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Simulating river meandering processes using stochastic bank erosion coefficient

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ABSTRACT

This study first compares the first order analytical solutions for flow field by Ikeda et. al. (1981) and Johanesson and Parker (1989b). Ikeda et. al.'s (1981) linear model of bank erosion was implemented to predict the rate of bank erosion in which the bank erosion coefficient is treated as a stochastic variable that varies with physical properties of the bank (e.g. cohesiveness, stratigraphy, vegetation density). The developed model was used to predict the evolution of meandering planforms. Then, the modeling results were analyzed and compared to the observed data. Because the migration of meandering channels consists of downstream translation, lateral expansion, and downstream or upstream rotations, several measures are formulated to determine which of the resulting planform is closest to the experimental measured one. Results from the deterministic model highly depend on the calibrated erosion coefficient. Because field measurements are always limited, the stochastic model yielded more realistic predictions of meandering planform evolutions. Because the coefficient of bank erosion is a random variable, the meandering planform evolution is a stochastic process that can only be accurately predicted by a stochastic model.

1. Introduction

One of the most perplexing and intriguing problems in open channel hydraulics is the phenomenon of river meandering. Motivations for the continued research on a mathematical model to simulate this ubiquitous river planform are to advance our ability to explain complex natural phenomenon, to resolve issues associated with river ecological functions, to protect hydraulic structures such as bridges and levees, to mitigate erosion and flooding in valuable agricultural and urban lands, to understand the influence of sinuosity on surface/groundwater interaction, and to develop insight into the formation of oil reservoirs created by ancient meandering rivers (Sun et al., 1996). Research conducted under the Streambank Erosion Control Evaluation and Demonstration Act of 1974 (Sec 32, Public Law 32-251, submitted in December 1981), found that approximately 142,000 bank-miles of streams and waterways are in need of erosion protection. The cost to prevent or control this erosion by means of conventional bank protection methods was estimated to be in excess of $1 billion US annually. The Upper-Mississippi River alone, the cost estimate exceeded $21 million annually.

Simulations of meandering rivers have been reported intensively in literature that includes three major approaches: 1) analytical solutions (Engelund, 1974; Ikeda et al., 1981; Johannesson and Parker, 1989a; Camporeale et al., 2007) 2) numerical solutions (Duan, 1998, 2001; Darby et al., 2002) 3) empirical solutions (Langbien and Leopold, 1966). Besides simulating the flow field to solve for flow velocity and shear stress, numerical and analytical models require the estimation of the rate of bank erosion to simulate the evolution of meandering planform from low to high sinuosities. The results of these models, however, are considerably different because of the differences in calculating the rate of bank erosion. Therefore, the goal of this study is to analyze the analytical method of bank erosion and modeling planform evolution by examining the available methods in literature, through developing metrics to measure error in modeling the evolution of meander planforms. The second goal of this effort is to represent this modeling method through a Monte Carlo simulation whose results we can compare to the usual deterministic representation.

Bank erosion is a natural adjustment mechanism of channels of dynamic equilibrium and non-equilibrium. Alluvial channels adjust themselves to reach regime conditions through the degradation and aggradation of the river bed and also through width adjustment and planform evolution. The rate of bank erosion may depend on a variety of parameters including soil properties, the frequency of freeze-thaw, the stratigraphy of the bank, the type and density of vegetation, and sediment grain size at the toe of the bank (Micheli and Kirchner, 2002; Perucca et al., 2007). Bank erosion caused by hydraulic forces acting on bank surface and the failure of banks from geotechnical instability of the bank are the most commonly observed bank erosion phenomena in nature. In general, bank erosion of non-cohesive materials usually proceeds through the following sequence: firstly, bed scouring that steepens the side bank; secondly, bank collapse from instability of the scoured bank; thirdly, deposition of the collapsed bank materials at the

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front of the bank; at last, transportation of the deposited material downstream (Darby et al., 2002; Duan, 2005). The first two stages of the sequence result from fluvial entrainment and geotechnical instability, and the last two stages depend on the sediment transport capacity near the banks. Several mechanisms for mass failure have been observed including planar, rotational, cantilever, or piping or sapping type failures (Osman and Thorne, 1988; Darby and Thorne, 1996). These processes have been of interest to geotechnical engineers with regards to the design of artificial slopes and embankments. Osman and Thorne (1988) developed a theoretical model to calculate the bank erosion of steep banks of cohesive materials, which researchers modified to include the location and depth of tension cracks (Darby and Thorne, 1994), pore-water and hydrostatic confining pressure terms (Darby and Thorne, 1996), soil moisture content, and stochastic property of bank failure (Duan, 2005). These solutions require the calibration of soil erodibility index and other parameters, and considerable field data to describe geotechnical properties of the banks. This physically based method has been applied to simulate bank erosion processes of laboratory cases (Darby et al., 2002; Duan and Julien, 2005), but is limited for long-term simulation of natural rivers because of data constraints. Therefore, this study focuses on the linear bank erosion model (Ikeda et al., 1981; Camporeale et al., 2005), a benchmark in modeling meander migration used as reference to compare contemporary efforts.

Regarding the rate of bank erosion, the approach by Ikeda et al. (1981) was among the pioneering works addressing bank erosion when studying alluvial channel processes. In their approach, the rate of bank erosion (ζ), is linearly related to the excess near bank velocity (u'_b), which is the difference between depth-averaged velocity at the outer bank and cross-sectional mean velocity, through the linear erodibility coefficient (E).

$$\zeta = Eu_b' \tag{1}$$

According to Ikeda's equation of linear bank erosion, the bank retreats if the excess near bank velocity is greater than zero; otherwise, the bank advances. Ikeda et al. (1981) solution to the velocity excess is based on the depth-averaged Navier–Stokes equations for shallow water flow in curvilinear coordinates, making the traditional assumptions of steady flow in a constant width channel, with small ratios of width to centerline radius of curvature. Ikeda et al. (1981) closed the system of equations using the previous analyses (Engelund, 1974; Ikeda, 1975; Kikkawa et al., 1976; Zimmerman and Kennedy, 1978) where a "scour factor", A, is used to define a relationship between the transverse bed slope and water surface slope. Engelund (1974) suggested a value of 4.0. The theories of Kikkawa et al. (1976) and Zimmerman and Kennedy (1978) showed that this parameter should increase with the streamwise velocity. Camporeale et al. (2007) showed that the scour factor is a function of the treatment of secondary currents in the formulation of the model. The authors choose to use an average value based on Suga's (1963) analysis of 45 river bends in 10 alluvial rivers in Japan, suggesting a value of 2.89. Using the above assumptions and solving for velocity at the outer bank using the 1st order approximation of Navier Stokes equation in curvilinear coordinate as follows,

Table 1
Migration rate and erodibility summary (Micheli and Kirchner, 2002) with percent error.

Migration rate (m a^{-1})	Standard error	Percent error (%)
1.3	0.4	30.77
1.5	0.1	6.67
0.23	0.02	8.70
0.25	0.01	4.00
Erodibility $\times 10^{-7}$		
0.58	0.02	3.45
0.64	0.03	4.69
3.7	0.5	13.51
8.4	0.7	8.33
	Average percent error	10.01

$$U\frac{\partial u_b'}{\partial s} + 2\frac{U}{H}C_f u_b' = b\left[-U^2\frac{\partial \mathcal{C}}{\partial s} + C_f\mathcal{C}\left(\frac{U^4}{gH^2} + A\frac{U^2}{H}\right)\right] \tag{2}$$

where U is the depth-averaged velocity for the stream reach, s is the streamwise distance, H is the reach-averaged depth, C_f is the friction factor, b is the reach-averaged half-width, $\mathcal{C}$ is the local curvature, g is the gravitational constant of acceleration, and A is the scour factor. This solution of near bank excess velocity was then used to predict bank erosion or deposition through the assumption that the rate of bank erosion/deposition is linearly proportional to the near bank velocity, Eq. (1).

This approach was then used intensively to predict bank erosion (Parker, 1982; Johannesson, 1985) and was foreseen by Hasegawa and Ito (1978). Several authors (Johannesson, 1985), however, corrected the Ikeda et al. (1981) model when discovering that it did not account properly for the streamwise pressure gradient. This term gives rise to the irrotational vortex and, thus, results in higher velocities over the inside bank than the outside bank when applied to a developed bend flow over a non-erodible bed that is horizontal in the transverse direction (Johannesson and Parker, 1989b). This result contradicts those findings by Kikkawa et al. (1976), which were also confirmed by the observations of Parker (1982) and Johannesson (1985). As a consequence, when applying the Ikeda et al. (1981) model, significant calibrations were required to obtain results matching field observations (Johannesson and Parker, 1989b).

Johannesson and Parker (1989b) developed a bend flow model based on the convective transport of primary flow momentum by the secondary flow that results in a significant outward redistribution of

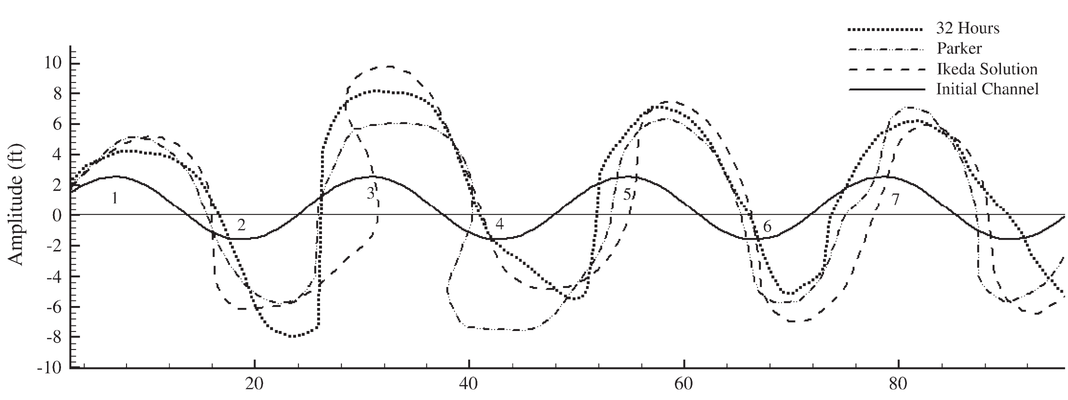

Fig. 1. Results of deterministic models Johannesson and Parker (1989b) and Ikeda et al. (1981) for a 32-hour simulation of J.R. Friedkin's (1945) experimental results.