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Study on River Migration and Stable Water Supply Countermeasure in the Reach of Kaoping Weir

STUDY ON RIVER MIGRATION AND STABLE WATER SUPPLY COUNTERMEASURE IN THE REACH OF KAOPING WEIR

Keh-Chia Yeh[1], Chung-Ta Liao[2], Shi-Min Lin[3], Ya-Fei Jia[4], and Sam S.Y. Wang[5]

ABSTRACT

Meandering tendency is a very common characteristic in natural rivers. The hydraulics and sediment transport of meandering river are usually more complex than the straight one's. A 2-D mobile-bed model, called CCHE2D, was adopted in this paper to simulate the river migration of the Kaoping weir reach. The secondary flow and bed load motion affected by transversal slope were considered in the model. Data associated with suspended sediment concentration, bed material grain sizes and cross sections were collected. These basic data were used to calibrate and validate the model. Meanwhile, a list of stable water supply plans was proposed to evaluate the effects on bed evolution around the intake of Kaoping Weir.

According to the results, the CCHE2D model had the capability of simulating the flow field, sediment transport rate, and bed change in the study reach. In the simulation of stable water supply plan, the velocity increased and bed deposition decreased around the intake of Kaoping Weir, which was based on the planning bed topography. In addition, the heightened concrete weir and planned lead dike can guide the flow toward the intake and therefore create scouring at the upstream and downstream of the rubber weir.

1. INTRODUCTION

Huge flood and sediment concentration, and the associated severe bed change, are the characteristics in Taiwan's rivers. These characteristics often make the river migration randomly and quickly. The hydraulics and sediment transport of meandering river are usually more complex than the straight one's. To accurately simulate the lateral migration for a 2-D depth-integrated mobile bed model, the secondary flow and bed load motion affected by transversal slope were required in the numerical model.

In this study, a 2-D mobile-bed model, called CCHE2D, was adopted to simulate the river migration in Kaoping River, Taiwan. Data associated with suspended sediment concentration, bed material grain sizes and cross sections were collected. These basic data were used to calibrate and validate the numerical model. Meanwhile, a list of stable water supply plans was proposed to evaluate the effects on bed evolution around the intake of Kaoping Weir.

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2. THEORETIC BASIS OF CCHE2D

2.1 Flow Model

Governing equations of the flow are two-dimensional depth integrated Reynolds equations in a Cartesian coordinate system are:

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=-g\frac{\partial \eta}{\partial x}+\frac{1}{h}\left(\frac{\partial h\tau_{xx}}{\partial x}+\frac{\partial h\tau_{xy}}{\partial y}\right)-\frac{\tau_{bx}}{\rho h}+f_{Cor}v \quad (1)$$

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}=-g\frac{\partial \eta}{\partial y}+\frac{1}{h}\left(\frac{\partial h\tau_{yx}}{\partial x}+\frac{\partial h\tau_{yy}}{\partial y}\right)-\frac{\tau_{by}}{\rho h}-f_{Cor}u \quad (2)$$

where u and v are depth-integrated velocity components in x and y directions, respectively; t is the time; g is the gravitational acceleration; η is the water surface elevation; ρ is the density of water; h is the local water depth; f_{Cor} is the Coriolis parameter; τ_{xx}, τ_{xy}, τ_{yx}, and τ_{yy} are depth integrated Reynolds stresses; and τ_{bx} and τ_{by} are shear stresses on the bed and flow interface. The shear stress terms at the water surface are dropped since wind shear driven effect is not considered in this version of the model.

Free surface elevation for the flow is calculated by the depth-integrated continuity equation:

$$\frac{\partial h}{\partial t}+\frac{\partial uh}{\partial x}+\frac{\partial vh}{\partial y}=0 \quad (3)$$

Two methods for calculating eddy viscosity are available in the current model, including the depth integrated parabolic eddy viscosity formula and depth integrated mixing length eddy viscosity model (Jia, et al. 1999, 2002).

2.2 Sediment Transport Model

The sediment transport model consists of suspended sediment transport and bed load transport simulation models for non-uniform sediment. The model is also designed to simulate channel bed with large slopes and curved channel secondary flow effects. The depth-integrated convection diffusion for the suspended sediment is solved.

$$\frac{\partial C}{\partial t}+u\frac{\partial C}{\partial x}+v\frac{\partial C}{\partial y}-\frac{\partial}{\partial x}[\beta\nu_t\frac{\partial C}{\partial x}]-\frac{\partial}{\partial y}[\beta\nu_t\frac{\partial C}{\partial y}]=S+S_r \quad (4)$$

where C is the depth-integrated sediment concentration, and β is the coefficient to convert the turbulence eddy viscosity to eddy diffusivity for sediment. S is a source term representing the balance of sediment pick up and deposition near the surface of the bed. More detail of this term can be found in the technical report of the sediment model (Wu, 2001).

In the processes of vertical integration, one has to either assume the water is shallow and the vertical variation of the flow is negligible or keep the dispersion terms to preserve the effect of vertical sediment profiles on bed form change. In the second case, the source term S_r would not be zero, but representing the dispersion terms. Computing the dispersion term is complicated and requires the knowledge of the vertical velocity and suspended sediment profiles in x and y directions. Several assumptions are necessary to make it possible to compute this term:

- Assume the vertical velocity in longitudinal and transverse direction is of power law (or logarithms) and linear distribution, the suspended sediment in vertical direction is of Rouse;
- Compute a local orthogonal curvilinear grid based on the flow direction and flow curvature;
- The dispersion terms can be computed on this grid;
- The computed dispersion terms will are transformed back into x-y coordinate; and
- Compute S_r.

2.3 Bed Load Motion Affected by Transversal Slope

Considering when a river channel has a curvature, the secondary current of the flow will affect the process of channel morphological change and one has to add this mechanism to the model in order to be able to simulate this phenomena. On a bed with transversal slope, the bed load motion is different from that with streamwise slope only. The particle path of motion is affected by main flow shear and streamwise slope, as well as by the gravity component on the transversal direction. Van Bendegom's formula is applied to calculate the angle θ_m of the sediment particle's motion due to the bed slope and is given by:

$$\tan\theta_m = \frac{\sin\alpha x - \dfrac{1}{G}\dfrac{\partial\zeta}{\partial y}}{\cos\alpha x - \dfrac{1}{G}\dfrac{\partial\zeta}{\partial x}} \tag{5}$$

where $G = f(\theta) = 1.7\sqrt{\theta}$ and αx is the angle between the flow direction and the x-axis of the Cartesian coordinate system; and θ is the Shields parameter:

$$\theta = \frac{u_*^2}{g\left(\dfrac{\rho_s}{\rho} - 1\right)d_{50}} \tag{6}$$

The expression of the G function and the coefficient are determined using the laboratory experimental data. Bed slope components $\partial\zeta/\partial x$ and $\partial\zeta/\partial y$ in Eq. (5) are computed by the finite element operators.

Natural rivers usually have meandering patterns. When water flows along a curved channel with varying curvatures, secondary current would occur due to the centrifugal force. The secondary flow is toward the outer bank of a meander bend in the upper portion of the flow depth, and it is toward the inner bank in the lower portion of the flow. It therefore contributes to moving the sediment in the transversal direction from the outer bank toward the inner bank of the channel systematically making the channel more and more curved; the flow is in turn affected by the bed topography and the channel pattern produced by the secondary flow. It is impractical to simulate the bed load and bed form change in curved channels without considering this process. However, because the depth-integrated model has no information about the secondary current, empirical or semi-analytical estimation of the secondary flow has to be used in order to predict the bed load motion in the curved channel. The most significant parameter of this problem is the angle between main flow direction and that of the shear stress near the bed. In the current model, this angle is approximated by (Engelund, 1974)

$$\tan\theta_s = 7\frac{h}{r} \tag{7}$$

where r is the radius of curvature of longitudinal mesh line ($r = ds/d\theta$). The error of this formula is about 3% according to Engelund (1974). Figure 1 shows the motion of a particle on the bed. The gravity pushes the moving particle to move down the transversal slope θ_b with an angle θ_m as estimated by the eq. (5) and in the curved channel, the secondary flow tends to move it against the transversal slope by an angle θ_s. Equilibrium shall be reached when these two effects cancel each other, and the sediment particles then move along the main flow direction which is the longitudinal direction.

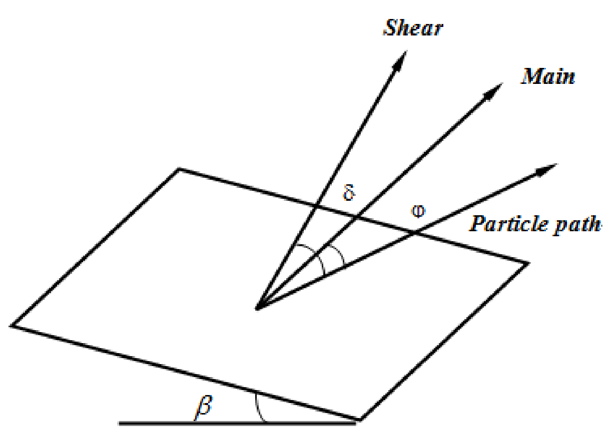


Figure 1 Bed load motion affected by secondary flow and gravity.

3. MODEL CALIBRATION AND VALIDATION

3.1 Background of Study Reach

Kaoping Weir, composed of concrete and rubber parts, was completed in 1999, which is one of the important water resource development projects in Taiwan. With an average supply of 1,100,000 tons of water per day, it plays an important role to meet the water resource needs in the Kaohsiung area. The simulated reach is from upstream Liling Bridge to Kaoping Bridge, which is about 20 km long (see as Figure 2). The upstream reach of Kaoping Weir has serious deposition problem in recent years. In addition, there are some bank erosion sites near the left bank of the upstream reach of Kaoping Weir.

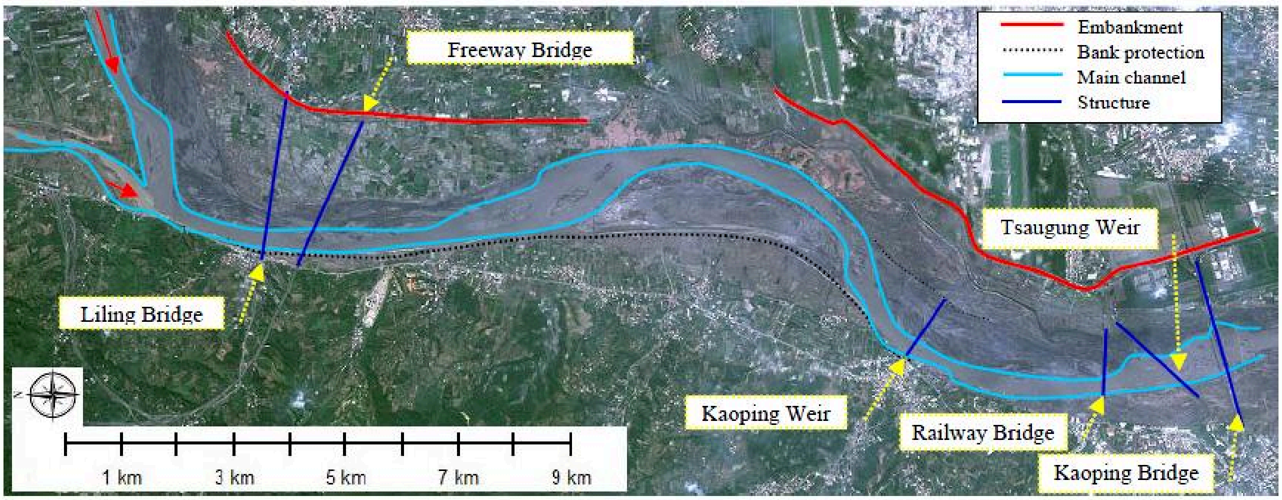


Figure 2 Study reach of Kaoping River, Taiwan.

During 2005~2006, several significant typhoon floods resulted in serious bed deposition around the intake of Kaoping Weir. To ensure the stable water supply, South Region Water Resources Office, WRA had carried out several stable water supply countermeasures in 2006~2008, including the rising of Kaoping Weir, building of left-bank spur dikes, etc. These countermeasures showed the success to ensure the stable water supply. However, typhoon Morakot occurred in 2009 resulted in an extreme flood that exceeded the design flood at Kaoping Weir. The flood over-topped the embankments, and brought huge damages of facilities and property. Figure 3 shows the migration of point bars and meandering pattern upstream of Kaoping weir after typhoon Morakot.

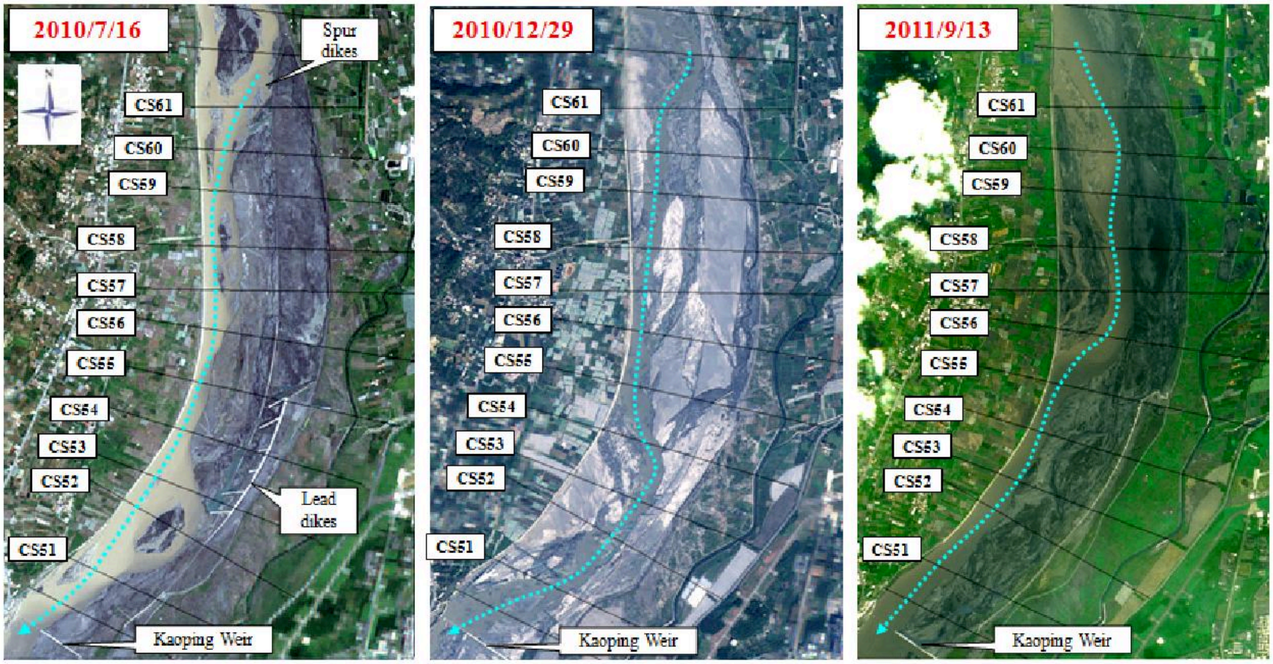


Figure 3 Migration of point bars and meandering pattern upstream of Kaoping weir.

3.2 Initial and Boundary Conditions

Figure 4 shows the computational grids of the study reach, which includes the upstream tributary of Launung and Chishan Creek to the downstream Kaoping Bridge. The cross-sectional data measured in 2006 is used as the initial bed condition, and the data of 2007, 2008 and 2009 are used for the calibration and validation by considering the significant typhoon events occurred from 2007 to 2009. The water stage hydrographs measured at Liling Bridge and Kaoping Weir are also compared with the simulated ones. Table 1 shows the typhoons and peak discharges for model calibration and validation in the Kaoping Weir reach.

Table 1 Typhoons and peak discharge for calibration and validation in Kaoping River, Taiwan.

Typhoon	Time	Peak Discharge(cms)	Water Stage(EL.m)	Note
Wutip	2007/08/08	8,462	19.43	Calibration
Wipha	2007/08/13	13,532	20.66	
Sepat	2007/08/16	11,087	20.10	
Krosa	2007/10/07	11,636	20.23	
Kalmaegi	2008/07/16	13,623	20.68	Validation
Fung-Wong	2008/07/26	8,942	19.56	
Sinlaku	2008/09/14	10,428	19.94	
Jangmi	2008/09/27	10,632	19.99	
Morakot	2009/08/08	35,000	24.40	Validation

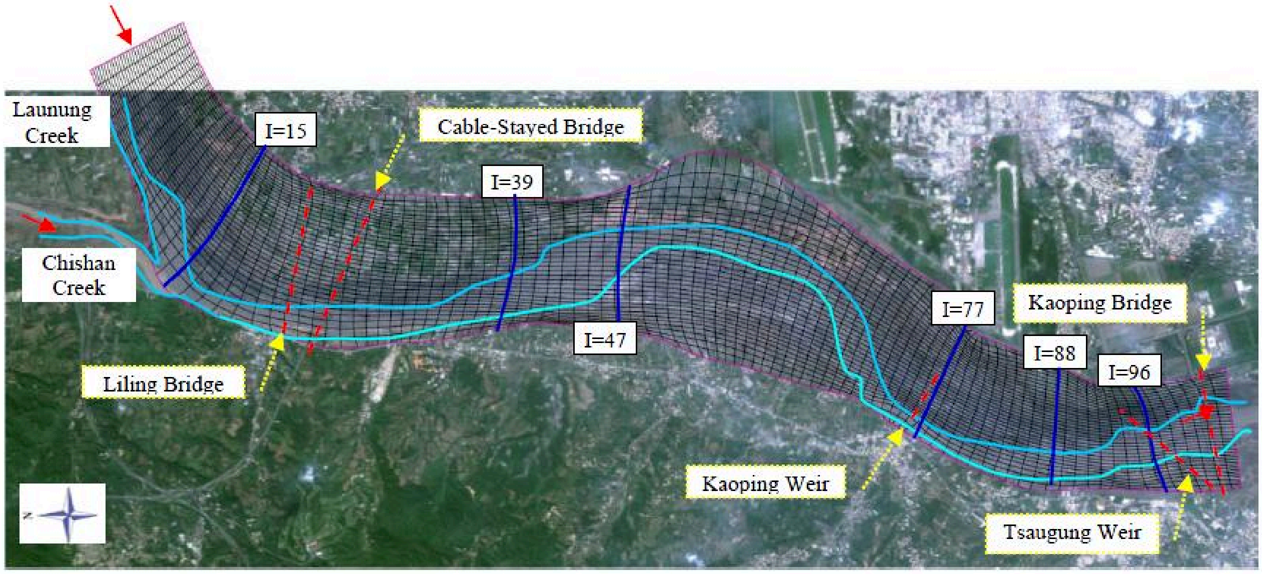


Figure 4 Computational grids (I x J = 102 x 35).

The inflow suspended sediment concentration (in ppm) is based on the rating curve obtained at Liling Bridge. The suspended load grain sizes measured at Liling Bridge during typhoon events provide the inflow sediment compositions (see as Figure 5). It is assumed that 80% of suspended load coming from upstream is wash load; for the bed material, 85% of it is suspended load and 15% is bed load. The downstream boundary condition is the water stage hydrograph at Kaoping Bridge, which is computed from HEC-RAS model.

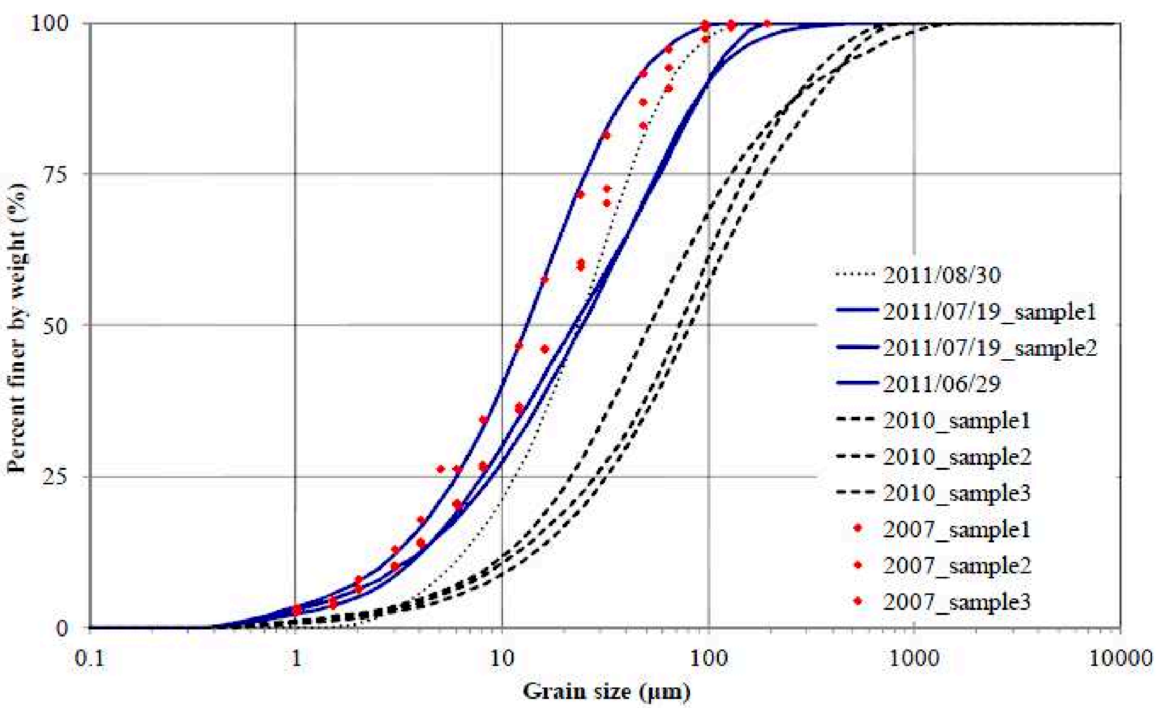
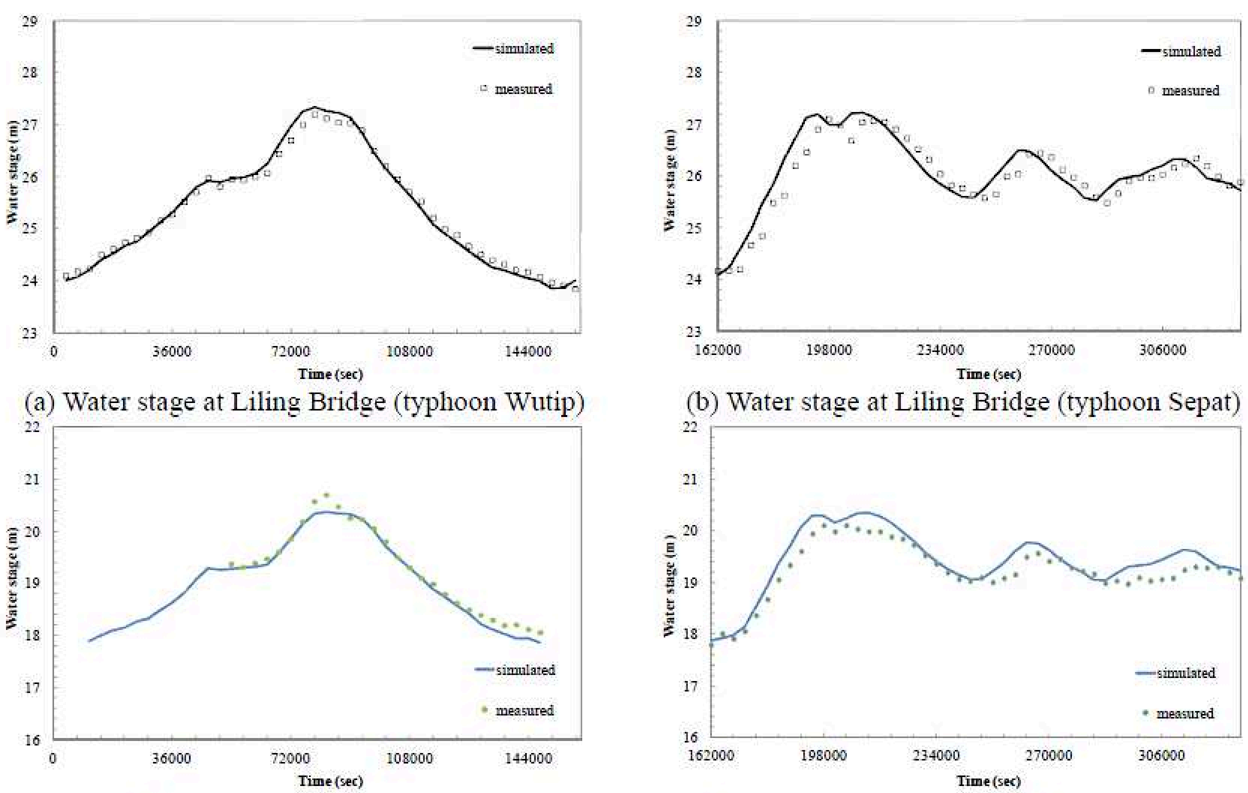


Figure 5 Suspended load grain sizes measured at Liling Bridge during typhoon events.

The mean particle size of bed-material in Kaoping River is about 0.1mm to 0.5mm. According to the bed samples obtained in 2006, three sediment size classes (0.05mm, 0.25mm, and 2.5mm) are used to specify the initial bed compositions in the model. Wu et al.'s (2000) sediment transport formula in the model is adopted. The main parameters in the model for bed evolution simulation are as follows: the adaption length for bed load is 4,000 m, the adaption coefficient for suspended load is 0.25, and the depth for the mixing layer is 0.1 m. Referring the management and planning report of Kaoping River, the Manning's coefficient ranges from 0.022 to 0.05 for the hydraulic structure, river bed and floodplain.

3.3 Calibration and Validation Results

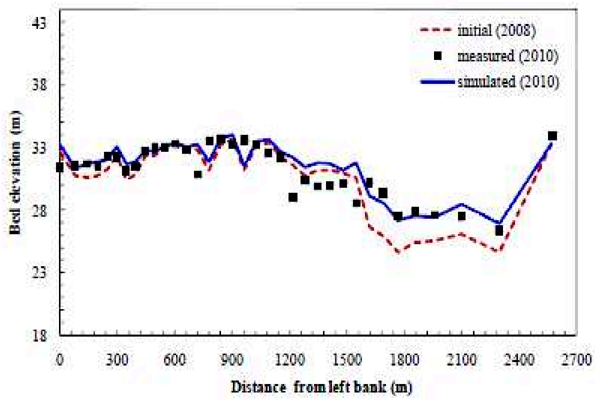
Figure 6 shows the simulated and measured water stage hydrographs at Liling Bridge and Kaoping Weir. The simulated water stages have similar trends with the measured ones, and the mean absolute error is smaller than 0.3m. Due to the neglect of lower discharge events, there were relatively large errors in the rising portion of the hydrograph. The deposition near the Kaoping Weir also affected the variation of water stage. The CCHE2D model is capable of predicting the water stages during the typhoon events in the Kaoping River.



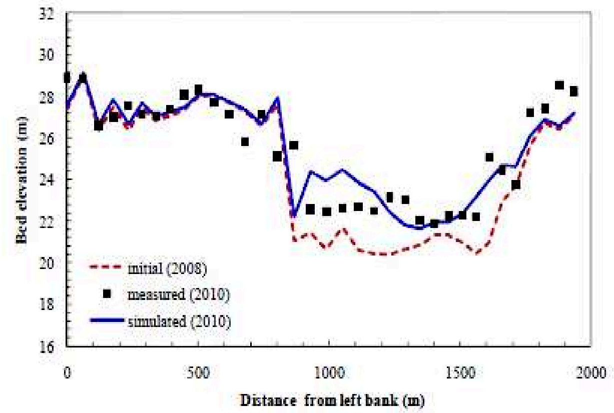
(a) Water stage at Liling Bridge (typhoon Wutip)
(b) Water stage at Liling Bridge (typhoon Sepat)
(c) Water stage at Kaoping Weir (typhoon Wutip)
(d) Water stage at Kaoping Weir (typhoon Sepat)

Figure 6 Simulated and measured water stage hydrographs.

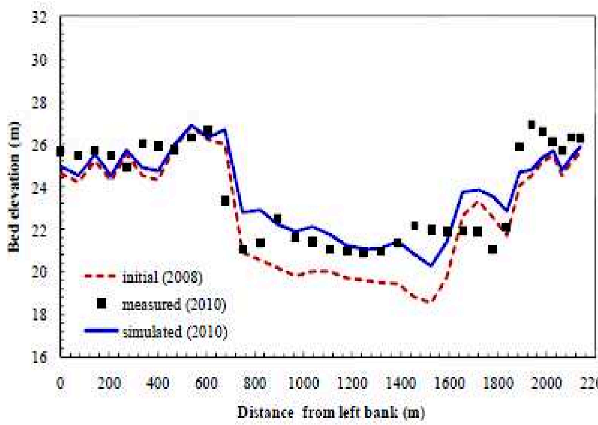
Figure 7 shows several simulated and measured cross-sections along the study reach after typhoon Morakot. It shows that the simulated cross-sections are agreed well with the measured ones. In cross-section I = 77, the bed elevation is a little over-estimated near the left bank of the main channel. Through field investigation, the over-estimated bed elevation is due to the neglect of the dredge volumes in the simulation after typhoon Morakot. Generally, the CCHE2D model has the capability in simulating the sediment transport and morphological changes in this meandering reach.



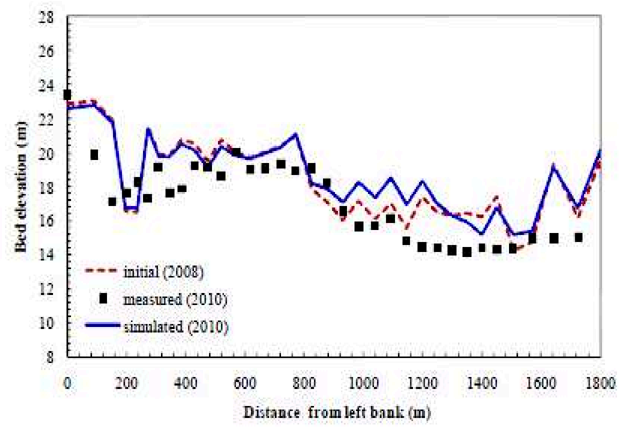
(a) Cross-section I=15



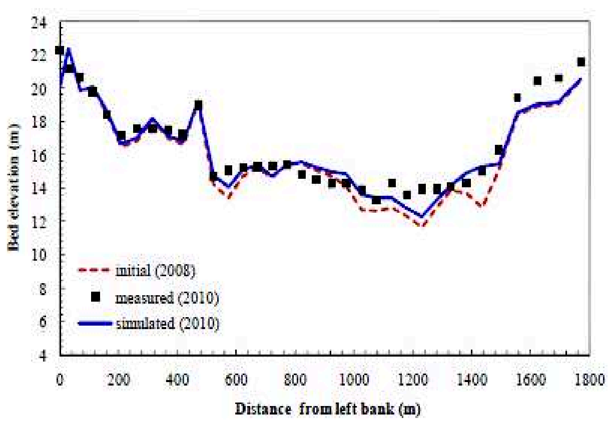
(b) Cross-section I=39



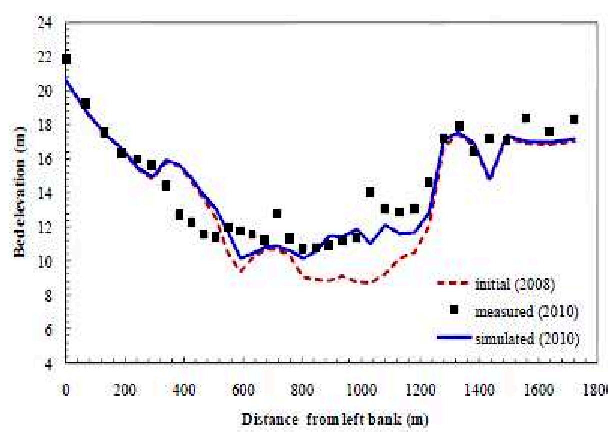
(c) Cross-section I=47



(d) Cross-section I=77



(e) Cross-section I=88



(f) Cross-section I=96

Figure 7 Simulated and measured cross-sections.

4. STABLE WATER SUPPLY COUNTERMEASURE

4.1 Engineering Layout

In the past few years, several significant typhoon floods resulted in serious bed deposition around the intake of Kaoping Weir, especially typhoon Morakot. To ensure the stable water supply of the Weir, some dikes are needed to guide the flow shifting toward the right bank from the upstream reach. For the future equilibrium of Kaoping River, the bed slope is also needed to be adjusted. Following is a list of countermeasures that may help to solve the sedimentation problem at Kaoping Weir (called Case 1).

a. Heighten the rubber and concrete weirs to ensure the stable bed slope of Kaoping Weir reach.
b. Build the dikes near the intake and concrete weir to lead the bank-full flow (see Figure 8).
c. Keep the stable the main channel width with 450m wide.

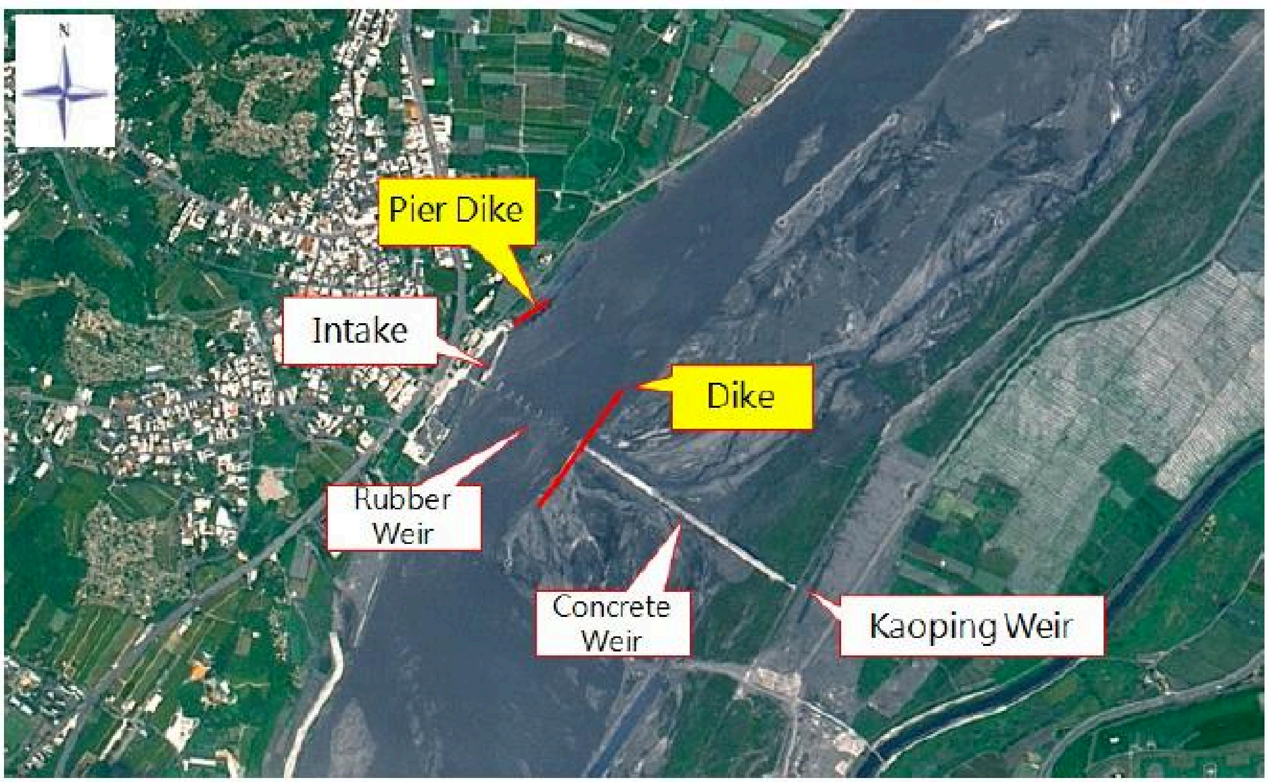


Figure 8 Planning dikes near the intake and concrete weir.

4.1 Simulated Results

Based on the stable water supply countermeasures mentioned above, CCHE2D model was applied to simulate the flow field and morphological changes for a single flood event as well as a series of floods occurred from 2010 to 2011. Figure 9 shows the distribution of flow velocity with Q_{100} occurred near the Kaoping Weir. Case 0 means no dikes and countermeasures proposed at Kaoping Weir. It indicates that main flow passes through the concrete weir at peak of Q_{100}, and the velocity magnitude is larger than 4m/s for Case 0. Due to the proposed countermeasures, the main flow has a trend that shifts toward the intake.

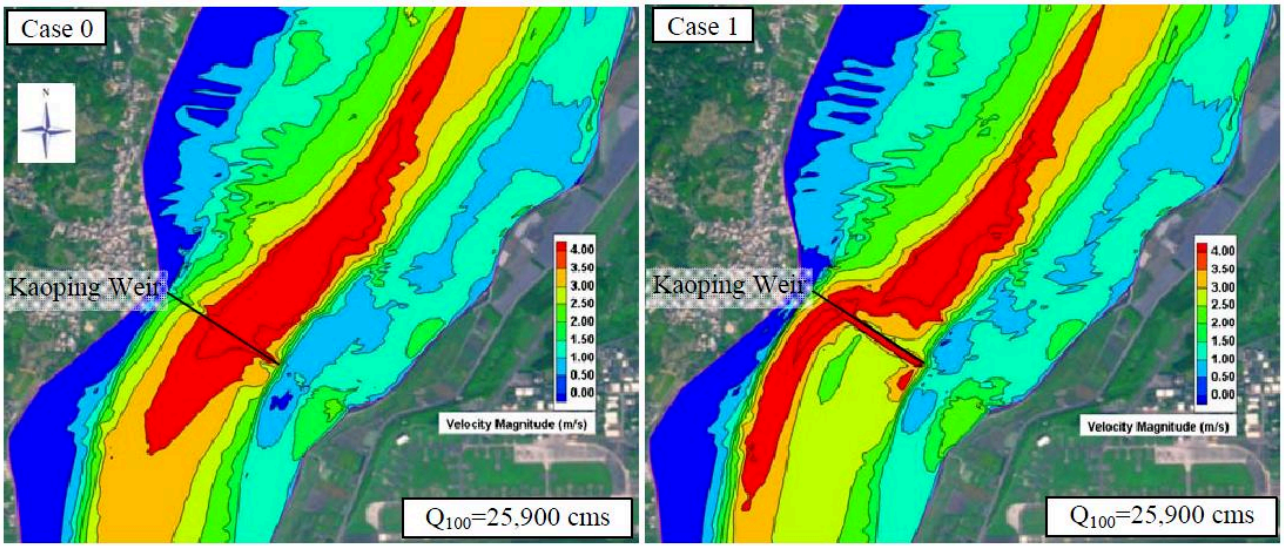


Figure 9 Distribution of flow velocity near the Kaoping Weir.

Figure 10 shows the comparison of the bed elevation and main channel direction for Case 0 and Case 1 after the abovementioned series floods. There is obvious deposition near the intake for Case 0, but slight deposition for the Case 1. The results show that if there are no countermeasures at Kaoping Weir, the sediment problem may become worse in the future. In addition, the raise of concrete weir and the construction of dikes guide the main flow toward the intake and therefore create scours at the upstream and downstream of the rubber weir. The proposed countermeasures can provide a relatively stable main channel pattern.

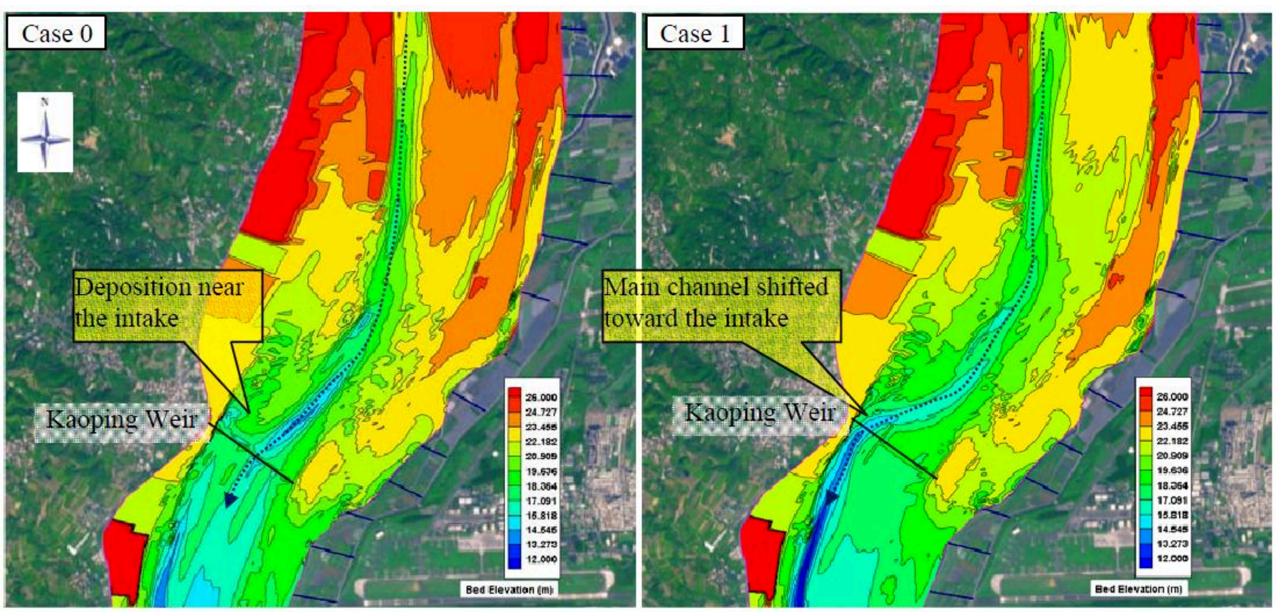


Figure 10 Comparison of bed elevation between Case 0 and Case 1 after long-term simulation.

5. CONCLUSIONS

The CCHE2D model is capable of simulating the flow field, sediment transport and morphological changes in the Kaoping Weir reach. Through the proposed countermeasures, the study reach shows a stable tendency after the long-term simulation composed of sequential historical major floods. Further study on experiment and long-term river migration simulations based on different engineering layouts is required to obtain an optimal countermeasure in the Kaoping Weir reach.

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