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NUMERICAL MODELING OF BANK EROSION PROCESSES AND ITS FIELD APPLICATION

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ABSTRACT

Bank erosion induced by alluvial river channel migration often causes problems: it encroaches valuable farming land, increases downstream channel deposition and downgrades water quality. In populated areas, abrupt bank collapse could not only compromise the integrity of residential buildings and civil facilities along the river, but also cause the loss of lives. Bank erosion is in general a very complex problem because it involves multi-processes such as bank surface erosion, bank toe erosion and bank material mass failure, etc. Each of these processes is related to several bank parameters: bank material property, slope, homogeneity, consolidation, and bank height as well as the strength of the flow in the river represented by the flow shear stress, water depth, and channel curvature, etc. Numerical models are useful and powerful tools for simulating bank erosion. The accuracy of bank erosion prediction of a particular model depends largely on the mechanisms of bank erosion processes implemented. In this paper, bank erosion mechanisms of alluvial rivers have been implemented into a general flow and sediment transport model, CCHE2D. Validations of the model using experiment data and field data with fixed and erodible banks have been performed. The model was finally applied to a field bank erosion case with good agreement to observed data.

Keywords: Bank erosion, numerical simulation, river channel migration

1. INTRODUCTION

Alluvial rivers often have lateral movement: meandering or channel migration. The inherited instability of the river channel flow tends to develop a meandering channel pattern: in a curved channel, the flow is forced to follow the channel's curvature, the centrifugal force thus created pushes the flow toward the outer bank and the associated super-elevation of the water surface pushes the flow back toward the inner bank. The balance of these two forces creates a lateral helical recirculation, known as helical flow or secondary current, in the channel bend. The upper part of the helical flow (near water surface) is toward the outer bank and the lower part (near bed) of the flow is toward the inner bank. Sediment transport is dominated by such a helical flow system. Since the near bed flow and sediment particles are moving toward the inner bank, more sediment load is distributed near the inner bank and less sediment load is near the outer bank than the mean sediment load. As a result, erosion would occur along the outer bank and deposition along the inner bank. Inevitably, a skewed channel cross-section is developed in channel bends with a lower bed near the outer bank and higher bed near the inner bank. More and more flow would be distributed along the outer bank with the bed development, resulting in deeper water and faster flow velocity, causing erosion and mechanic instability of the outer bank. This is in general the mechanism of channel erosion and subsequent channel migration.

Secondary motion in a channel bend is observed in laboratory experiments as well as field investigations. The transversal component of secondary flow velocity near the bed is always toward the center of curvature. The occurrence of secondary flow makes the total velocity near the bed deviate from the longitudinal direction. Many laboratory experiments have been conducted to investigate the longitudinal and transversal components of flow velocity in the flumes with different conditions. Empirical functions to describe the transversal component of secondary flow velocity have been formulated based on these experimental data.

Nagata et al. (2000) and Duan et al. (2001) developed 2-D channel meandering models that adopt the moving grid techniques. In their approaches, flow, sediment transport, bed change, and bank erosion are simulated on the old mesh at each time step. After the bank lines have been moved by erosion and deposition, a new mesh conforming to the new bank lines is created, and the flow field and bed topography are interpolated from the old mesh to the new one. The computations of flow, sediment transport, bed change, and bank erosion are then continued on the new mesh at the next time step.

In this paper, a bank erosion model is developed based on a general hydrodynamic and sediment transport model, CCHE2D. Bank surface erosion, basal erosion and mass failure are simulated based on the approaches of Osman and Thorne (1988a,b), Hanson and Simon (2001). The secondary helical current effects on suspended sediment and bed load sediment transport have been considered. Since this is a two dimensional model, computational mesh can be adjusted when the bank boundaries move due to erosion. Numerical tests with fixed bank experiments are conducted to validate the secondary current effect and one movable bank experiment data was used to test the bank erosion and mesh stretching module.

2. CCHE2D HYDRODYNAMIC AND SEDIMENT TRANSPORT MODEL

CCHE2D is a depth-integrated 2D model for simulating free surface turbulent flows, sediment transport and morphological change. This is a finite element based model with the collocation method and quadrilateral mesh (Jia, et al. 1999, 2002). The following briefs the sediment transport model related to bank erosion.

On a bed with a 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 (see Talmon, et al, 1995) is applied to calculate the angle φ of the sediment particle's motion due to the bed slope :

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

Where

$$G = f(\theta) = 1.7\sqrt{\theta} \tag{2}$$

and α is the angle between the flow direction and the *x*-axis of the Cartesian coordinate system; and θ is the Sheilds parameter:

$$\theta = \frac{u_*^2}{g\left(\frac{\rho_s}{\rho} - 1\right)d_{50}} \tag{3}$$

The expression of the *G* function and the coefficient are determined using the laboratory experimental data (Talmon, et al, 1995).

When water flows along a curved channel with varying curvatures, secondary current would occur due to the centrifugal force. The secondary flow is towards 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 towards the inner bank of the channel systematically and 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 not possible 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)

$$tan\,\delta = 7\frac{h}{r} \tag{4}$$

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

Similar to the bed load sediment, the secondary flow effect for the suspended sediment was also modeled by adding a source term taking into account for the net lateral motion of the suspended sediment (Figure 1). Log profile, linear distribution and Rouse distribution were applied for the main flow, secondary flow and suspended sediment concentration in the vertical, respectively.

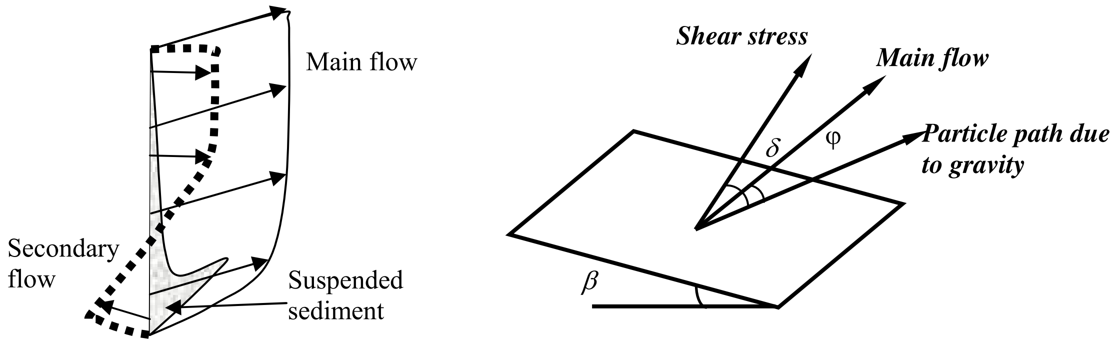

Figure 1 Suspended load and bed load motion affected by the secondary flow

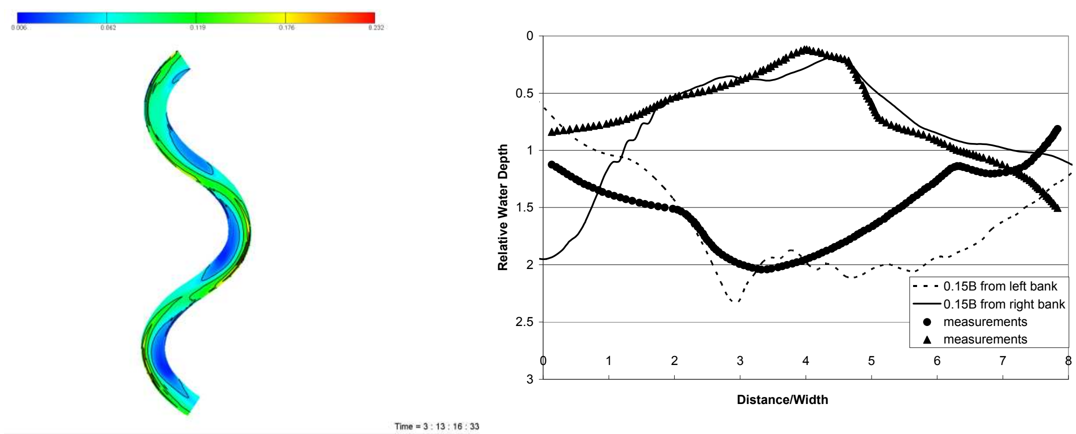

Figure 2a Computed water depth and comparison of numerical results (curve) and experimental data (Case3)

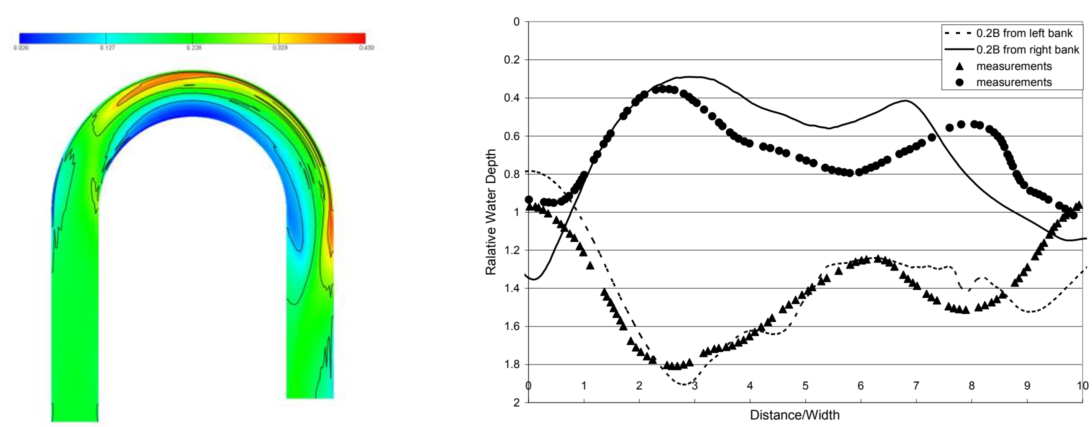

Figure 2b Computed water depth and comparison of numerical results (curve) and experimental data (Case4)

3. VALIDATION OF SEDIMENT TRANSPORT AND BED MORPHOLOGICAL CHANGE SIMULATION MODELS USING FLUME EXPERIMENTAL DATA

The sediment transport and bed morphological change simulation model were tested using physical model data. Four of the experiment test cases published by Struiksma et al (1985) were simulated. These are physical models with different channel geometry, curvature, flow conditions, and sediment size distributions. The sediments of all cases are quite uniform except Case 2.

The patterns of bed elevation in bendways or meander channels, deeper near the outer bank and shallower near the inner bank, are correctly reproduced. The magnitude of the predicted erosion and deposition in the channels agreed very well to the measurement (Fig. 2). The agreements of the numerical simulation and the data indicated that the CCHE2D model can reproduce the flow and sediment transport physical process in laboratory flumes correctly. Because the flume channel provided by the paper are often short (just the part of the channel with curvature), the length and shape of the leading and tailing channel reaches are unknown; it may affect the specification of accurate boundary conditions especially the upstream boundary conditions. This may therefore affect the accuracy of the predicted bed elevation change and equilibrium bed forms.

4. BANK EROSION MODELING

Channel bed degradation increases bank heights, and lateral erosion on bank surface makes the bank retreat. Once the stability criterion is exceeded, a bank mass failure would occur. The failed bank material deposits first on the bed near bank toes and then is eroded away by the flow. The bank erosion process can significantly affect sediment balance in a channel and channel morphology evolution. Arulanandan et al. (1980) proposed an empirical formula to compute the fluvial erosion of cohesive bank materials:

$$\frac{dw}{dt} = \frac{r}{\gamma_s}\left(\frac{\tau - \tau_c}{\tau_c}\right) \tag{5}$$

where *dw/dt* is the lateral erosion rate near the bank toe (m/min), τ is the flow shear stress (dynes/cm^2) applied on the bank toe, $\tau = \gamma RS$, τ_c is the critical shear stress (dynes/cm^2) for bank toe erosion, related to the sodium adsorption ratio, pore fluid salt concentration, dielectric dispersion, etc., γ_s is the unit weight of the soil (kN/m^3), and r is the initial rate of soil erosion (g/cm^{2}min), given by $r = 0.0223\tau_c \exp(-0.13\tau_c)$.

Depending on geometries and soil properties, river banks may fail by various mechanisms, which may be planar, rotational, cantilever, piping-type, and sapping-type. Planar and rotational failures usually occur on the homogeneous, non-layered banks, cantilever failures usually happen on the layered banks, while piping- and sapping-type failures most likely occur on the heterogeneous banks where seepage flow is often observed. Osman and Thorne (1988) analyzed the planar and rotational failures (Fig. 3). The factor of safety is defined as

$$f_s = \frac{F_r}{F_d} \tag{6}$$

where F_r and F_d are the resisting and driving forces, respectively. When $f_s < 1$, a bank mass failure occurs. Usually, the failed material deposits first on the bed near the bank toe and then is disaggregated and eroded away by the flow if the flow is strong enough. For large rivers, the failed material depositing near the bank toe does not strongly disturb the flow, but for small rivers and streams, this influence may disturb the flow distribution. In the current approach, the failed bank material is considered as an input to the bed load. Since the time step for bank erosion is much larger than sediment transport, this side input is set uniform through the next bank erosion step. This input will result in higher near bank sediment concentration or bed load. If the bank erosion is too fast, near bank bed elevation would increase to slow down the bank erosion.

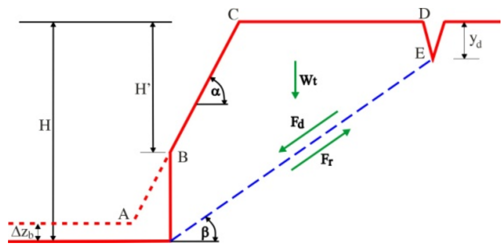

Figure 3 Mode of Bank Mass Failure (after Osman and Thorne, 1988)

In Osman and Thorne's model, a bank has an initial slope; after the first collapse occurs, a new slope will be established, and the bank will then keep this slope. The mass failure occurs later will not change the slope (parallel retreat). Considering that the river banks one studies have been experiencing bank failures for a long time, the bank slope observed is likely to be the bank mass failure slope. It is reasonable to assume that the bank slope is a known value and only the parallel retreat processes are needed to be simulated. Under this condition, the lateral bank retreat after one failure event is calculated by

$$BW = \frac{H - H'}{\tan \beta} \tag{7}$$

The critical ratio of the new and old bank height determined by

$$\frac{H}{H'} = \frac{1}{2}[\frac{\omega_2}{\omega_1} + \sqrt{(\frac{\omega_2}{\omega_1})^2 + 4}] \tag{8}$$

$$\omega_1 = \cos\beta \sin\beta - \cos^2\beta \tan\phi \tag{9}$$

$$\omega_2 = 2(1-K)\frac{c}{\gamma_s H'} \tag{10}$$

will be used to test if a mass failure would occur: if the ratio of computed *H* and *H'* is higher than that from equation (7), a bank failure is computed.

5. BANK SURFACE EROSION MODEL

Cohesive material erosion is proportional to excessive shear stress and a coefficient which decreases with the critical shear stress. In the Osman and Thorne's model (1988) the bank surface erosion was proportional to the difference of the shear stress and the critical stress, the difference was then normalized by the critical stress:

$$\varepsilon = k\frac{\tau - \tau_c}{\tau_c} \tag{11}$$

Where ε is bank erosion rate, k is the initial bank erosion rate which is proportional to critical stress:

$$k = 223\times10^{-4}\tau_c e^{-0.13\tau_c} \tag{12}$$

τ is the shear stress in a cross section and τ_c is the bank critical shear stress. Partheniades (1965) computed erosion rate of cohesive materials using

$$\varepsilon = k(\tau_0 - \tau_c)^a \tag{13}$$

Field data of almost 200 sites indicated (Hanson and Simon, 2001) that k is a function of critical shear stress:

$$k = 0.1\tau_c^{-0.5} \tag{14}$$

6. MESH STRETCHING

Computational mesh should be stretched to widen the channel as the channel bank lines move due to bank erosion. The distance of the bank movement is comparable to the channel width. One should point out that this stretch is not completed in one step, but was done in many finite steps, and each was caused by a small step of bank erosion. Mass and momentum conservation may be affected if the distance of a bank movement is too large. Once a mesh is stretched, the discretization of the computational domain should be updated. One has to re-compute all the numerical parameters and differential operators again every time a mesh stretch is performed. Mesh adjustment will be needed to redistribute the mesh nodes in the new computational domain (widened channel) and new finite element operators will be re-computed. Interpolation of the computational results from the previous mesh to the stretched one is required before re-computing the flow if the stretching is significant. In general, bank materials are much less erodible than the bed materials. The bank lines are therefore much less mobile than the bed. The time scales to compute bank erosion are normally much larger than that for the bed change and the flow. Therefore, although computation of bank erosion is complicated, its associated computation cost is not very high, particularly if the quasi-steady approach is adopted using a channel forming flow discharge.

Figure 4 shows the development of simulated channel morphology. In the process of development, the outer bank line retreat gradually and the main channel of this bend shifts accordingly; the cross-section form of the channel also changes particularly at the beginning stage, and the water depth near the outer bank becomes larger while that near the inner bank becomes smaller. This change makes it possible to form a point bar near the inner bank, then the point bar later becomes dry. Although the distance of the two banks increases, the width of the wetted channel remained approximately the same. Another feature of the simulated results is that when the main channel moves toward the outer bank due to bank erosion, a small channel near the inner bank is formed behind the point bar. This probably is because the small channel shortcuts from one bend to the next, the local water surface slope and sediment transport capacity is not small. This phenomenon appears in almost all the simulation cases. Figure 5 shows several images of channel pattern in the Hassayampa River, Arizona, and a small stream nearby. These images confirmed that the main mechanism of the numerical model is consistent to reality.

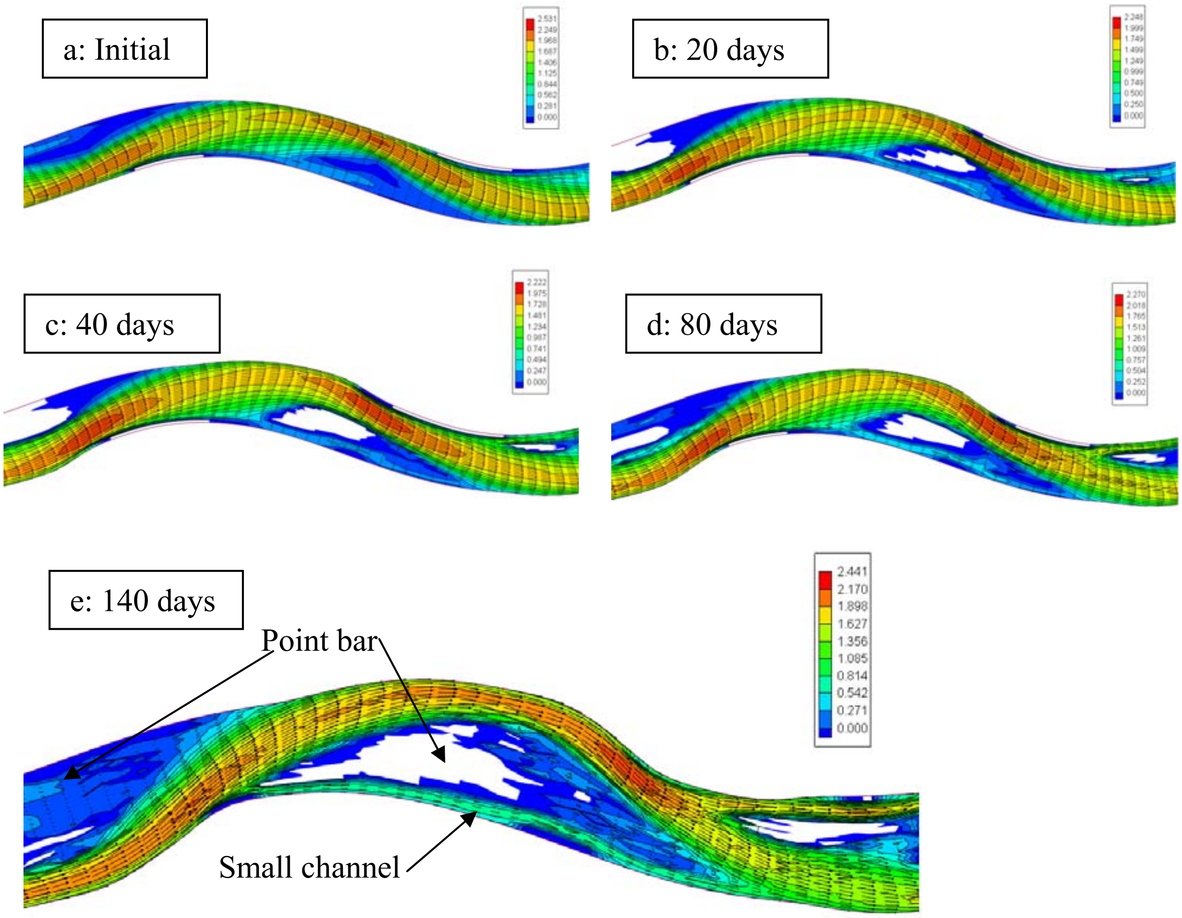

Figure 4 Simulated bank erosion and channel morphologic change using bankfull discharge (The color contour indicates flow velocity magnitude).

Figure 5, Curved river channel pattern in nature. a: Hassayampa River, Arizona, b: Hassayampa River, a little downstream; c: a small stream near by Hassayampa River

7. APPLICATION OF THE BANK EROSION MODEL TO A FIELD CASE

To demonstrate the capability of the developed bank erosion model, a field bank erosion case was simulated using the data provided by the *Flood Control District of Maricopa County*, *Arizona*. The field case is a real bank erosion event which occurred in Hassayampa River, Arizona. On February 14, 2005, a major flooding event occurred, and the embankment of the Hospitality RV Park was eroded. Bed roughness in the Hassayampa River may vary in a large range because of the sand bars, bushes and trees.

Table 1 shows the parameter sensitivity. The bank erosion width (encroachment) and length along the channel increase when the bank critical shear stress is less. The critical stress used was in the range of the field data (Simon et al 2003) for low cohesivity bank materials. From the photo graph of the scene and observations of the field trip of the investigators in February, 2006, it seems the bank materials in the Hassayampa River are not very cohesive. One finds that the agreement of the simulated results is very good when the critical shear stress is set around 15~20 dyne/cm^2. It is clear that the developed bank erosion model can be applied to study field bank erosion cases. The results of this field case are close to what happened in the field, and the parameters used were in reasonable range.

Table 1 Computed bank erosion and tested bank critical shear stresses

Run No.	Time Step (second)	Critical Shear Stress (dyne/cm^2)	Length of eroded bank (m)	Maximum Erosion width (m)	Average erosion width (m)
1	600	25	163	1.124	0.48
2	600	20	180	2.021	0.93
3	600	15	210	3.813	1.68
Observed			152		1.6

8. **CONCLUSIONS**

Bank erosion is a complex fluvial process, and it causes problems for human society. Numerical models can be developed to simulate bank erosion by computing all the involved physical processes, such as main and secondary flow, sediment transport processes and mass failure. The capabilities for simulating the secondary flow effects on suspended sediment and bed load sediment transport have been developed and implemented to the CCHE2D model. The bank surface erosion and mass failure mechanisms have been also developed with the eroded bank materials being transported as bed load. The model was designed for banks with cohesive and homogeneous materials. The mesh stretching technique was used to dynamically vary the mesh and handle the moving boundary (banks) problem. Several sets of experimental data were used to validate the developed sediment transport capabilities in curved channels with good agreements. Bank erosion capabilities were tested using a field case. With realistic soil and erodibility parameters, the model produced reasonable bank erosion results consistent with observed data.

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