International Conference on Hydroinformatics

2014

Numerical Simulation Of Sediment Transport And Bedmorphology Around A Hydraulic Structure On A River

Van Thinh Nguyen

Carlos Serrano Moreno

11th International Conference on Hydroinformatics
HIC 2014, New York City, USA

NUMERICAL SIMULATION OF SEDIMENT TRANSPORT AND BEDMORPHOLOGY AROUND A HYDRAULIC STRUCTURE ON A RIVER

NGUYEN, VAN THINH (1), SERRANO MORENO, CARLOS (1)
(1): Department of Civil and Environmental Engineering, Seoul National University,
1 Gwanak-ro, Gwanak-gu, Seoul, 151-742, Republic of Korea

ABSTRACT

In this study, we modified and applied an open source CFD software package, the TELEMAC-MASCARET, to simulate sediment transport and bed morphology around Gangjeong Weir on Nakdong River in Korea. The simulations have been carried out with the real river bathymetry and the weir geometry, and for different operation scenarios of the weir. The hydrodynamic parameters and bed evolutions obtained from the numerical results have been validated against field observation data. Particularly, the scour depth has been verified against the results obtained from a well-known empirical formula. Agreement between numerical computations, observed data and empirical formula is judged to be satisfactory on all major comparisons. This study is not only to point out the locations where deposition and erosion taken place due to the weir gate operation, but also to analyze the mechanism of formation and evolution of scour holes after the weir gates.

INTRODUCTION

Scour around hydraulic structures is one of critical problems in hydraulic engineering; under prediction of scour depths can lead to costly failures of the structure, while over prediction can result in unnecessary construction costs. Unfortunately, up-to-date empirical scour prediction methods and equations based on laboratory data are not always accurate enough and able to reproduce field conditions. Due to physical scales and fluid properties, lab-scale models should be derived from field conditions according to the Hydraulic Similitude Laws, however this task is somehow over the capacities of the laboratory. Unlike physical models, computational fluid dynamics (CFD) tools can perform using real field dimensions and various operating conditions to predict turbulent flows and sediment scour.

After completion of the Four Major Rivers Restoration Project, several new weirs have been installed in the main Korean rivers. Consequently, sediment deposition and erosion around such structures have became a major issue in such rivers. This study applies an open source CFD software package, the TELEMAC, to simulate sediment transport and bed morphology around Gangjeong Weir, which is the largest multipurpose weir built in Nakdong River during the Four Major Rivers Restoration Project. The real bathymetry of the river and the geometry of weir have been input in the numerical model. Numerical results have been validated against available field observations and empirical formulas from literature to predict maximum eroded depths of scour near hydraulic structures.

METHODOLOGY

Due to the complicated geometry and the extension of the study region, a 2D-numerical approach will be carried out. After validating the capability of available river flow and sediment transport software products, the TELEMAC-MASCARET model was chosen. This software uses finite element method and is capable to deal with complicated geometries by the use of unstructured grids. TELEMAC is a well-known software with an abundant history of development and application over many years in fluvial and maritime hydraulics (Brière *et al.*, [1]; Villaret *et al.*, [6]). Recently, this software has been released as an open source product, which provides users the opportunity to adapt and modify the code in order to reach a better performance of their simulations. In this case study, the routine "noerod.f" to deal with non-eroded locations has been modified in order to take into account the effect of the non-erodible areas built on downstream of the weir as bed protection, and to define the possible maximum eroded depth depending on the depth of rock layer underneath of the riverbed following geology observations.

Hydrodynamic calculations: TELEMAC 2D

The hydrodynamic calculations will be carried out by TELEMAC 2D by solving depth averaged Reynolds Averaged Navier-Stokes Equations (k-ε model), as follows

$$\frac{\partial h}{\partial t}+\frac{\partial hu}{\partial x}+\frac{\partial hv}{\partial y}=0 \qquad (1)$$

$$\frac{\partial (hu)}{\partial t}+\frac{\partial (huu)}{\partial x}+\frac{\partial (huv)}{\partial y}=-h\cdot g\,\frac{\partial Z}{\partial x}+h\cdot F_x+div\left(h\cdot \nu_e\cdot \overrightarrow{grad}(u)\right) \qquad (2)$$

$$\frac{\partial (hv)}{\partial t}+\frac{\partial (hvu)}{\partial x}+\frac{\partial (hvv)}{\partial y}=-h\cdot g\,\frac{\partial Z}{\partial y}+h\cdot F_y+div\left(h\cdot \nu_e\cdot \overrightarrow{grad}(v)\right) \qquad (3)$$

Where h is the water depth, u and v are the velocity components, Z is the free surface elevation, F_x and F_y are source terms and ν_e is the effective viscosity, the summation of the molecular viscosity and the turbulent viscosity $(\nu_e=\nu+\nu_t)$. The turbulent viscosity is obtained as shown in Eq. (4) considering c_μ =0.09.

$$\nu_t=c_\mu\,\frac{k^2}{\varepsilon} \qquad (4)$$

Sediment transport module: SISYPHE

Sisyphe is the module to calculate sediment transport processes. Transport rates are decomposed into bed and suspended loads, and are calculated as a function of the flow field and sediment properties at each node of the grid. This module is internally coupled with the hydrodynamic module; the flow field and river bathymetry are updated at each time step. The hydrodynamic variables (velocity, water depth, etc.) are transferred to the morphodynamic module, which sends back an updated bed elevation to the hydrodynamic module.

In order to compute the bed load, it is possible to choose between different well-known formulas, such as Meyer-Peter-Müller, Einstein-Brown and Van Rijn's formulas. In this study, the bed gradation data has an average size of D_{50} = 1.68 mm, Van Rijn's formula [4] is used, since it is designed to deal with a range of sediment sizes between 0.2 mm and 2 mm. As shown in Eq. (5), for any application of the bed load formula, the bed transport rate depends on a non-dimensional sand transport rate defined in Eq. (6) following Van Rijn's formula where a balance between a non-dimensional bed shear stress, θ_p, and a non-dimensional Shield's parameter, θ_c, is established.

$$Q_b = \phi_s \sqrt{g(s-1){D_{50}}^3} \qquad (5)$$

$$\phi_s = 0.053 \cdot {D_{50}}^{-0.3} \left(\frac{\theta_p - \theta_c}{\theta_c} \right) \qquad (6)$$

Suspended load of the sediment is calculated by solving the advection-diffusion equation for the sediment concentration C. Due to the presence of several weirs on the upstream of the study domain, sedimentation processes have occurred on the upstream of these weirs, a clear water condition is assumed at the initial and inlet boundary conditions, so the sediment concentration at the initial step and the inlet is set to be 0. As shown in Eq. (7), where ε_s is the sediment diffusivity coefficient, the suspended sediment particle velocities are denoted as u_p and v_p, and are obtained as a summation of the velocities of the flow field u and v and the settling velocity parameter, w_p, defined by Van Rijn [5].

$$\frac{\partial C}{\partial t} + u_p \cdot \frac{\partial C}{\partial x} + v_p \cdot \frac{\partial C}{\partial y} = \frac{1}{h}\left[\frac{\partial}{\partial x}\left(\varepsilon_s \frac{\partial C}{\partial x} \right) + \frac{\partial}{\partial y}\left(\varepsilon_s \frac{\partial C}{\partial y} \right) \right] \qquad (7)$$

Bed evolution is determined by solving the Exner's equation, Eq. (8), by setting a balance between the bed load transport rates, Q_b, the river bed level, Z_f; and the porosity is also taken into account, n=0.4.

$$(1-n)\frac{\partial Z_f}{\partial t} + \nabla \cdot Q_b = 0 \qquad (8)$$

CASE STUDY

This study focuses on the effect of the operation of Gangjeong Weir on the river bed. The objective is not only to identify the areas where erosion is taking place, but also to predict the evolution of the scour holes that may appear around the structucre. As shown in Figure 1, this weir is a singular structure including movable and fixed parts.

Figure 1. Overview of Gangjeong weir in Nakdong River

The weir is operated following different scenarios that are related to the river discharge or other managing purposes, as shown in Table 1 different operations of the weir will have different impacts on the evolution of the river bed. The simulations are based on the hydrologic data available on the website of the Korean Water Management Information System (WAMIS), and the discharge registered in Nakdong River is used as upstream boundary condition. At the downstream boundary, a calculated water surface level from a specific empirical rating formula for Nakdong River, Eq. (9), is used at the outlet boundary condition.

$$WSE = 0.0217 \cdot Q^{0.6018} + 14 \tag{9}$$

Table 1. Different operation scenarios of Gangjeong Weir

Simulation Case	Flow regimes		
	Overflow through the fixed weir	Overflow through the movable weir	Underflow through the gates
Case 1: Operational condition	No	Yes (Weir gates partially open)	No
Case 2: Flood Scenario	Yes	Yes (Weir gates fully open)	No
Case 3: Flushing	Yes	No	Yes
Case 4: Planned Scenario	Yes	No	No

The study region has a total length of 1.8 km, a width of 800m at the upstream boundary and 600m at the downstream boundary. Figure 2 shows the computational hybrid grid used for the simulations, which is coarser on the flood plain (30m), finer (20m) along the main river, and finest near the weir (10m), where the high gradient of the flows and bed evolution are expected. Besides, a concrete bed is defined 20 m right downstream of the weir gates, where no erosion will take place during the simulation.

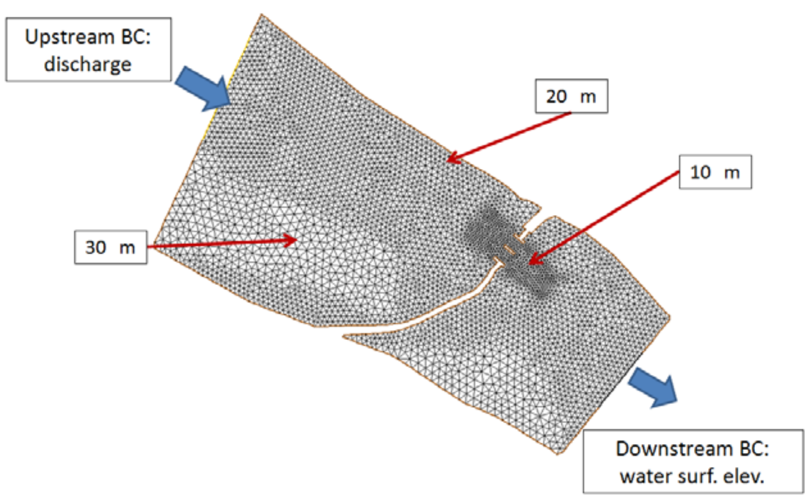

Figure 2. Computational Grid used in the simulation of Case 2 with the weir gates fully open.

The simulations performed for each scenario calculate the flow field for 15 days long. After running Cases 1, 3 and 4 no significant change on the river bed was found since those scenarios correspond to low flow situations when the flow velocities are not strong enough to flush away material from the river bed. The result obtained from the simulation of Case 2, when the flood is occurred with a peak discharge of 7000 m^3/s as shown in Fig. 3. When the weir gates are fully open, a strong erosion takes place behind the weir gate just after the concrete protection bed and the sediments are flushed downstream, while an erosion in the area upstream of the weir gates appears. According to the observation of the river bed geology, a rock layer is located at about 8m deeper underneath of the initial bed level, therefore a maximum eroded depth is set to this observed value. Due to a crucial role of this rock layer, a further analysis of the formation and evolution of scour holes based on empirical formula is necessary.

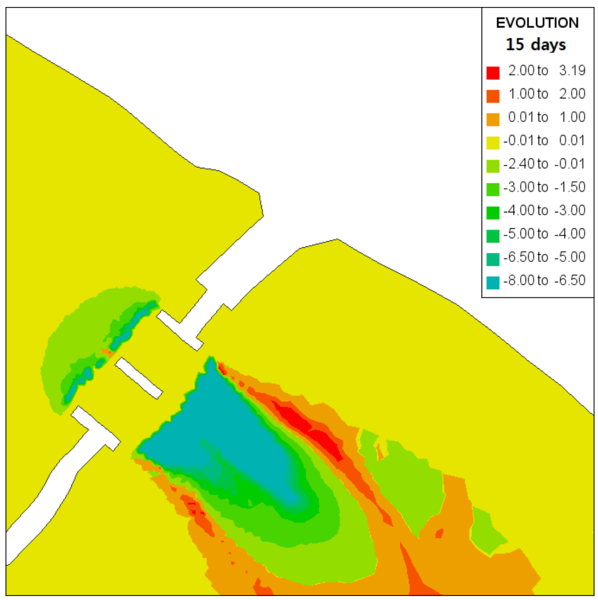

Figure 3. Bed evolution obtained in the 15-day simulation of Case 2.

In order to verify the accuracy of the numerical simulations, at first we calibrate the numerical results against hydrodynamic parameters obtained from filed observations. Due to the limitation of available data from field survey, hereby we can show only a comparison of water levels between the numerical results and observations for low and high flow regimes, as shown in the Table 2. Fig. 3 shows a bed evolution on up- and downstream of the weir, which is obtained from 15 days real-time simulation for the high flow regime.

Table 2. Water Surface Elevation measurements in Gangjeong Weir

Flow Regime	Operational Scenario	Observed WSE in Gangjeong Weir	Calculated WSE in Gangjeong Weir
High Flow (7700 m^3/s)	Case 2	20.96m	21.2m
Low Flow (480 m3/s)	Case 1,3, 4	16.63m	16.81m

The second step of the calibration is the verification of the bed evolution values obtained from sediment transport module with observations and the well-known empirical formula. As found in literature, Hoffmans [2] & [3] provided an empirical formula obtained from his experimental research, as shown in Eq. (10), to predict the maximum equilibrium scour depth that takes place after a weir or sill as in this study. This formula offers an estimation of the equilibrium scour depth, $y_{m,e}$, that depends on the initial flow depth, h_0, the average velocity around the scour hole, U_0, the critical mean velocity, U_C, and a non-dimensional parameter, ω, that depends on the turbulence intensity Eq. (12). Where the critical mean velocity in Eq. (11) depends on the shear velocity u_*, and the Chezy coefficient *C*. The turbulence intensity, obtained from Eq. (13), depends on the geometry of the sill; where *D* is the height of the sill, *L* is the length of the bed protection, and *C* is the Chezy coefficient.

$$\frac{y_{m,e}}{h_0} = \frac{\omega U_0 - U_C}{U_C} \tag{10}$$

$$U_C = u_* \frac{C}{g} \tag{11}$$

$$\omega = 1 + 3r_0 \tag{12}$$

$$r_0 = \sqrt{0.0225\left(1-\frac{D}{h_0}\right)^{-2}\left(\frac{L-6D}{6.67h_0}+1\right)^{-1.08} + 1.45\frac{g}{C^2}} \tag{13}$$

Before applying this formula to validate the sediment transport results obtained from the numerical simulation, we carried out a number of simulations with the same geometries and physical conditions as in the laboratory experiments of Hoffmans [3], such as the scouring caused by the flows over 3m height trapezoidal and triangular sills with an initial water depth of 3.5m. Table 3 shows a reasonable agreement between the simulations and the predictions provided by Hoffman's formula for these validated cases. Even the formula shown above is the empirical approximation that can provide a closest approach to validate this numerical simulation, it is important to consider all assumptions made by Hoffmans to obtain this formula when applying it to the field. One critical assumption is that the equilibrium scour depth needs to be greater that the initial flow depth. In Gangjeong Weir case the initial flow depth is around 15m, applying Hoffmans' formula leads to a prediction of the equilibrium scour depth of 20.8m, which is an unreal value due to the existence of a rock layer at 8m depth underneath of the river bed, and the Hoffmans' formula does not take in account this rock layer. Because of the assumptions taken to apply the empirical formula, it is necessary to perform long simulations as a steady flow that take into account the presence of the rock layer in order to obtain a reasonable explanation on the mechanism of the scour hole development; then to compare obtained results with the available observations as shown in the following paragraph.

Table 3. Comparison between the equilibrium scour depth values obtained by using Hoffman's formula and the sediment transport simulations performed by TELEMAC.

Equilibrium scour depth estimation approach	Equilibrium scour depth (m)	
	Trapezoidal Sill	Triangular Sill
Hoffman's formula prediction	8.89	4.85
TELEMAC numerical simulation	7.87	4.43

Fig. 4 (a) shows the evolution of the river bed after one month real-time simulation with a constant discharge of 4000 m^3/s. A comparison between the simulation result and the observation is shown in Figs. 4(a) and 4(b), it shows that the numerical model is capable to reproduce a bed morphology similar as in reality. However, it should be stated that some differences between the observed and the simulated bathymetries are still remained; the reason may come from the assumption in the numerical simulation that the rock layer is uniformly located 8m underneath of river bed, which differs from the reality.

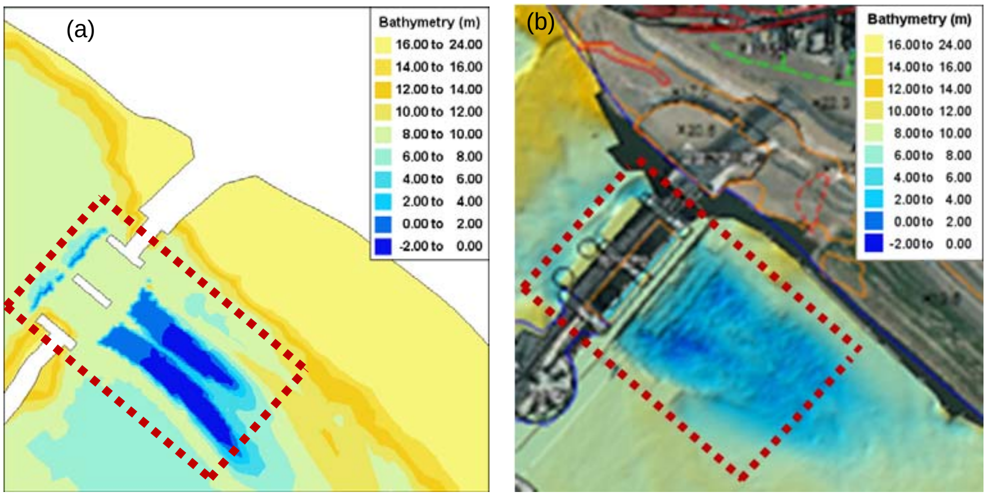

Figure 4. River bed bathymetry at Gangjeong Weir: (a) 1 month real time simulation of Case 2; (b) Observed bed bathymetry measured by using a Multi-beam Echo-sounder.

In spite of the fact that the observation of the bed evolution image is helpful to identify the areas where the sediment transport phenomena is relevant, it is necessary to analyze the evolution of the river bed morphology with respect to time to understand the mechanism and the formation of scour holes. Fig. 5 shows the formation of the scour hole and its evolution after one month real-time simulation.

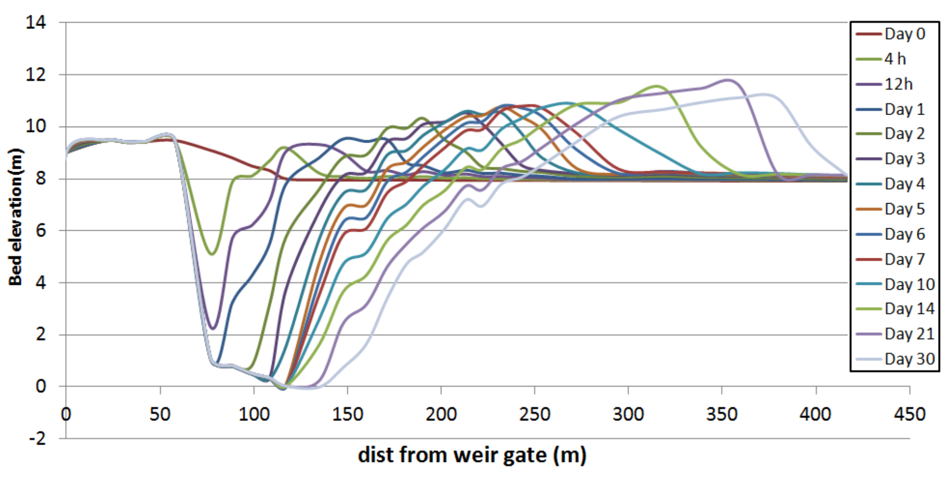

Figure 5. Evolution of the river bed after the weir gate

Although the empirical approach was not accurate enough to deal with the problem, a qualitative agreement between the theoretical description of the formation of the scour hole and the simulated result shown in Fig. 5 is observed. Hoffmans suggested that there are different steps in the formation of the scour hole: the initial phase, the development phase, the stabilization, and the equilibrium phase. Fig. 5 shows that during the first day of the simulation the erosion takes place just after the region where the river bed protections ended, the scour hole gets deeper (initial and development phases), and from the 5th day even the erosion keeps constant (stabilization phase) the hole is extended to the downstream direction. At the end of the simulation the erosion on the vertical direction decreases as well as the propagation downstream of the hole does (equilibrium phase).

CONCLUSIONS

Based on the results from different numerical simulations of sediment transport and the evolution of bed morphology for the different operation scenarios of the gate at Gangjeong Weir, we can have following conclusions:

- The areas where erosion may take place can be identified from the simulation of the different operational scenarios. The low flow scenarios (Case 1, 3 & 4) seem to have a non-significant effect on the bed morphology.
- The highest change in bed morphology occurs when the gates are fully open during flooding. A scour hole appears behind the weir gates and sediment flushing from the upstream area near the gates may occur as well.
- A reasonable good agreement has been observed between the simulated result and the measurements of the actual river bathymetry. The definition of the location of the rock layer underneath of river bed becomes crucial to obtain an accurate of the simulation, however its importance is not that relevant when identifying the area affected by erosion.
- According to the time dependent evolution of the scour holes, it shows a qualitative mechanism that follows Hoffmans' theory. First, a strong erosion in the vertical direction is followed by the longitudinal propagation of the hole to the downstream, as well as the amount of sediment eroded decreases reaching to an equilibrium situation.

ACKNOWLEDGEMENT

This research was supported by a grant (11-TI-C06) from Advanced Water Management Research Program funded by Ministry of Land, Infrastructure and Transport of Korean government.

REFERENCES

[1] Brière C., Abadie S., Bretel P. and Lang, P., "Assessment of TELEMAC system performances, a hydrodynamic case study of Anglet, France", *Coastal engineering,* Vol. 54, No. 4, (2007), pp 345-356. doi: 10.1016/j.coastaleng.2006.10.006

[2] Hoffmans G.J.C.M. and Verheij H.J., "*Scour Manual*", Balkema, Rotterdam, (1997).

[3] Hoffmans G.J.C.M., "*The Influence of Turbulence on Soil Erosion*", Eburon, (2012).

[4] Van Rijn L.C., "Sediment transport, part I: bed load transport", *Journal of hydraulic engineering*, Vol. 110, No. 10, (1984), pp 1431-1456. doi: 10.1061/(ASCE)0733-9429(1984)110:10(1431)

[5] Van Rijn L.C., "*Principles of Sediment Transport in Rivers, Estuaries and Coastal Seas*", Aqua Publications, (1993).

[6] Villaret C., Hervouet J. M., Kopmann R., Merkel U. and Davies A. G., "Morphodynamic modelling using the Telemac finite-element system", *Computers & Geosciences*. (2011),Vol 53, pp 105-113. doi: 10.1016/j.cageo.2011.10.004