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Modelling of meander migration in an incised channel

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Abstract

An updated linear computer model for meandering rivers with incision has been developed. The model simulates the bed topography, flow field, and bank erosion rate in an incised meandering channel. In a scenario where the upstream sediment load decreases (e.g., after dam closure or soil conservation), alluvial river experiences cross section deepening and slope flattening. The channel migration rate might be affected in two ways: decreased channel slope and steeped bank height. The proposed numerical model combines the traditional one-dimensional (1D) sediment transport model in simulating the channel erosion and the linear model for channel meandering. A non-equilibrium sediment transport model is used to update the channel bed elevation and gradations. A linear meandering model was used to calculate the channel alignment and bank erosion/accretion, which in turn was used by the 1D sediment transport model. In the 1D sediment transport model, the channel bed elevation and gradations are represented in each channel cross section. In the meandering model, the bed elevation and gradations are stored in two dimensional (2D) cells to represent the channel and terrain properties (elevation and gradation). A new method is proposed to exchange information regarding bed elevations and bed material fractions between 1D river geometry and 2D channel and terrain. The ability of the model is demonstrated using the simulation of the laboratory channel migration of Friedkin in which channel incision occurs at the upstream end.

Key Words: Numerical model, River channel migration, Meandering river, Linearization analysis, Sediment transport

1 Introduction

The prediction and management of channel migration processes is one of the most difficult challenges in hydraulic engineering. A number of theories have been proposed to explain river meanderings. They include the Coriolis effect (Eaking, 1910), large-scale turbulence (Yalin, 1977; Grishannin 1979; etc), maximization or minimization of energy to dissipating river's excess energy (Langbein and Leopold, 1966; Yang, 1971; Chang, 1979; etc.), channel instability to local disturbance (Ikeda et al., 1981; Blondeaux and Seminara, 1983; Seminara ant Tubino, 1989; Zolezzi and Seminara, 2000; etc.), and others. River meandering bends and cutoffs enrich channel and floodplain diversity, which benefits the surrounding aquatic and riparian habitats. The placement of riprap or other bank stabilization measures along the channel bank to protect infrastructure often limits natural channel dynamics that promote healthy ecosystems. Accurate predictions of channel migration are crucial to the success of river management in order to balance natural channel processes for healthy ecosystems with protection of near channel infrastructure.

The process of channel migration has attracted many researchers in the hydraulic and environmental community. De Vriend (1977) derived the vertical distribution of the secondary flow in a shallow curved channel and presented a numerical method for the computation of the depth-averaged flow field and the bed shear stress. Investigations of Ikeda et al. (1981), Parker et al. (1982), and Howard and Knutson (1984) examined the mechanics of channel meanders with erodible banks to explain why channels meander. Later, linear theory was used to reproduce the evolution of meandering channels based on cross-stream flow variation and sediment transport of uniform material (Struiksma et al., 1985; Crosato, 1987; Johannesson and Parker, 1989; Struiksma and Crosato, 1989; Parker and Johannesson, 1989; Howard, 1992; Zolezzi and Seminara, 2001; Crosato, 2008) and mixed materials (Sun et al., 2001a,b). The influences of main flow adaptation length, bed deformation adaptation length, secondary flow adaptation length, sloping bed, and sediment transport formula were presented in Struiksma et al. (1985), Struiksma and Crosato (1989), and Crosato (2008). Zolezzi and Seminara (2001) pointed out the effects of meandering wave number and width-depth ratio associated with sub-resonant channels where small perturbations may migrate downstream and vice versa in super-resonant channels. Camporeale et al. (2005) reviewed the physical mechanisms involved in linear models and showed the importance of the secondary currents in the simulation of meandering rivers. They pointed out that nonlinear models

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have similar quantitative behavior as linear models, but the multilobed pattern can be presented only with a nonlinear model. Odgaard (1989a, b) related rate of bank migration to the difference between near-bank and centerline depth, instead of the linearized models which related rate of bank migration to the difference between near-bank and centerline velocity. Also there were some process-based models to calculate lateral erosion. Motta et al (2012a, b) related meander migration to the physical processes (hydraulic erosion and mass failure) responsible for bank retreat. Parker et al. (2011) provided a framework for channel migration that incorporate physical processes controlling bank erosion and deposition and allows change of width.

Also 2D models were developed to simulate erodible bed and banks (Duan et al., 2001; Darby et al., 2002; Jang and Shimizu, 2005). Duan et al.'s (2001) bank erosion model used the conservation of near-bank sediment mass balance. Chen and Duan (2006) also simulated meandering channel evolution based on the analytical solution of flow field and the bank-erosion model by Duan et al. (2001). Darby et al.'s 2D model (2002) incorporated a mechanistic model of bank erosion and simulated the deposition of failed bank material debris and its subsequent removal from the toe of the bank. Crosato et al. (2012) simulated migrating alternate bars form with a physics-based depth-averaged model.

One of the most commonly referenced linearization analyses for meandering rivers is that by Johannesson and Parker (1989). Their work provides a re-derivation of the analysis by Engelund (1974) and Ikeda et al. (1981). The basic idea behind these analyses is to express the flow variables as a sum of two parts. The first part is the solution to the case of flow in a straight channel. The second part represents the deviation from the straight channel solution for the case of a curved channel. The deviation is assumed to be linearly related to the curvature of the channel. These perturbed flow variables are substituted into the three dimensional flow equations. The equations are then simplified and grouped into the terms responsible for the straight channel solution and those due to the channel curvature. The simplified equations are then reformulated into ordinary differential equations that can be solved analytically or through relatively simple numerical methods. Ikeda et al. (1981) assumes bank erosion rates are related to the deviation of near-bank flow velocity from cross sectional average velocity.

Research conducted by Zolezzi and Seminara (2001) and Seminara et al. (2001) used a similar technique to Johannesson and Parker (1989), but their derivation accounts for the dispersive transport of momentum by the secondary flow with a 2D formulation.

Several applications using the analyses of Johannesson and Parker (1989) have been documented. Johannesson and Parker verified their model with data from Muddy Creek, Wyoming. Larsen (1995) applied this model to the Lower Mississippi River and Pole Creek in Wyoming. Thomas (1998) and Larsen et al. (2002) applied this model to the Sacramento River in California. These applications assumed that flow remains constant and used an effective discharge for channel formation instead of daily averaged discharge. Sun et al. (2001a, b) improved Johannesson and Parker's (1989) linearization theory by incorporating multiple-sized sediment transport equations.

While the above models have been applied to some natural river migration predictions, an improvement is desired to predict the channel meandering in a non-equilibrium river where incoming sediment load is different from the sediment transport capacity. One example where this need exists is in rivers after dam construction or removal. After a dam is constructed, the dam traps sediment, and the downstream channel typically experiences erosion. Following dam removal, sediment in storage behind the dam is temporarily deposited downstream. Starvation of sediment at the upstream deepens the channel cross section, flattens the channel slope, increases the water depth, and reduces the channel average velocity. The deepening of the channel also results in a higher bank, which may influence the channel migration in two opposite ways. It may lead to a destabilizing of the banks or a collapse of the banks. On the other hand, the failed material from a higher bank consumes more energy to remove and slows down the channel migration. An example was provided by Constantine et al. (2009) in the Sacramento River where large, failed, root-bound blocks of sand-silty soil formed a buffer to flow following failure. Current meandering models (Johannesson and Parker, 1989; Howard, 1996; Sun et al., 2001a, b) consider equilibrium sediment transport where channel experience no erosion/deposition in the longitudinal direction, and the sediment transport equation is simplified to calculate the channel cross-stream slope. A meandering channel with the ability to predict channel erosion and deposition is desired.

This paper presents a model that combines the meandering model with traditional one-dimensional sediment transport to predict channel migration during channel erosion and deposition. Channel geometry and bed gradations are updated using sediment conservation between incoming and outgoing sediments, channel erosion/deposition, and sediment erosion and deposition due to bank migration. The hydraulic and sediment transport are calculated with a quasi-steady model which can simulate a daily flow rate if needed. The terrain elevation is updated by tracking the erosion or deposition in the channel and by exchanging bed elevation and bed material information between a one-dimensional (1D) channel and 2D terrain.

The model presented in this paper proposes a new method to exchange information regarding channel bed elevation and bed material fractions between a 1D channel and 2D terrain. Sun et al.'s (2001b) work of uniform cell properties can obtain the channel bed elevation and bed material fractions from a 2D terrain. Improvements in this paper are proposed to return this information from a 1D channel into 2D terrain. Exchanges of information between a 1D channel and a 2D terrain are important to the simulation of incised channels. The proposed model divides each 2D terrain cell into three sub-areas: low elevation area (LEA), water surface elevation area (WEA), and high elevation area (HEA).