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Cutoff processes and their importance for bed and planform morphodynamic adaptation

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ABSTRACT: The majority of current meandering river models treat the cutoff process as a geometric scheme: when the threshold distance between external banks of two bends are getting close enough, the model leaves behind over-matured bends and joins the two channels, then the oxbow lake is produced instantaneously. This does not describe the realistic scenarios. Combining the hydrodynamic model (TELEMAC-2D), morphodynamic model (SISYPHE), and channel migration submodel (MEANDRE), we constructed an integrated numerical model to simulate meander neck cutoffs and their accompanying natural evolutions in bedload dominated rivers. This model is capable to simulate not only in the plane geometry change aspect, but also the real day-to-day channel migration and cutoff events. This model successfully reproduced the laboratory experiment of self-formed cutoff performed by Han and Endreny. It is also effective for a series of test cases including Kinoshita-curve idealized channel cases. Future applications are extended to real world scale simulations.

1 INTRODUCTION

The dynamic of river meandering is one of the dominant factors to change fluvial geomorphology, and whereafter change the surficial appearance of the Earth (Figure 1). By the effects of both fluid mechanics and sediment transport, meandering rivers are migrating gradually but significantly, and their migration in planform mostly can be described by two effects: producing sinuosity (by channel migration) and eliminating sinuosity (by cutoff). According to the definition of meander cutoffs by Tower [1904], a cutoff is the shorter path which a river follows in virtue of having cut through the neck of a lobe or spur. Cutoff can generate sudden and sharp decline in length and sinuosity. In this paper we only focus on neck cutoffs.

As one of the major processes during the evolution of meandering rivers, cutoff plays an important role so that geomorphologists, land managers or land users would not disregard it. However, through the years, the numerical modeling of meandering rivers has been a hot topic in the field of geomorphology and morphodynamics, but on the contrary, directly modeling against cutoffs is rarely seen.

Several numerical models have incorporated cutoffs for long term simulations [Sun et al., 1996; Howard, 1996; Darby et al., 2002; Crosato, 2008; Frascati and Lanzoni, 2010; Asahi et al., 2013; Schwenk et al., 2015]. The majority of these models treat the cutoff process as a geometric scheme. When the threshold distance between external banks of two bends are getting close enough,

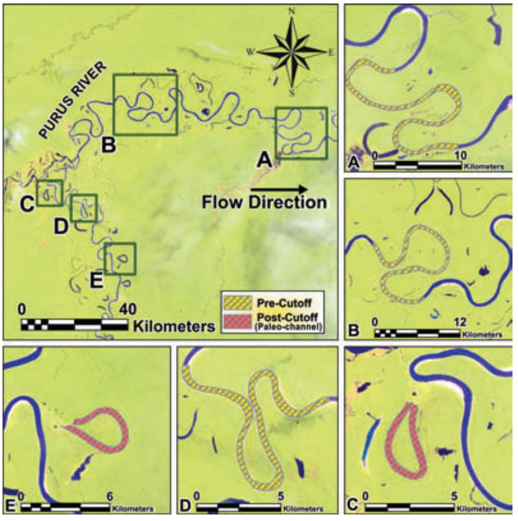

Figure 1. Cutoffs along the Purus River, Brazil. Some bends are under pre-cutoff condition (A, B and D), while others are under post-cutoff condition or oxbow lakes (C and E). A river maintains dynamic equilibrium condition by migrating and producing cutoffs [Gutierrez and Abad, 2014].

the model leaves behind over-matured bends and joins the two channels, then the oxbow lake is produced instantaneously. However, field researches have demonstrated that cutoff processes are complex: Kiss and Sipos [2015] monitored the formation of cutoffs and oxbow lakes in Hungary; Gay et al. [1998] described the cutoffs in Power River, Montana; Micheli and Larsen [2011] documented and measured cutoffs on the Sacramento River between 1904 and 1997. All these show cutoff is more dynamic than just an instantaneous redirection of flow and sediments. Herein, a model for cutoff occurrence and oxbow lake development is presented.

2 THE MODEL

Our model includes four components: 1) the initial triangular mesh generation; 2) the two-dimensional depth-averaged hydrodynamic model TELEMAC-2D; 3) the sediment transport and bed evolution model SISYPHE; and 4) the channel migration and cutoff detection submodel MEANDRE. The initial mesh of triangular cells for computation is generated using a free distributed software Blue Kenue™ by National Research Council, Canada. TELEMAC-2D and SISYPHE are parts of the open-source TELEMAC-MASCARET finite element method computer program developed by EDF-R&D, National Laboratory for Hydraulics and Environment & Saint Venant Laboratory for Hydraulics, France. The MEANDRE is co-developed by U.S. Department of Agriculture (USDA), University of Pittsburgh and EDF R&D.

2.1 *Initial mesh generation*

Our philosophy of mesh generation is quite simple: set fine mesh for the channel and coarse mesh for the floodplain for computing efficiency. Specifically, the mesh size in channel (d_s) is 10% of the channel width (i.e. b/5, b = channel half width); the mesh size on floodplain is up to 10 times larger than channel mesh size. The assignment of initial bed morphology and floodplain topography is done by projecting the triangulated x, y and z coordinates of points in space to the correlated area, as needed. For most of our cases, we assign a channel slope and valley slope (= channel slope × sinuosity) to imitate natural meandering rivers. Accordingly, we have the initial model setup in three dimensions (see an example in Figure 2).

2.2 *Hydrodynamics and morphodynamics*

TELEMAC-2D solves the two dimensional time dependent shallow water equations using finite element method [Lang, 2013]. It also provides users a number of turbulence models to choose, herein, we use the standard k-epsilon model.

SISYPHE computes sediment transport and therefore produces morphodynamic processes [Tassi and Villaret, 2014]. Several well-known and

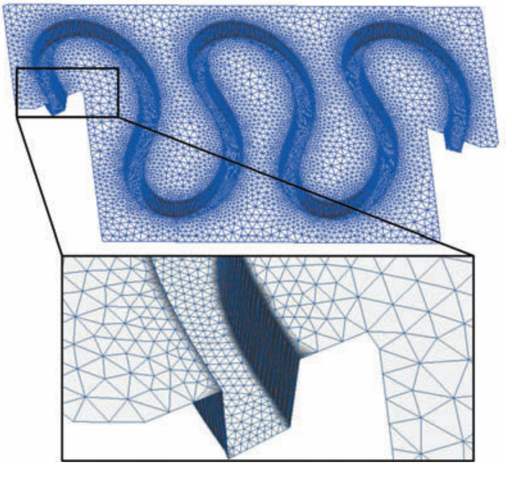

Figure 2. Unstructured triangular mesh: channel mesh size d_s = b/5 (b = channel half width); floodplain mesh size = 3 ~ $5d_s$.

classical bedload transport formulae are provided to users to select, such as Meyer-Peter-Müller formula, which is used in our model. The Exner equation is used in the SISYPHE model to solve bed evolution.

More details about TELEMAC-2D and SISYPHE can be found in manuals Lang [2013] and Tassi and Villaret [2014], respectively.

2.3 *Channel migration and cutoff detection*

Plane channel migration is observed by the retreat and advance of bank lines which are related to erosional (outer bank with fluvial erosion and bank geotechnical processes) and depositional (inner bank) processes. Herein, no geotechnical processes are included in the computations for bank retreat. MEANDRE [Langendoen et al., 2015] deals with bank erosion and accretion, and cutoff detection. Previous studies have already proposed the algorithm for searching cutoff in numerical modeling [Sun et al., 1996; Camporeale et al., 2005]. We use a modified version of Camporeale et al. [2005]'s algorithm. The modifications include, the outer bank line is used instead of channel centerline, which can take channel width effect into account to deal with variable channel width cases; the search process is optimized. This algorithm dramatically decreases iteration times. A brief description with a sketch of this algorithm is shown as follows (Figure 3):

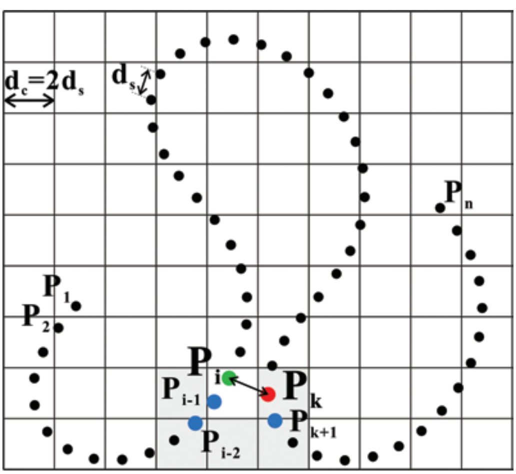

Figure 3. Cutoff detection algorithm: outer-bank line are discretized into nodes P_1, P_2, ..., P_n; the figure shows P_i is being scanned so blue and red points are being examined; finally the distance between P_i and P_k is found shorter than d_c, and at the mean time the stream-wise distance of these two nodes are larger than $5d_c$, which means a cutoff has been detected.

1. The outer-bank line is discretized to equal intervals (d_s) and n nodes are sorted onto a uniform square grid board. The size of each cell is exactly equal to the threshold distance of cutoff d_c, where d_c is set to be equal to $2d_s$ in our model, i.e., 20% of channel width or 0.4b;
2. n operations are needed to fully scan all nodes. From upstream to downstream, when one specific node (P_i) is being scanned, except for the cell contains P_i itself (i.e. center cell), only 5 cells that are immediately adjacent to the center cell and meanwhile not upper than the center cell will be traversed. In other words, standing at the center cell, the 5 cells to be traversed are West, East, South-West, South, and South-East of the center cells;
3. Traverse all nodes in the center cell itself. Search a node that has a shorter distance with node P_i than d_c, and also the stream-wise distance between these 2 nodes are larger than $5d_c$. Then execute the same searching statements in the 5 nearby cells.
4. If a node fulfills conditions to have cutoff is found, record the coordinates of the 2 nodes where cutoff is found, then oxbow lake and new shortened channel are formed.

3 RESULTS

3.1 *Reproducing experimental cutoff*

We practiced our model to reproduce a laboratory experiment done by Han and Endreny [2014a]. The results of this experiment are shown in Figure 4.

In Figure 4, M3 shows the initial stage; M4 is the pre-cutoff stage; M5 is when cutoff is occurring; M6 is 5 hours after cutoff; and M7 is 10 hours after cutoff. In each stage from M3 to M7, all the data of river water surface elevation, river bed elevation and Digital Elevation Model (DEM) of

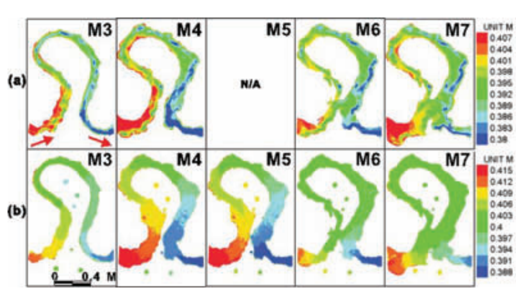

Figure 4. Experimental results: (a) Bed elevation from M3 to M7 (M5 is missing since data was not captured at M5 to avoid the potential interference to the cutoff; (b) Water surface elevation from M3 to M7.

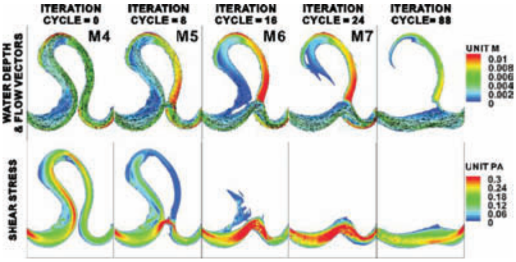

Figure 5. Modeling results (water depth and bed shear stress). ITERATION CYCLE = 0, 8, 16 and 24 stand for M4, M5, M6 and M7 in the experiment, and ITERATION CYCLE = 88 refers to the formation of the new straight channel after cutoff, which is an extension of the experiment. For simplicity the floodplain topography is not shown.

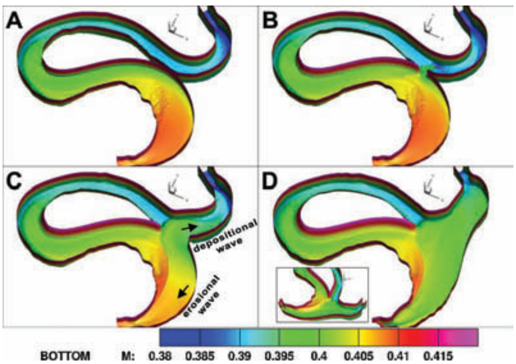

Figure 6. A: pre-cutoff condition, B: connectivity between the bends is initiated, C: the erosional and depositional waves are propagated, C to D: width and bed adjustment take place. The quality of the mesh (along the main channel and the floodplain) is maintained during the transitional cutoff process.

river table were recorded using a digital cameral [Han and Endreny, 2014b].

We reproduced each stage from M3 to M7, and yielded more details on the cutoff process. The water depth, flow vectors and bed shear stress are shown in Figure 5, while the bed morphology is shown in Figure 6. The figures of water depth and flow vectors clearly indicate how an oxbow lake is formed. Shear stresses increase in the neck cutoff region, but decreases when the new straight channel forms. In Figure 6, the depositional wave to downstream and the erosional wave to upstream is visible.

3.2 *Kinoshita-shape idealized channel*

Based on the well-known Kinoshita formula, we created a series of bends to form an idealized channel to observe the behaviors of bed and planform morphodynamic adaption during quasi- long-term river evolution. The initial conditions are: channel width = 0.4 m, water depth = 0.02 m, channel total length = 83 m, meander channel mesh size = 0.02 m, Kinoshita θ_0 of the central bend = 120°, Kinoshita θ_0 of the other bends = 30°.

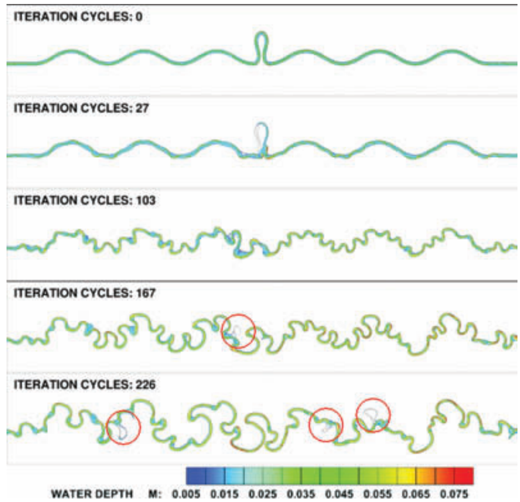

Figure 7. Modeling result of quasi- long-term river evolution. ITERATION CYCLES = 27 shows the first central cutoff is happening. ITERATION CYCLES = 103 represents the channel has gained the dynamic equilibrium mature meanders. In ITERATION CYCLES = 167 and 226, marked in the circles, we can observe the oxbow lakes after cutoffs. Notice that this model can record both before and after hydraulic conditions of oxbow lake and once the oxbow lake is formed, the model can preserve it in the floodplain topography for future oxbow lake reactivations.

4 CONCLUSIONS AND FUTURE WORK

The results of our integrated model suggest that this is a reliable model to simulate cutoffs, yielding full records of relatively complete details during the cutoff events, including bed morphology and planform pattern, than treating cutoff only an adjunctive process of river meandering and dealing with them hastily. Future research will extend to the real world scale simulations such as the Ucayali River—Pucallpa river reach (Peru).

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