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Combined Vertical And Lateral Channel Evolution Numerical Modeling

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COMBINED VERTICAL AND LATERAL CHANNEL EVOLUTION MODELING

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Abstract: Combined vertical and lateral channel evolution modelling is rarely done beyond conceptual and empirical analyses. In this study, a new geofluival numerical model is developed to simulate combined vertical and lateral channel changes. Vertical erosion is predicted with a 2D depth-averaged model SRH-2D while lateral erosion is simulated with a new bank erosion module. SRH-2D and the bank module are coupled together spatially and temporally through a common mesh with two meshing strategies. The new geofluvial model is first tested and verified with a meander channel under the laboratory setting. The model is then applied to a 16.7-kilometer reach of Chosui River, Taiwan, for its channel evolution over a three-year period. The predicted results are compared with the field data. It is shown that the geofluvial model correctly captures major erosion and deposition patterns.

INTRODUCTION

Vertical stream bed erosion has been studied routinely and its modelling is getting widespread acceptance. The same cannot be said with lateral stream bank erosion since its measurements or numerical modelling are quite challenging. This study concerns with the development of a new lateral bank erosion module that is process-based and the integration of the bank module into a two-dimensional (2D) depth-averaged mobile-bed model. The objective is to develop a geofluvial model that is suitable to simulate combined vertical and lateral erosion in an alluvial stream over a specified period of time.

Review of various bank erosion modules was carried out recently by Lai (2014) and not repeated herein. Among various models, the one that is most comprehensive and practical was reported by Langendoen and Simon (2008) who incorporated a bank module into a one-dimensional (1D) mobile-bed model CONCEPTS (Langendoen, 2000). Their geotechnical algorithm generalizes the limit equilibrium method of Simon et al. (2000) by employing vertical slices to distribute the weight of the failure block along the failure plane and enabling the automatic detection and insertion of tension cracks. Recently, a 2D depth-averaged mobile-bed model, SRH-2D, was coupled with the deterministic bank stability and toe erosion model (BSTEM) to improve predictions of channel adjustment and planform development (Lai et al., 2012). The stream vertical changes were predicted with the 2D mobile-bed model SRH-2D (Lai, 2010; Lai and Greimann, 2010) and lateral erosion were based on the bank module of Simon et al. (2000; 2011) and Langedoen and Simon (2008). Satisfactory results were obtained when it was applied to multi-layer cohesive banks at the Goodwin Creek, Mississippi.

In this study, further advancement of developing a practical geofluvial model is reported. The study focuses on two areas: a process-based lateral erosion module that is simple to apply and a flexible procedure to accommodate the bankline changes.

The GEOFLUVIAL MODEL

Vertical Erosion: The in-stream vertical fluvial processes are simulated with SRH-2D which is a 2D depth-averaged hydraulic and sediment transport model. Its hydraulic modeling theory was documented by Lai (2010). The model adopts the arbitrarily shaped element method of Lai et al. (2003), the finite-volume discretization scheme, and an implicit integration scheme. The numerical procedure is sufficiently robust that SRH-2D can simultaneously model all flow regimes (sub-, super-, and trans-critical flows) and both steady and unsteady flows. The special wetting-drying algorithm makes the model very stable to handle the flow over dry surfaces. The mobile-bed sediment transport module adopts the methodology of Greimann et al. (2008); theories have been described by Lai and Greimann (2010). The mobile-bed module predicts vertical stream bed changes by tracking multi-size, non-equilibrium sediment transport for suspended, mixed, and bed loads, and for cohesive and non-cohesive sediments, and on granular, erodible rock, or non-erodible beds. The effect of gravity and secondary flows on the sediment transport is accounted for by displacing the direction of the sediment transport vector from that of the local depth-averaged flow vector.

Basal Erosion: Basal erosion is the direct removal of bank materials laterally by flowing water in a stream. A number of methods may be used to compute basal erosion such as Nagata et al. (2000) and Duan et al. (2001). A new approach is adopted by the present study. An arbitrary number of banks can be chosen for simultaneous modeling of lateral bank retreat and vertical main channel processes. Bank geometry is represented by an arbitrary number of bank nodes independent of the 2D mesh. The only requirement is that the toe and top nodes of each bank should be identified on both the bank geometry and the 2D mesh and they should match each other. The benefit of dual bank representations is that the lateral erosion may be computed with an accurate bank shape without inducing 2D mesh irregularity. At the bank toe, vertical erosion is predicted by the 2D mobile-bed module while the lateral erosion is computed using a semi-empirical equation expressed as $\varepsilon_L = k(\tau / \tau_c - 1)$ where ε_L = lateral erosion rate (m s^{-1}), k = erodibility coefficient (m s^{-1}), τ = shear stress on the bank node (Pa), and τ_c = critical shear stress (Pa). Once the toe vertical and lateral erosion rates are computed, the lateral erosion of the wetted bank is computed by assuming that the shear stress decreases linearly from bank toe to the intersect of water surface elevation with the bank. The linear assumption is appropriate with the present model since the bank has been lumped together as a single unit and only the total amount of eroded bank materials is sought. Uncertainties of total basal erosion induced by the linear assumption may be compensated for by calibrating the erodibility coefficient.

Bank Retreat Rate: The bank failure after basal erosion is accounted for as follows. The bank profile from toe to top remains a straight line at a user specified angle (e.g., at the angle of repose) and the final bank retreat is computed such that the total area (volume) of bank retreat equals the area eroded in the basal erosion step. Therefore, the proposed bank module is called uniform retreat module. This failure calculation is only strictly valid for non-cohesive banks. It, however, may be applied to other bank types if only the gross bank retreat distance over a specified time period is of the interest. More complex process-based bank modules (e.g., Langendoen and Simon, 2008; Lai et al., 2012) are needed if bank mass failure timing or bank face shape is to be simulated. But such a simulation is still at the research stage and yet to be demonstrated for practical streams (Lai et al., 2012).

The bank retreat rate of the uniform retreat module is derived to give an analytical form with the above assumptions and the mass conservation requirement. The derivation has been described by Lai et al. (2013) and is not repeated.

Coupling Procedure: A bank zone is used to represent a bank section along which an arbitrary number of banks are simulated for bank retreat. The representation of banks on a 2D mesh is only used by the 2D module for data exchange with the bank module. Bank retreat computation by the bank module adopts a separate representation of each bank in which an arbitrary number of nodes are used to determine the bank shape. The dual representations of a bank are adopted to improve the accuracy of bank retreat simulation.

Two approaches are used to accommodate bank retreat and to realize data exchange during a continuous dynamic simulation: the moving mesh and the fixed mesh approaches. With the moving mesh approach, the longitudinal mesh lines are aligned with the bank toe and top initially. The bank line "alignment" is enforced continuously while banks retreat by moving the 2D mesh with the bank. The moving mesh procedure, however, has the potential to distort the mesh too much to cause model instability. The fixed mesh approach does not move the mesh during a dynamic simulation. Instead, bank toe and top are found through a "fitting" (interpolation) procedure. Fixed mesh removes the mesh distortion issue, but bank toe and top can only be approximately represented by the 2D mesh. Therefore, a much refined 2D mesh is often required to capture bank retreat reasonably. Details of the two methods may be found in Lai et al. (2013).

A MEANDER CHANNEL UNDER A LABORATRY SETTING

The geofluvial model is first verified by simulating a laboratory meander case by Nagata et al. (2000). The experiments were carried out in a tilting flume with its geometry shown in Figure 1. The channel cross section was initially trapezoidal and uniform along the channel. Two simulation runs are carried out. Run 1 had a flow discharge of 1,980 cm^3/s, bed slope of 1/300 and initial water depth of 3 cm. Run 3 had a flow discharge of 1,000 cm^3/s, bed slope of 1/100 and initial water depth of 1.42 cm. The bed and bank consisted of fairly uniform sand with a medium diameter of 1.42 mm.

Both the moving mesh and fixed mesh approaches are used for simulation. The initial mesh with the moving mesh approach is the same for both runs (see Figure 2a); while two initial meshes are used with the fixed mesh approach as shown in Figure 2b and c. The bed and bank are set to have uniform sand of a diameter of 1.42 mm. The upstream discharge is imposed as the boundary condition and the sediment feed rate is estimated using the Engelund and Hansen (1972) equation. The only downstream boundary condition is the water elevation that is specified using the measured data. The same Engelund-Hansen equation is used to compute the entrainment rate in the non-equilibrium sediment transport partial differential equation. The bedload adaptation length uses the Philip and Sutherland (1989) formula. A uniform Manning's roughness coefficient of n=0.0168 is used. Both the left and right banks are simulated for retreat with the following bank properties: the critical shear stress is computed by assuming the Shields number of 0.027 to be 0.62 Pa; and the bank erodibility coefficient is calibrated leading to $k = 2.0 \times 10^{-4}\ ms^{-1}$ (used for all model runs).

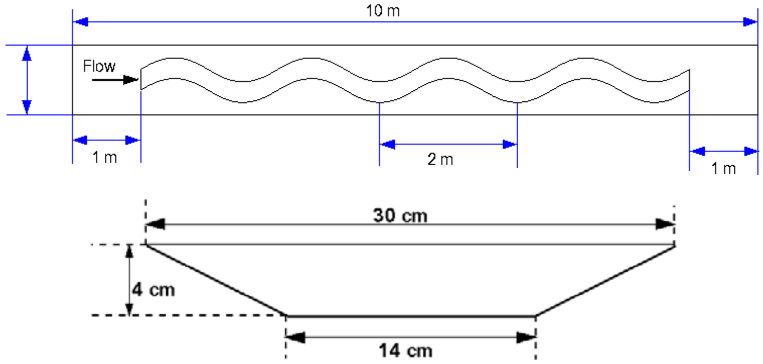
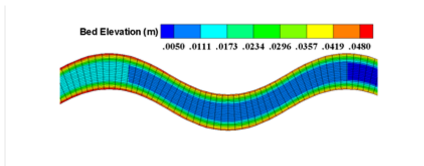
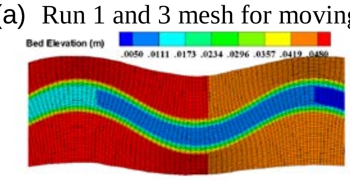
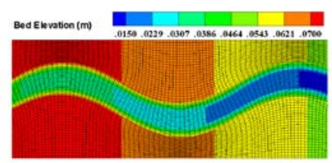


Figure 1. Initial planform and cross section of the meander channel



(a) Run 1 and 3 mesh for moving mesh

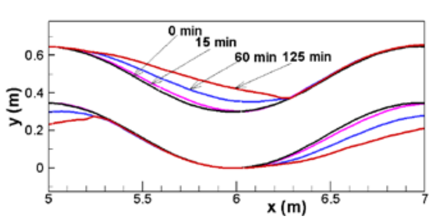




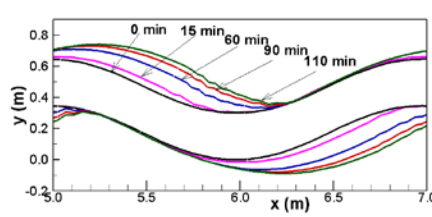
(b) Run1 mesh for fixed mesh (c) Run3 mesh for fixed mesh

Figure 2. Initial channel meshes with both the moving and fixed mesh approaches

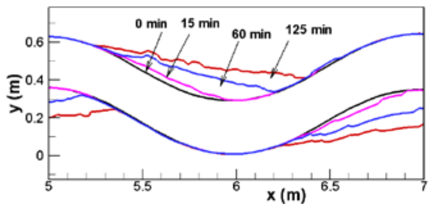
Model results with Run 1 and Run 3 are shown in Figure 3 which compares the predicted bank retreat process using both the moving and fixed mesh approaches, as well as the measured data. The results show that bank erosion starts at the downstream half of the outer bend and extends into the inner bend, while bar deposition occurs on the downstream half of the inner bend. The three sets of bank retreat results, two simulated and one measured, agree with each other reasonably well. The model under-predicts the retreat for Run 1 but better agreements are obtained with Run 3. Both the moving and fixed mesh approaches predict similar bank retreat results despite their vastly different methodologies used. This demonstrates that both approaches are implemented correctly and the procedure works well.



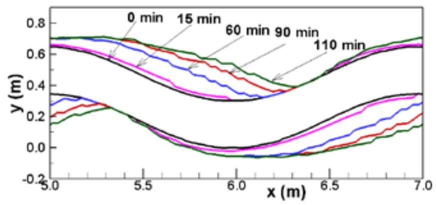
(a) Run1 Prediction with Moving Mesh



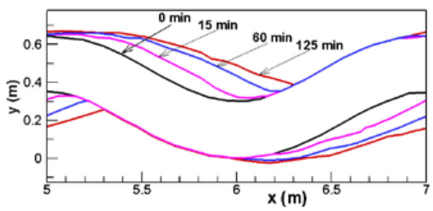
(d) Run 3 Prediction with Moving Mesh



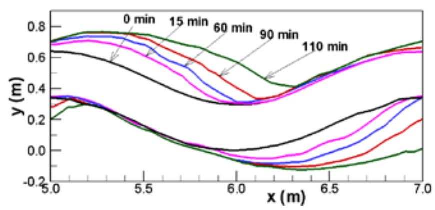
(b) Run1 Prediction with Fixed Mesh



(e) Run3 Prediction with Fixed mesh



(c) Run 1 Measured Data



(f) Run3 Measured Data

Figure 3. Comparison of predicted and measured bank retreat

MORPHOLOGICAL CHANGES OF A RIVER REACH

The geofluvial model is next applied to simulate vertical and lateral morphological processes of a reach on the Chosui River, Taiwan. The selected study reach is shown in Figure 4; the solution domain covers about 16.7 kilometers of longitudinal river channel and an average width of 1.9 kilometers. The final mesh used consists of 16,698 mixed quadrilateral and triangular cells mesh cells, which is used for both the moving and fixed mesh approaches.

The simulation is carried out for the time period of July, 2004 to August, 2007. The measured bed bathymetry and topography in April 2004 are used as the initial condition (see Figure 4). Other inputs are as follows. The flow resistance is represented by the Manning's coefficient (n) and a constant value of n=0.027, estimated using the field data, is used. The initial bed gradation is based on the survey data made in April 2004 which showed that the bed had a medium diameter of 1.44 ~ 1.78 mm. A total of five sediment size classes are used to represent the sediment within the reach: (1) 0.0625-0.125 mm; (2) 0.125-0.25 mm; (3) 0.25-0.5 mm; (4) 0.5-2.0 mm; and (5) 2.0-32 mm. The Engelund-Hansen sediment capacity equation is used as the erosional rate potential. At the upstream boundary the hourly recorded discharge is imposed and the sediment supply rate is estimated to be about 75% of the capacity computed by the Engelund-Hansen equation. At the downstream boundary, the stage-discharge rating curve developed from the measured data is sued.

A lower right bank section is selected for lateral bank erosion modeling together with the vertical processes. The bank zone, represented by the 2D mesh, is shown in Figure 5 with bank toe and top bank lines marked. A total of 21 banks, shown as black circular symbols, are chosen for bank retreat modeling. The bank erosion parameters are as follows: (1) a constant time step of one hour is used with the bank module; (2) all banks have a porosity of 0.3, the critical shear stress of 0.5 Pa, erodibility of 3.0×10^{-5}, the angle of repose of 30^{o}, and the volumetric sediment composition of 0.5, 0.35, 0.15, 0.0, and 0.0 for the five size classes, respectively. The critical shear stress of 0.5 Pa is estimated based on 0.045 critical Shields parameter and 0.65 mm diameter. The erodibility is the only calibration parameter and is determined by comparing model results with the measured bank retreat data.

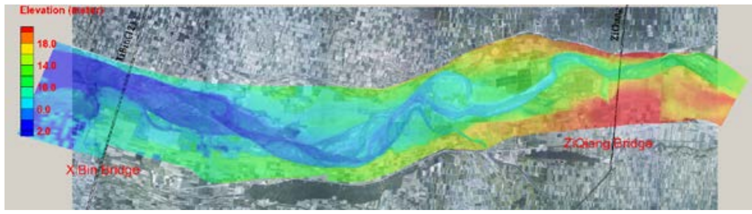


Figure 4. Solution domain and initial bed topo (aerial photo in July 2004).

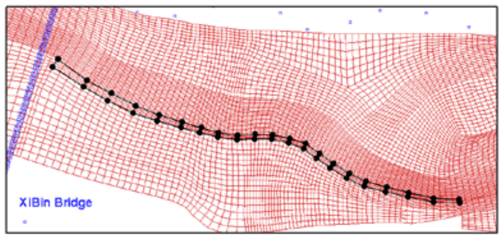
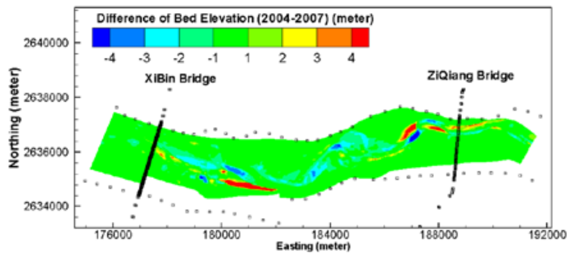
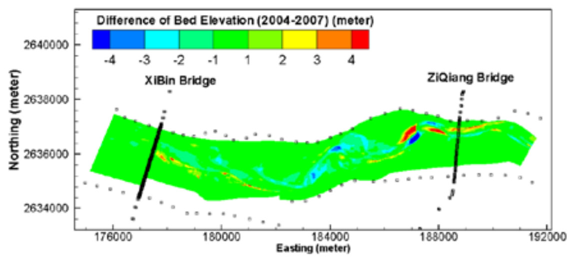


Figure 5. The bank zone (black polygon) selected for the modeling; upper black circles represent bank toes of all banks and lower ones are the bank top nodes.

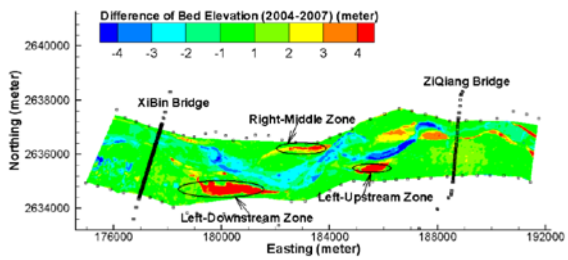
Combined vertical and lateral simulation is carried out for about 3 years (July 2004 to August 2007). A comparison of the predicted and measured net erosion and deposition depth over the 3-year period is shown in Figure 6. Overall, the model is capable of predicting the erosion and deposition patterns well, but less satisfactory quantitatively. High discrepancy upstream of Ziqiang bridge is expected since the upstream boundary is located within a bend and results near the boundary are subject to high uncertainty due to boundary conditions applied. Immediately downstream of the bridge, the model correctly predicts the “straightening” trend of the channel. Both the first left and right bars downstream of the bridge are eroded while the opposite main channel experiences deposition. The model predicts the potential erosion in the “Left_Upstream zone” (see Figure 10c for the zone labels). The predicted amount of erosion is much less than the measurement due probably to the neglect of bank erosion. Erosion in the “Right-Middle” zone is not predicted at all by the model. Attempts have been made to simulate this zone with the bank erosion module. However, such efforts are unsuccessful since there is not enough water flowing towards the area. The bank erosion experienced in the zone is probably due to undocumented features or events such as local peculiar topographic features that caused more water directed to the area and non-fluvial bank erosion processes. Bank erosion in the “Left-Downstream” zone is explicitly simulated with the bank module. The model predicts the bank retreat reasonably but the amount of bank retreat is under-predicted. With the moving mesh approach, a better agreement of the bank retreat distance with the measured data is not achieved since further increase of the calibration parameter erodibility has led to the distortion of the mesh causing model instability. With the fixed mesh approach, much smaller bank retreat is predicted since the mesh used is too coarse.



(a) Prediction with Moving Mesh



(b) Prediction with Fixed mesh



(c) Measured Data

Figure 6. Predicted and measured net erosion (positive) and deposition (negative) depth from July 2004 to August 2007

CONCLUDING REMARKS

A geofluvial model, SRH-2D, has been developed for combined vertical and lateral channel evolution modeling. Vertical erosion is predicted with a 2D depth-averaged model while lateral erosion is simulated with a new bank erosion module. The bank module treats the entire bank as a whole for its bank properties and retreat. SRH-2D and the bank module are coupled together spatially and temporally through a 2D mesh with both the moving mesh and fixed mesh approaches. But the bank shape is represented with a separate list of nodes independent of the 2D mesh. The proposed coupling procedure is flexible and stable; the model setup is general and straightforward; and a minimized set of calibration parameters are needed for practical application. The new geofluvial model is first tested and verified with a meander channel under the laboratory setting. The model is shown to perform well for such simple channels. The model is then applied to a 16.7-kilometer reach of Chosui River, Taiwan, over a three-year period. The predicted results are compared with the field data for model validation. It shows that the latest geofluival models are adequate for a quantitative prediction of combined vertical and lateral morphological predictions of a simple channel, but yet to be demonstrated for morphologically dynamic rivers such as the Chosui River. However, the model may still be used for qualitative prediction of the future morphological trend and for finding potential erosion and deposition trouble spots. The geofluvial model is more ideally suited for relative comparison among different engineering alternatives for river maintenance, flood protection, restoration, and other river projects.

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