqrt{\cos^2 \beta \tan^2 \phi_i - \sin^2 \psi \sin^2 \beta}}{\tan \phi_i} \tag{eq. 10}
\]

- \( \tau'_{*c,i} \): Critical dimensionless shear stress with slope adjustment, species \( i \)
- \( \tau_{*c,i} \): Critical dimensionless shear stress, species \( i \)
- \( \psi \): Angle between flow and slope
- \( \beta \): Angle of packed bed
- \( \phi_i \): Angle of repose, species \( i \)
Methods

Experimental Data

Experimental data from the physical model reported in Khosranejad (2012) was used to validate the numerical model for predictions of equilibrium scour depth and deposition patterns for cylindrical and diamond shaped piers. The experimental flume has a 10 m length; 1.21 m width; and 0.45 m depth. The flume contained a 20 cm depth of uniformly graded, non-cohesive sand with a $d_{50} = 0.85$ mm. For a 16.51 cm diameter cylindrical pier, the experimental setup included an inflow average velocity of 0.25 m/s and a uniform flow depth of 18.6 cm. The diamond pier had a width of 23.35 cm; average inflow velocity of 0.21 m/s; and a uniform flow depth of 15.7 cm. For both cases, physical model results were reported as the maximum scour depth and deposition height; the maximum scour depth over time; and a contour plot of the final equilibrium bed elevation. Results from Khosranejad (2012) will be referenced below as the “physical model”.

Numerical Model Setup

Both pier configurations were set up in the numerical model to replicate the conditions described for the physical model. Simulations were first performed by completing steady-state solutions for the hydraulics only, which were used as the initial condition for the sediment transport simulations. The sediment model was activated with a single sediment species with a diameter of 0.85 mm and density of 2650 kg/m$^3$. The computational mesh was defined using a uniform cell size of 1.25 cm, and the extents of the domain were reduced to 2 m upstream and downstream of the pier, thus affording a finer resolution in the area of interest. The upstream boundary was defined by transferring the velocity profile from the steady state solution, and the downstream boundary was defined with a fixed sub-critical water surface elevation. Other important model setup inputs include the selection of the RNG turbulence model; 2nd order momentum advection; the Nielsen (1992) bedload transport equation; $\tau_{sc} = 0.03$; and a surface roughness of $6*d_{50}$. Simulations were run until achieving an equilibrium scour depth, and results were then compared against physical model measurements. All simulations were completed using FLOW-3D/MP on a single compute node with two Intel Skylake processors. The approximate run time on 40 cores for 4000 seconds of simulation time was 24 hours.

One of the major challenges of 3D sediment modeling is the need to define empirical relationships to quantify the sediment transport processes – bedload, entrainment, and settling. The selection of the appropriate transport coefficients can be difficult and may introduce a high degree of uncertainty into the analysis. The predicted changes in bed elevations will be a function of a complex set of interactions between the hydraulic solution and the transport processes that occur simultaneously at each simulation timestep. In these cases, parameter sensitivity testing can be used to evaluate the range of influence for how possible inputs affect the solution. In this study, sensitivity testing was performed for cell size, the bedload transport equation, $\tau_{sc}$ and the surface roughness height to determine the extent of their effect on simulation results.
Results and Discussion

Results for the diamond pier case are shown in Figures 2 and 3. The results from the numerical model are in excellent agreement with the physical model. The predicted maximum scour depth of 8.5 cm is within 3% of the measured value of 8.3 cm. Further, we see good overall agreement with the deposition pattern downstream of the pier, and the predicted maximum deposition height of 6.0 cm is within 9% of the measured value of 5.5 cm. The general shape and pattern of the deposition is consistent with those found in the physical model; however, the location of the maximum deposition is shifted slightly downstream relative to the observed data. We also observe excellent comparison in the predicted maximum scour depth over time as illustrated in Figure 3. Note that a slight discontinuity in the contour lines can be observed in plots presented in this section. This discontinuity is a rendering artifact and does not reflect the actual predicted scour patterns at these locations.

![Figure 2](image1.png)

**Figure 2.** Equilibrium bed elevation changes predicted by the numerical model for the diamond pier. (A) Isometric view of scour and deposition adjacent to the pier. (B) Comparison between numerical results (top) vs physical model measurements (bottom).

![Figure 3](image2.png)

**Figure 3.** Comparison of numerical model results of maximum scour depth and deposition height with physical model measurements (circles) for the diamond pier case.
Results for the cylindrical pier case are shown in Figures 4 and 5, and these also show excellent agreement between the numerical and physical model. The overall deposition and scour patterns compare favorably with those observed by the physical model, but the overall size and shape of the scour region is slightly larger in the numerical model. The predicted average depth of the scour hole is approximately 7.5 cm deep, is observed near a 60 degree angle from the front of the pier, and is within 12% of the maximum measured scour depth of 6.7 cm. The predicted maximum deposition height of 2.9 cm is within 30% of the physical model measurement of 4.1 cm. Additionally, we can observe the location of the deposition in the numerical model is shifted downstream in relation to the measured data.

Note that the scour at the nose of the pier is underpredicted when compared against measured data. This is consistent with other 3D numerical simulations of scour at blunt shaped piers, and it has been proposed that this is caused by the inability of RANS turbulence models to fully resolve the complex HSVS (Khosranejad, 2012). This effect is less pronounced for the diamond shaped pier where the sharp leading edge on the upstream side of the pier is likely inhibiting the formation of the HSVS.

Figure 4. Equilibrium bed elevation changes predicted by the numerical model for the cylindrical pier. (A) Isometric view of scour and deposition adjacent to the pier. (B) Comparison between numerical results (top) vs physical model measurements (bottom).

Figure 5. Comparison of numerical model results of maximum scour depth and deposition height with physical model measurements (circles) for the cylindrical pier case.
Sensitivity Testing

The parameter sensitivity tests evaluated the effects of mesh cell size, bedload equation, \( \tau_{cc} \), and roughness height on predicted scour and deposition for the diamond shaped pier. The mesh sensitivity tests evaluate the results of three different cell sizes on simulation results (Figures 6 and 7). These results indicate that the general scour and deposition patterns are consistent for all cell sizes. However, we can clearly observe a dependency of scour and deposition magnitude on mesh size. Compared with the results for the smallest cell size (1.25 cm), increasing the cell size to 1.75 cm and 2.5 cm decreased the predicted scour magnitudes by 25% and 30%, respectively. We can also observe a reduction in deposition height for the larger mesh sizes. Since shear stress is the primary mechanism for bed erosion, accurately predicting it in the numerical model is of primary importance. Any model setup input affecting shear stress can directly affect scour rates at the packed bed. The size of the mesh cells can directly affect the resolution of the spatially varying flow features and thus the calculated shear stresses near the base of the pier. This is especially important considering the complexity of the flow and turbulent boundary layers near the pier. Additionally, smoothing of the packed bed elevation may result from the surface reconstruction occurring at each timestep.

Results for the bedload equation sensitivity tests are illustrated in Figures 8 and 9. Simulations were completed using the Van Rijn and Meyer-Peter Müller bedload equations and compared against results for the Nielsen equation. These results show the Nielsen and Meyer-Peter Müller equations generally produce a consistent pattern and shape for both scour and deposition, though the Meyer-Peter Müller equation predicts scour magnitudes that are 14% less than Nielsen. The Van Rijn bedload equation resulted in maximum scour predictions 30% less those
predicted by Nielsen. The results of bedload sensitivity are interesting in that the Nielsen equation is predominantly used in coastal applications for uniform gravel and sands (Garcia, 2008), but provided the closest match with measured data in the current test case. The form of the Nielsen equation is very similar to Meyer-Peter Müller, therefore it is reasonable to expect similarity between the two results, as was observed in the general patterns of scour and deposition. Additionally, given the Van Rijn equation was derived for fine particles (0.2 - 2.0 mm), it was somewhat surprising that it performed the worst of the three available bedload equations. We suspect these results may actually be indicating an underprediction of erosion due to entrainment, which is being compensated with bedload equations that result in higher transport rates. In this study, sensitivity testing on the entrainment equation parameters were not performed, but these results may indicate the need for further evaluation of the interaction between bedload transport and entrainment processes for this case.

![Figures 8 and 9](image)

**Figure 8.** (Above) Bedload equation sensitivity results comparing numerical model results of maximum scour depth and deposition height with physical model measurements (circles).

**Figure 9.** (Left). Equilibrium scour and deposition predicted from the numerical model for different bedload transport equations: (A) Nielsen (initial setting); (B) Meyer-Peter Mueller; (C) Van Rijn.

Results for the sensitivity tests of $\tau_{sc}$ are shown in Figures 10 and 11. We tested values of $\tau_{sc} = 0.027$ and $\tau_{sc} = 0.033$, and compared the results with the initial simulation value of $\tau_{sc} = 0.030$. Decreasing the value of $\tau_{sc}$ decreases the threshold of particle motion and results in larger computed bedload and entrainment transport rates. Increasing $\tau_{sc}$ has the opposite effect, increasing the threshold for motion and decreasing transport rates. The simulation results were consistent with this expected behavior. Setting $\tau_{sc} = 0.033$ resulted in a 14% decrease in the scour magnitude prediction. Setting $\tau_{sc} = 0.027$ resulted in only a slight increase in the predicted maximum scour depth, but we can qualitatively observe the spatial extent of the scour region has significantly increased. Regardless of the chosen $\tau_{sc}$ values, scour and deposition patterns are largely consistent between the numerical and physical models.
Results for the sensitivity test of the roughness height are shown in Figures 12 and 13. For riverine applications, the roughness height is often calculated as a function of a representative grain size diameter, and a wide range of literature is available that proposes values for the roughness height multiplier. García (2008) summarizes these studies and reports values for roughness height that range from 1 - 6.6 \( d_{50} \). Van Rijn (1982) also reviewed studies of roughness height and reported a range of effective roughness height between 1 - 10 \( d_{90} \) for plane beds. These reviews indicate a considerable degree of uncertainty for defining the roughness height as a function of grain size. To understand the effect of this input, we tested roughness height values of 2.5 \( d_{50} \) and 9 \( d_{50} \) to compare with the initial parameter set value of 6\( d_{50} \). Modifying the roughness height directly affects the computed dimensionless shear stress values that drive both the bedload and entrainment functions. Increasing the roughness height will have the expected effect of increasing shear stress and scour magnitudes. Alternatively, decreasing roughness height should result in decreased scour magnitudes. From the results, we observe differences in the magnitude of both deposition and scour are consistent with the expected outcomes of increasing or decreasing bed shear stress. Increasing the value of roughness height to 9 \( d_{50} \) resulted in a 15% increase in predicted scour depth, while decreasing the roughness height to 2.5 \( d_{50} \) resulted in a 36% decrease in predicted scour depth.
Conclusions

We tested the implementation of a fully mobile bed 3D sediment transport within the commercial CFD software, FLOW-3D. The model has the capability for simulating morphological changes due to bedload transport, entrainment, settling, advection and slope failure. Numerical model results were validated against measured physical model data for cylindrical and diamond shaped piers. Simulation results show that the numerical model was in close agreement with the physical model for general scour and deposition patterns of both pier shapes. The model also showed close agreement with predictions of maximum scour depth, and compared within 3% and 12% for the diamond and cylindrical shaped piers, respectively. Predictions for the maximum deposition height showed a higher degree of variation and compared to predicted values within 9% and 30% for the diamond and cylindrical piers, respectively.

Overall, the use of 3D CFD numerical models coupled with sediment transport models shows excellent promise as a tool for evaluating complex scouring events where conventional methods may result in a high degree of uncertainty. The model shows to be a useful tool for predicting general deposition and scour patterns. However, the challenges for successful 3D sediment transport simulations should not be understated. One of the most immediate challenges is the computational expense for simulations at a practical scale. This limits the current range of applications to small spatial and temporal scales. However, with the increasing availability of HPC, improving computer processing speeds, and increases in numerical code efficiency, this limitation will continue to diminish. Computational resource limitations directly affect accuracy by limiting the possible size of mesh cells. As observed in the current study, the cell size can
affect the magnitude of scour and deposition. Reducing mesh cell size can improve the resolution of the hydraulic conditions that are driving the scour processes, and the resulting predictions of scour magnitudes. However, the reduction in cell size also come at the cost of increased simulation run times. Future developments and improvements to the numerical model are planned to improve run time efficiency and reduce mesh dependency. Regardless, mesh dependency studies are always recommended to understand the effects of cell size on the solution.

The selection of model inputs to define the sediment transport parameters also poses significant challenges. These transport equations may only be valid under a limited range of grain sizes and hydraulic conditions, and using them outside of these prescribed ranges many introduce additional uncertainty into the analysis. Additionally, these inputs may have a complex set of interactions that can be difficult to evaluate. Sensitivity testing allows modelers to identify critical input parameters, evaluate interacting variables, and validate known influences. Sensitivity testing was performed in the current study and found variation of scour depths up to 36% for the range of variables tested. It is also important to mention that any conclusions drawn from the current study are limited to the range of inputs and boundary conditions that were tested. Extrapolating these results to other applications or ranges of hydraulic conditions should be treated with caution. Moving forward, we plan to continue further validation and sensitivity testing of the numerical model for a range of other common sediment transport applications.

References


