River, Coastal and Estuarine Morphodynamics: RCEM 2009 – Vionnet et al. (eds)

Merging of RVR Meander with CONCEPTS: Simplified 2D model for long-term meander evolution

Davide Motta
Department of Civil and Environmental Engineering, University of Illinois, Urbana-Champaign, Urbana, IL, USA

Jorge D. Abad
Department of Civil and Environmental Engineering, University of Illinois, Urbana-Champaign, Urbana, IL, USA
Department of Civil and Environmental Engineering, University of Pittsburgh, PA, USA

Eddy J. Langendoen
US Department of Agriculture, Agricultural Research Service, National Sedimentation Laboratory, Oxford, MS, USA

Marcelo H. Garcia
Department of Civil and Environmental Engineering, University of Illinois, Urbana-Champaign, Urbana, IL, USA

ABSTRACT: RVR Meander is a simplified two-dimensional (2D) hydrodynamic and migration model (Abad and Garcia, 2006) while CONCEPTS (CONservational Channel Evolution and Pollutant Transport System) is a one-dimensional (1D) hydrodynamic and morphodynamic model (Langendoen and Alonso, 2008; Langendoen and Simon, 2008; Langendoen et al., 2009). Originally, RVR Meander reported only the use of Ikeda et al. (1981)'s hydrodynamic model, where the bank migration (ξ) was modeled by using the concept of near bank excess velocity (u_e). In this regard, the bank migration was expressed as $\xi = u_e E_o$, where E_o is a bank migration coefficient, calibrated upon historical centerlines. The bed morphology was not modeled according to the sediment mass conservation (Exner equation), but instead it was assumed that the transversal bed slope was directly related to local curvature. On the other hand, CONCEPTS uses an advanced treatment of the bank retreat. However, since CONCEPTS is a 1D model, it does not incorporate corrections for secondary flow and transversal bed slope: therefore its applicability to meander bends might underestimate the shear stress along the stream banks and consequently underpredict the migration rate. This paper shows the preliminary results of an ongoing effort to merge both models, with the goal of implementing a hydrodynamic and morphodynamic model capable of reproducing the flow field and the river migration for predicting long-term evolution needed in engineering and geological applications.

1 INTRODUCTION

Figure 1 shows a typical configuration of river migration. Herein, intrinsic coordinates are used (s^*: streamwise coordinate, n^*: transverse coordinate). The angular amplitude is given by θ. The width, depth, water surface and bed elevation of the channel are defined as $2B^*$, D^*, H^* and η^* respectively. Originally, RVR Meander included Ikeda et al. (1981)'s hydrodynamic model where the bed morphology is not calculated by using the sediment mass conservation equation (Exner equation), but instead it is computed by assuming that the transversal bed slope is related to the local curvature by $S_t = -ADC(s)$, where A is a transversal slope parameter (Zimmerman and Kennedy, 1978; Odgaard 1981), and $C(s) = -\partial\theta(s)/\partial s$ is the local curvature. The bank migration ($\xi = u_e E_o$) was modeled by using the concept of near bank excess velocity (u_e) and a calibrated bank migration coefficient (E_o). In the updated version, the bed morphodynamics can also be computed with the models advanced by Blondeaux and Seminara (1985) and Zolezzi and Seminara (2001), which incorporate the sediment mass conservation equation (Exner equation). Moreover, the routines implemented in the 1D CONCEPTS model for the bank evolution processes, i.e. fluvial erosion, cantilever and planar failure (Langendoen and Simon, 2008), were extracted and introduced into the new platform. The resulting updated version RVR Meander + CONCEPTS can be applied to non-straight channels for engineering and geological time scales and the modules for bank evolution allow for a physically-based representation of the migration process replacing the use of an empirical formulation based on excess near-bank velocity.

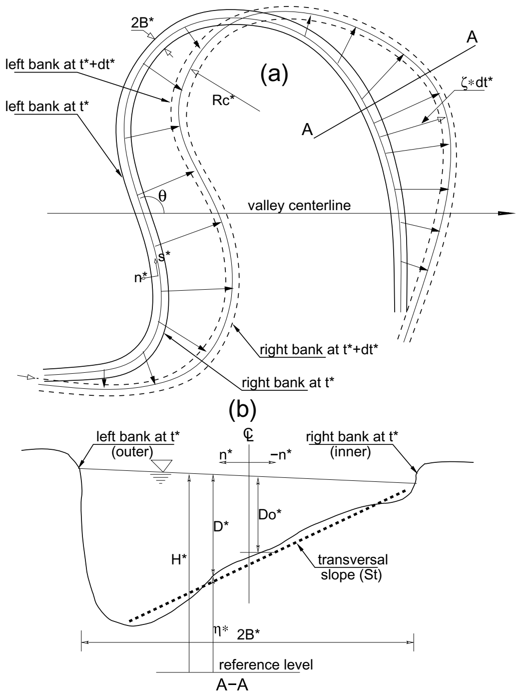

Figure 1. (a) Planform migration, (b) cross-section configuration. Variables are given in dimensioned values.

2 HYDRODYNAMIC AND BED MORPHODYNAMIC MODELS

As mentioned, RVR Meander + CONCEPTS incorporates several simplified 2D hydrodynamic and morphodynamic models: the Ikeda et al. (1981)'s model, the Blondeaux and Seminara (1985)'s model, and the Zolezzi and Seminara (2001)'s model. For the purpose of this paper, only the Ikeda et al. (1981)'s model is presented. Starting from the streamwise and transverse momentum equations and the water conservation equation:

$$U\frac{\partial U}{\partial s} + V\frac{\partial U}{\partial n} + \frac{\partial H}{\partial s} + \frac{\beta\tau_s}{D} = \nu_0 f_{11} \tag{1}$$

$$U\frac{\partial V}{\partial s} + V\frac{\partial V}{\partial n} + \frac{\partial H}{\partial n} + \beta\frac{\tau_n}{D} = \nu_0 g_{11} \tag{2}$$

$$\frac{\partial (DU)}{\partial s} + \frac{\partial (DV)}{\partial n} = \nu_0 m_{11} \tag{3}$$

The previous equations are expressed in dimensionless values, with $\beta = B^*/D^*$, $(U,V) = (U^*,V^*)/U_o^*$, $(s,n) = (s^*,n^*)/B^*$, $D = D^*/D_0^*$, $H = gH^*/U_0^{*2}$, $(\tau_s,\tau_n) = (\tau_s^*,\tau_n^*)/\rho U_o^{*2}$, where U_o^* and D_0^* are the velocity and depth for bed slope equal to the valley slope and τ_s and τ_n are the local bed shear stresses in the streamwise and transverse directions

$$\tau = (\tau_s,\tau_n) = (U,V)C_f\sqrt{U^2+V^2} \tag{4}$$

C_f is the friction coefficient, ρ is the water density, ν_0 is B^*/R_c^* (R_c^* is a reference radius of curvature), and

$$f_{11} = -n\mathcal{C}(s)\left(\frac{\beta\tau_s}{D} + V\frac{\partial U}{\partial n}\right) - \mathcal{C}(s)UV \tag{5}$$

$$g_{11} = -n\mathcal{C}(s)\left(V\frac{\partial V}{\partial n} + \frac{\partial H}{\partial n} + \frac{\beta\tau_n}{D}\right) + \mathcal{C}(s)U^2 \tag{6}$$

$$m_{11} = -\mathcal{C}(s)\left(VD + n\frac{\partial (VD)}{\partial n}\right) \tag{7}$$

Following linearization, the perturbed variables are:

$$U_1(s,n) = a_1 e^{-a_2 s} + n\Bigg[a_3\mathcal{C}(s) + a_4 e^{-a_2 s}\int_0^s \mathcal{C}(s)e^{a_2 s}ds\Bigg] \tag{8}$$

$$V_1(s,n) = \frac{a_1}{2}a_2 e^{-a_2 s}(n-1) + \frac{a_2}{2}\left(nu(s,n) - u(s,1)\right) + \frac{a_5}{2}(n^2-1) \tag{9}$$

$$D_1(s,n) = \left(\chi^2 F_0^2 + \frac{A}{\chi}\right)\mathcal{C}(s)n \tag{10}$$

$$\eta_1(s,n) = -\frac{A}{\chi}\mathcal{C}(s)n \tag{11}$$

where $F_0^2 = U_0^{*2}/gH^*$, $\chi = (S/S_0)^{1/3}$, S is the channel slope and S_0 is the valley centerline. The final results in dimensionless variables are given as:

$$U(s,n) = 1 + \nu_0 U_1(n) \tag{12}$$

$$V(s,n) = \nu_0 V_1(n) \tag{13}$$

$$D(s,n) = 1 + \nu_0 D_1(n) \tag{14}$$

$$\eta(s,n) = F_0^2 H(s,n) - D(s,n) \tag{15}$$

The curvature can be calculated with different methods: parametric, numerical $\Delta\theta/\Delta s$ backward or central scheme, fitting a local circle or with parametric cubic splines. Details of those and of some of the above equations and implementation can be found in Abad et al. (2009).

3 PHYSICALLY-BASED BANK EVOLUTION

The processes of fluvial erosion and mass bank failure (cantilever and planar) were included in RVR Meander + CONCEPTS, following Langendoen and Simon (2008) and Langendoen et al. (2009). The evolution of both right and left bank is computed considering a natural bank profile and the presence of horizontal layers characterized by different properties.

The fluvial erosion rate E, in the horizontal direction, for each of the layers in the left and right bank is modeled using an excess shear stress relation as follows

$$E = M\frac{(\tau - \tau_c)}{\tau_c} \tag{16}$$

where M is the erosion rate coefficient and τ_c is the critical shear stress. Both are characteristic of each layer material. τ is the shear stress on the layer. Several methodologies are used to calculate the shear stress at natural cross sections and implemented into 1D models (Lundgren and Jonsson, 1964; Khodashenas and Paquier, 1999). The effect of secondary currents in the near-bank shear stress was studied for straight channels with trapezoidal cross sections (Knight et al., 2007) and cohesive river banks (Papanicolaou et al., 2007). These methodologies are mostly applied to straight channels, therefore, their validation to apply them to meandering configurations is necessary. Depending on the planform configuration and bed morphodynamics, the distributions of near-bed and near-bank shear stresses could differ dramatically from straight channels. At field scale, there are some detailed measurements of in situ shear stresses, however, most of the time, these values reflect particular cases with no generalized findings. Several laboratory measurements have been done as well (Ippen et al., 1962; Hicks et al.,1990). Several empirical methodologies were also applied to describe the distribution of near-bed and near-bank shear stresses (Lane, 1955; Cantelli et al., 2007). The method for computing the shear stress on the banks proposed and implemented in RVR Meander + CONCEPTS is as follows: for each bank, the shear stress corresponding to the layer at the base is equal to the one calculated at the bank with the hydrodynamic solution, while, for the overlying layers, the shear stress at the base layer is scaled according to the ratio between the shear stresses on the different layers determined with the vertical depth or normal area method presented by Lundgren and Jonsson (1964).

The cantilever failure is associated to overhanging slumps of mass generated by preferential retreat of highly erodible layers. The occurrence of cantilever failure is determined from geometrical considerations, once an undercut threshold is exceeded.

The planar failure, i.e. the failure of blocks along a planar failure surface, is solved using a limit equilibrium method, which invokes the search for the smallest factor of safety, which is the ratio of available shear strength to mobilized shear strength.

Details of the physically-based bank evolution processes, equations and modeling can be found in Langendoen and Simon (2008) and Abad et al. (2009).

4 COUPLING RVR MEANDER AND CONCEPTS

The migration distance of the centerline is calculated, at each node (i.e., cross section), considering the displacement of the toes of the left and right bank. It is assumed that all the material eroded from the bank goes into suspension and does not deposit (purely erosional regime). As a consequence, the channels widens, and, after every time step, the new width used to recompute the hydrodynamics is taken as the minimum in the reach.

As other meander migration models, in order to avoid the propagation of numerical errors related to the computation of the channel curvature, two different and alternative techniques were implemented in RVR Meander + CONCEPTS. The first one is based on the filtering of the curvature (Crosato, 2007)

$$C_i = \frac{C_{i-1} + 2C_i + C_{i+1}}{4} \tag{17}$$

where $i-1$, i and $i+1$ are consecutive nodes. The second is a Savitzky-Golay filter applied to the coordinates of the migrated centerline, which is essentially a generalization of the moving window averaging, with an underlying function within the moving window which is not a constant, but a polynomial of higher order, least-squares fitted to all the points in the moving window.

5 PRELIMINARY TESTS

RVR Meander + CONCEPTS was applied to the case of Kinoshita curve, which is described in intrinsic coordinates by (Abad and Garcia, 2009a,b)

$$\theta = \theta_0 \sin(\kappa s) + \theta_0^3 (J_s \cos(3\kappa s) - J_f \sin(3\kappa s)) \tag{18}$$

where J_s and J_f are the skewness and flatness coefficients, θ_0 is the maximum angular amplitude, and κ is the wave number, given by $\kappa = 2\pi/\lambda$ where λ is the arc-wavelength of the channel. For these preliminary tests, the parameters adopted for the Kinoshita curve are $J_s = 1/32$, $J_f = 1/192$ and $\theta_0 = 110°$, which correspond to upstream-skewed high-sinuosity configuration.

The following parameters were assumed for the channel: channel flow = 2.5 m^3/s, initial bankfull channel width = 5.0 m, initial bottom channel width = 3.0 m, channel depth = 1.1 m, sediment size = 0.001 m and valley slope = 0.003.

As regards the bank properties, right and left bank were assumed as initially equal, characterized by a slope 1H:2V and a single layer with erosion rate coefficient = 10^{-8} m/s and critical shear stress = 0.20 Pa.

The shear stress on each bank was assumed equal to the one calculated at the corresponding bank with the hydrodynamic solution valid for the bed. Both fluvial erosion and cantilever failure were considered.

Figure 2 shows the shear stress at the beginning of the simulation and after 4 years. Flow is from left to right. The shear stresses are higher at the outer bank and the channel width increases, because of the bank erosion.

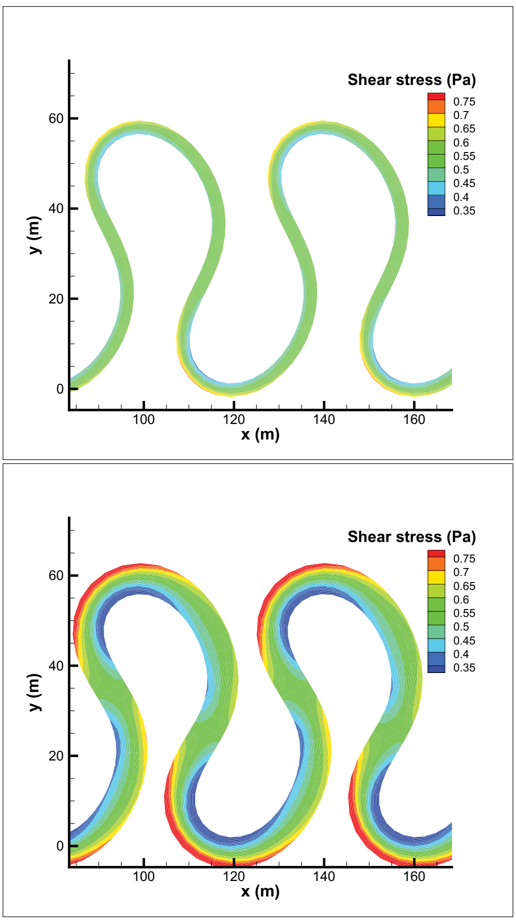

Figure 2. Shear stress at the beginning of the simulation (above figure) and after 4 years (below).

In Figure 3 the evolution of a cross section (initial configuration and configuration after 2 and 4 years) can be observed. Overhanging blocks are absent, since the cantilever failure process is considered.

Figure 4 and Figure 5 show the configuration of bed and banks at the beginning of the simulation and after 4 years.

Finally, observe in Figure 6 the centerline evolution, with a tendency toward cutoff.

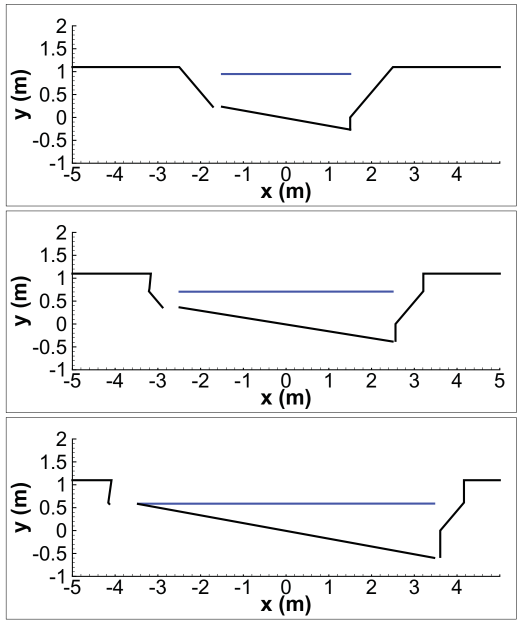

Figure 3. Evolution of a cross section: initial configuration (above figure) and configuration after 2 years (center) and 4 years (below).

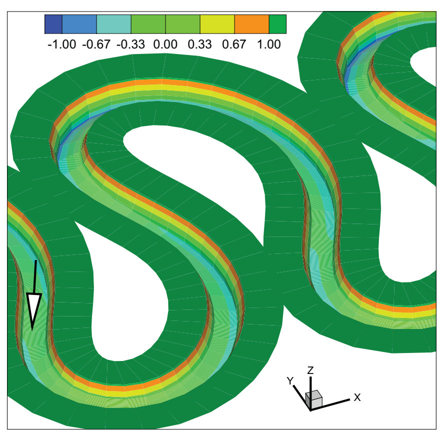

Figure 4. Initial configuration of bed and banks.

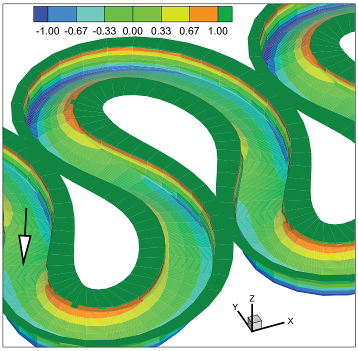

Figure 5. Configuration of bed and banks after 4 years.

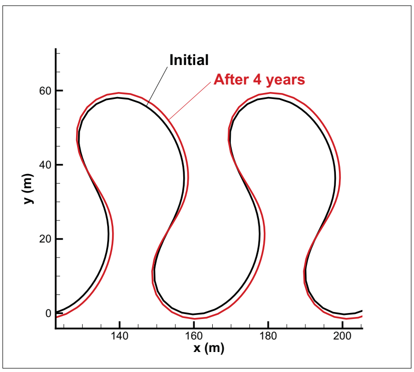

Figure 6. Centerline evolution.

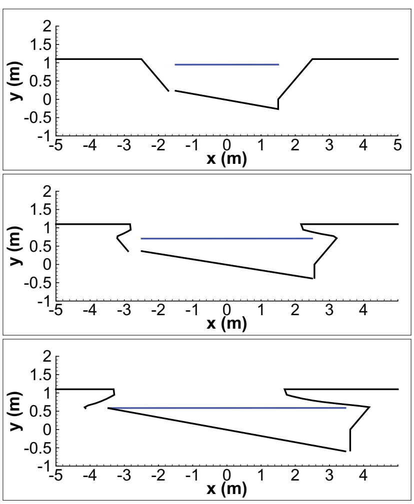

Figure 7. Evolution of a cross section: initial configuration (above figure) and configuration after 2 years (center) and 4 years (below), cantilever failure not considered.

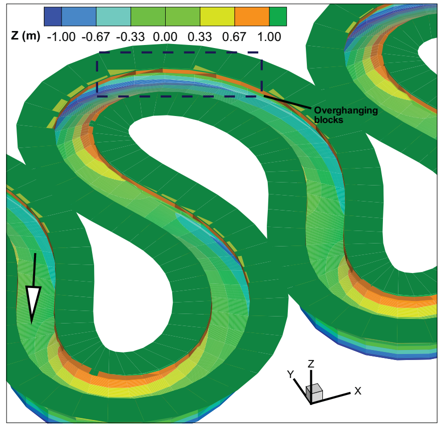

Figure 8. Configuration of bed and banks after 4 years, cantilever failure not considered.

If the cantilever failure process is not considered, overhanging blocks are present, as observed in Figure 7 and Figure 8.

6 CONCLUSIONS

The new platform RVR Meander + CONCEPTS was developed with the goal of providing a tool for reproducing the flow field and long term river migration for engineering applications. Modeling the physical processes which govern the bank evolution allows for avoiding the use of a calibrated migration coefficient. The platform is currently being transfered to a GIS environment, to take advantage of features already presented in the original RVR Meander such as pre-processing, statistical calculations and post-processing tools (Abad and Garcia, 2006).

REFERENCES

Abad, J.D., Motta, D., Langendoen, E., Garcia, M.H., Alonso, C., 2009. Report on merging of RVR Meander and CONCEPTS: simplified 2D model for long term meander evolution. VTCHL UofI.

Abad, J.D., Garcia, M.H., 2009. Experiments in a high-amplitude Kinoshita meandering channel: 1. Implications of bend orientation on mean and turbulent flow structure. Water Resources Research 45.

Abad, J.D., Garcia, M.H., 2009. Experiments in a high-amplitude Kinoshita meandering channel: 2. Implications of bend orientation on bed morphodynamics. Water Resources Research 45.

Abad, J.D., Garcia, M.H., 2006. RVR meander: A toolbox for re-meandering of channelized streams. Computers and Geosciences 32, 92–101.

Blondeaux, P., Seminara, G., 1985. A unified bar-theory of river meanders. Journal of Fluid Mechanics 157, 449–470.
Cantelli, A., Wong, M., Parker, G., Paola, C., 2007. Numerical model linking bed and bank evolution of incisional channel created by dam removal. Water Resources Research 43, 1–16.
Crosato, A., 2007. Effects of smoothing and regridding in numerical meander migration models. Water Resources Research 43.
Hicks, F.E., Jin, Y.C., Steffler, P.M., 1990. Flow near sloped bank in curved channel. Journal of Hydraulic Engineering 116(1), 55–70.
Ikeda, S., Parker, G., Sawai, K., 1981. Bend theory of river meanders. part 1. linear development. Journal of Fluid Mechanics 112, 363–377.
Ippen, A.T., Drinker, P.A., Jobin, W.R., Shemdin, O.H., 1962. Stream dynamics and boundary shear distributions for curved trapezoidal channels. Department of Civil Engineering, Massachusetts Institute of Technology .
Khodashenas, S.R., Paquier, A., 1999. A geometrical method for computing the distribution of boundary shear stress across irregular straight open channels. Journal of Hydraulic Research 37, 381–388.
Knight, D.W., Omran, M., Tang, X., 2007. Modeling depth-averaged velocity and boundary shear in trapezoidal channels with secondary flows. Journal of Hydraulic Engineering 133(1).
Lane, E.W., 1955. Design of stable channels. Journal of Hydraulic Engineering 120, 1234–1279.
Langendoen, E.J., Alonso, C.V., 2008. Modeling the evolution of incised streams. i: model formulation and validation of flow and streambed evolution components. Journal of Hydr. Engineering 134(6), 749–762.
Langendoen, E.J., Simon, A., 2008. Modeling the evolution of incised streams. ii: streambank erosion. Journal of Hydraulic Engineering 134(7), 905–915.
Langendoen, E.J., Wells, R.R., Thomas, R.E., Simon, A., Bingner, R.L., 2008. Modeling the evolution of incised streams. iii: model application. Journal of Hydraulic Engineering 135(6), 476–486.
Lundgren, H., Jonsson, I.G., 1964. Shear and velocity distribution in shallow channels. J. Hydraulics Div., ASCE 90 (HY1), 1–21.
Odgaard, A.J., 1981. Transverse bed slope in alluvial channel bends. Journal of the Hydraulic Division 107 (HY12), 1357–1370.
Papanicolaou, A.N., Elhakeem, M., Hilldale, R., 2007. Secondary current effects on cohesive river bank erosion. Water Resources Research 43.
Zimmerman, C., Kennedy, J.F., 1978. Transverse bed slopes in curved alluvial streams. Journal of the Hydraulics Division 104 (HY1), 33–48.
Zolezzi, G., Seminara, G., 2001. Dowstream and upstream influence in river meandering. Part 1. general theory and application to overdeepening. Journal of Fluid Mechanics 438, 183–211.