Study on local scour around bridge pier due to the dam removal

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ABSTRACT

Erosion and sedimentation are severe problems in Taiwan’s river. The existence of dam, weir and river-crossing structure often makes local reach with obvious scouring phenomena. In this study, a three-dimensional numerical model, called CCHE3D, is adopted to simulate the flow field and local scour around bridge pier. The influences due to the dam removal in downstream reach are considered. From the simulated results, the local scour holes occur along the bridge abutment. The sediment transport in the scour hole is related to the turbulence in the approach flow and the turbulence stimulated by the bridge pier.

KEY WORDS: CCHE3D model, bridge pier, local scour, dam removal

INTRODUCTION

In Taiwan, there is a great amount of sediment yield in river basin, and it often causes riverbed deposition, especially in impounding regions of dam and weir. The existence of dam, weir and river-crossing structure often makes mid-downstream local reach with obvious scouring phenomena. The riverbed changes rapidly due to the huge discharges that often have resulted a large amount of property damage and threats to the safety of hydraulic structures. The 1-D or 2-D depth-averaged hydraulic model has the limitation for the understanding of downward flow toward the bed. To investigate the mechanism and details of hydrodynamics and local scouring near the in-stream structures, the study of 3-D numerical model is needed.

Local scouring is a common threat to in-stream structures such as bridge piers or abutments constructed in alluvial rivers. The hydrodynamic force of the approach flow is blocked by the structures standing in its path way and additional turbulence fluctuations are simulated which provide excessive erosion power and thus create a deep scouring hole around the structures. A large number of laboratory experiments, field measurements, and numerical simulations by many scientists has improved the understanding of physical mechanisms of scouring. It results in development of semi-empirical equations and numerical models for predicting the depth of local scouring under a variety of flow, sediment and structure conditions.

This paper takes Dongshih Bridge, located in the lower reach of Dajia River, Taiwan as study site. A three-dimensional numerical model, called CCHE3D, is adopted to simulate the flow field and local scour around bridge pier. Data associated with suspended sediment concentration, local scour depth, bed material grain sizes and cross sections are collected. These basic data are used to calibrate the numerical model. In addition, the influence on local scour around bridge pier due to the dam removal in downstream reach is discussed.

NUMERICAL MODEL

CCHE3D is developed for computing three dimensional, free surface and turbulent flows, sediment and pollutant transport in open channels. The flow field is solved by using Reynolds equations. Efficient Element Method is used to discretize unsteady governing equations spatially, and a time marching scheme is applied to solve the equation system. Free surface is computed with the depth-averaged continuity equation. The flow velocity and dynamic pressure field are solved by using a velocity correction method. Turbulence stresses in the momentum equations are linear functions of the main rate of strain and the eddy viscosity which is calculated by a turbulence closure model.

Local Scour Scheme

The local scour scheme of CCHE3D has been proposed and applied successfully in a laboratory case of bridge pier under non-uniform sediment conditions (Jia et al., 2013). It is assumed that the sediment entrainment and transport in the scour hole are related to the turbulence in the approach flow and the turbulence stimulated by the bridge pier. The turbulence fluctuations in the water are brought into the sediment layer via the strong vertical flow. The intruding turbulence fluctuation near/in sediment layer enhances the power of the flow to entrain sediment and this enhancement can be modeled using additional shear stress related to the intruding turbulence fluctuation.

The approach flow to a local scour region is approximated as a uniform open channel flow like in many experiment study cases. In general, a log velocity distribution in vertical can be assumed and turbulence properties of approach flows are well understood. The vertical profile of the eddy viscosity distribution in a uniform flow is expressed as:

\[ \nu_v = \kappa \nu_w z (1 - z / h) = \kappa \nu_w h \zeta (1 - \zeta) \]  

(1)

where \( \kappa \) is the von Kármán’s constant, \( h \) is flow depth, \( z \) is vertical coordinate, and \( \nu_w \) is a reference shear velocity representing the turbulence generated by the flow in the approach channel before the flow reaches the local scour region. According to Nezu and Nakagawa (1993), turbulence fluctuation components and kinetic energy in uniform flows can be expressed by:
where these two equations and by using
\[ v_i = \frac{k}{\nu} \]  
(3)

where the energy dissipation rate can be computed as:
\[ \varepsilon = \frac{k}{v_i} = \frac{4.78}{k} \exp(-2\zeta) \]  
(4)

The subscript \( u \) indicates uniform flow or approach flow. Eq.(4) describes the energy dissipation in the uniform flow. Eq.(1), (2), and (4) provide estimations of turbulence characteristics near a local scour region in the approach flow. It is postulated that Eq.(4) is a reasonable estimation and the mixing length turbulence eddy viscosity model is applicable in the scour hole.

\[ v_i = \sqrt{\frac{\partial u_i}{\partial x_i} \frac{\partial u_i}{\partial x_i}} \]  
(5)

With this, turbulence energy near the local scour region can be estimated by substituting Eq.(4) and (5) into (3):
\[ k = \frac{\sqrt{\varepsilon}}{u_i} = 4.78 \frac{u_i}{k} \exp(-2\zeta) \]  
(6)

Eq.(6) is applicable to uniform flows because it will change to Eq.(2) in uniform flow conditions if the logarithmic law of the wall is respected. In a scour hole, the 3-D velocity gradient terms will generate higher turbulence kinetic energy. Eq.(6) includes the information of approach flow (\( u_i \)) and that for the complex flow around the local scour region.

Observations indicated that near the base of scour hole, the vertical motion and the horse shoe vortex carry the turbulence fluctuation into the sediment layer. These additional turbulence fluctuations would increase the sediment entrainment. Because the scour hole and the horse shoe vortex created a separation, the turbulent flow of the approach channel clashes onto the surface like a free jet and being pushed to side-ways horizontally and to impinge into the scour hole. With this consideration, the turbulence energy in the scour hole bed surface is approximated by the depth-averaged value of Eq.(6).

\[ \overline{\varepsilon} = 4.78u_i \frac{u_i}{k} \]  
(7)

Integration of the vertical distribution only for the lower part of the water depth (0–0.5\( \zeta \)) is because the lower part of the flow will most likely run into the scour hole and affect the erosion. The term with velocity gradients accounts for the local turbulence energy in the scour hole. The turbulence kinetic energy by Eq.(7) is considered near the bed and around the pier. The corresponding total turbulence fluctuation introduced is expressed as:
\[ U'' = 2\overline{\varepsilon} \]  
(8)

Observations suggested that sediment transport in a scour hole is strongly affected by vertical flows normal to the bed. Jia et al. (2013) is interpreted as that turbulence fluctuation penetrating into the sediment layer around the local scour region is due to the mean velocity perpendicular to bed surface. The sediment entrainment in scour hole is assumed to be related to this turbulence, called intruding fluctuation, which is formulated by
\[ w_i' = \frac{w_i}{u_i} |k| \]  
(9)

where \( w_i' \) is the near bed available turbulence fluctuation and \( w_i'' \) is the fluctuation brought into sediment layer (intruding turbulence) by the perpendicular velocity.

\[ R_i = \frac{w_i}{\sqrt{u_i + v_i + w_i}} \]  
(10)

In Eq.(10), \( w_i \) is the mean velocity perpendicular to the bed, \( R_i \) is a non-dimensional scale for evaluating how much of the available near bed turbulence energy is impinged into the near bed sediment layer for triggering additional sediment motion. Sediment transport formulations are normally developed based on flow shear stress. The intruding turbulence fluctuations are converted to shear velocity. From Eq.(2), the fluctuation velocity of uniform flows near the bed (\( \zeta = 0 \)) is related directly to mean bed shear stress:
\[ u' = 2.3u_i, \quad v' = 1.63u_i, \quad w' = 1.27u_i, \quad U' = 3.1u_i \]  
(11)

Assuming the turbulence in the scour hole is homogenies, and the coefficients to convert fluctuation velocities to shear velocities in the scour hole are approximately the same as those for uniform flow in Eq.(11). Thus the coefficient for fluctuations in all directions including the available turbulence should be:
\[ w_i' = \frac{1}{\sqrt{3}} U' = \partial u, \quad \varrho = 1.79 \]  
(12)

According to Eq.(8) and (9)
\[ w_i' = \sqrt{\frac{2}{3} \varrho} |k| \]  
(13)

Assuming the intruding fluctuation can also be related to a shear velocity using the same relation:
\[ w_i' = \partial u, \quad \varrho = 1.79 \]  
(14)

With this relation, the shear velocity induced by the intruding turbulence fluctuations can be approximated by
\[ u_i = \frac{C_{uw}}{\varrho} \sqrt{\overline{w_i^2} |k|} = 0.456C_{uw} \sqrt{\overline{w_i^2} |k|} \]  
(15)

The total effective shear stress for sediment entrainment including the vertical impact effect can be expressed:
The intruding shear stress is only effective when the flow has a component perpendicular to the bed surface. $C_s$ is a calibration coefficient, $u_{*n}$ is the shear stress computed using near bed flow parallel to the bed (log law). One can see that the effective shear velocity is affected by the flow parallel to the bed and the intruding turbulence fluctuation.

CASE STUDY

Field Site Description

Fig. 1 shows the aerial photo of the study reach. During the 921 Earthquake in 1999, the broken zone of a fault had caused cracks in the Shigang Dam and stilling basin, distortion of several gates, and raised #17 and #18 spillway at right section of the dam by 10m around. The Shigang Dam had lost its regulating capability since the earthquake. In addition, the end section of the transmission tunnel was broken by 2.2 m. As a result, the tunnel cannot function properly. The Shigang Dam has now been renovated at the end of 2000, thus making it look brand-new and regain its water supply capability. However, it has severe scouring problems downstream the river-crossing structure in the lower reach of Dajia River. There are also serious depositions in reservoir and dam. The influence and existence of Shigang Dam are also an important issue for the regulation planning of Dajia River.

Initial and Boundary Conditions

In this study, a three-dimensional numerical model is adopted to simulate the flow field and local scour depth around the bridge pier of Dongshih Bridge. The boundary conditions, inflow discharge and sediment hydrograph at upstream; water stage hydrograph at downstream are calculated by a validated 1-D mobile-bed model. The typhoon Morakot is selected as the flood event, which is the representative event in recent years.

Fig. 2 and Fig. 3 show the bridge piers and abutments of Dongshih Bridge. The initial bed elevations of the computational mesh are interpolated using the measured DEM data of 2013. The computational domain ranges from the upstream CS48 to downstream CS46, which are about 600 m long and 330 m wide. The grid numbers along the longitudinal, horizontal and vertical are 271, 452, and 15, respectively. The diameter of pier is 2.5 meters. Three size classes ranging from 0.3 mm to 239.9 mm are selected to compute the associated sediment transport.

Model Results and Discussions

Fig. 4 and Fig. 5 show the simulated velocity distribution on the free surface layer when the inflow discharge is 500 m$^3$/s. There is relatively high velocity between the pier abutments in main channel, and the velocity is decreasing behind the bridge pier. Fig. 6 shows the simulated flow fields around the bridge piers on the free surface layer. It can be seen that the circulation between the piers is simulated by considering the highly three-dimensional turbulent flow. In the front of the first bridge pier, the rising of water surface and downward flow produce the highly complex vortex and circulation. It would cause the local scour around the bridge pier and abutment.

Fig. 7 shows the simulated bed changes at Dongshih Bridge after the typhoon Morakot. The erosion occurs between the five abutments in the main channel of Dajia River, which are caused by the contraction of bridge piers. There are also depositions behind the bridge abutments. Fig. 8 shows the simulated flow fields and local scour depth around the bridge abutment. It can be seen that the local scour holes occur along the bridge abutment. The sediment transport in the scour hole is related to the turbulence in the approach flow and the turbulence stimulated by the bridge pier. The turbulence fluctuations in the water are brought into the sediment layer via the strong vertical flow.
CONCLUSIONS

A three-dimensional numerical model is adopted to simulate the flow field and local scour around bridge pier. From the simulated results, the local scour holes occur along the bridge abutment. It agrees with the observed data. The influences due to the dam removal in downstream reach are not obviously. The erosion at Dongshih Bridge is caused by the contraction of piers and turbulence in the approach flow due to the highly complex vortex and circulation where the turbulence fluctuations in the water are brought into the sediment layer via the strong vertical flow.

Figure 4 Simulated velocity distribution on the free surface layer when the inflow discharge is 500 m$^3$/s.

Figure 5 Simulated velocity distribution on the free surface layer around the bridge piers when the inflow discharge is 500 m$^3$/s.

Figure 6 Simulated flow fields around the bridge piers on the free surface layer when the inflow discharge is 500 m$^3$/s.

Figure 7 Simulated bed changes at Dongshih Bridge after the typhoon Morakot.

Figure 8 Simulated flow field and local scour depth near the front of bridge pier and abutment after the typhoon Morakot.

REFERENCES


