Impact of Floodplain Vegetation on Morphological Process in the Straight Compound Open-Channel: A Numerical Study

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Abstract*: The present paper introduces a numerical model that is capable of simulating the morphological change of a straight open-channel. The computational procedures take three steps, namely flow prediction, estimation of bedload, and building the new channel shape in response to the bedload transport. The one-dimensional depth-averaged equation, called the lateral distribution method, with vegetation drag term is used for flow prediction, and the vectorized formula proposed by Kovacs and Parker (1994) is used to estimate bedload. The Exner's equation is solved to predict the channel shape with the help of the sliding algorithm proposed by Menendez et al. (2008). First, the flow model is applied to a compound channel without vegetation on the floodplain. Then, non-dimensional eddy viscosity is calibrated for vegetated flows. Finally, the model is applied to a hypothetical compound channel with floodplain vegetation. The impacts of vegetation on the flow and morphological process are investigated and discussed.*

Keywords: *compound channel, floodplain, morphological process, sediment transport, vegetation*

1. INTRODUCTION

Nowadays, use of urban floodplain has increased for recreational purposes of citizens. To improve the stream amenity, planting trees on the floodplain seems to be a good choice. This also improves the habitat suitability of the stream ecosystem. However, in hydraulic engineers' view, planting trees on the floodplain is delicate. That is, trees on the floodplain reduce the conveyance of the floodplain and transfer the discharge to the main channel, with rising flood level. This is a negative point. On the other hand, trees on the floodplain may retard the erosion and sedimentation of the stream, which provides an affirmative point of planting trees.

This paper presents a numerical model that is able to predict the deformation of the channel cross section due to sediment transport under uniform flow condition. The impact of trees in the floodplain on the flow and morphological change is investigated. The model can also be used for cutting management of riparian vegetation in the stream.

2. GOVERNING EQUATIONS

A model, capable of predicting the morphological change of an open-channel, should solve equations of the fluid flow, particle movement on the sloped bank, and bed elevation change. Thus, the numerical model consists of hydrodynamic, sediment transport, and morphological components with an algorithm describing the sliding phenomenon of the side bank.

2.1. Hydrodynamic model

In the present study, in order to obtain the depth-averaged velocity in a channel cross section, the lateral distribution method introduced by Wark et al. (1990) and Knight and Shiono (1990) is used. In a channel cross section, the lateral distribution of the depth-averaged longitudinal velocity U can be obtained by solving the following flow equation:

$$\rho g h S_x = B_g \rho C_f U^2 + F_v - \rho h \frac{\partial}{\partial y}\left(\overline{\varepsilon_y} \frac{\partial U}{\partial y} \right) \quad (1)$$

where x and y denote the longitudinal and lateral directions, respectively, ρ is water density, g is the gravity, h is the local flow depth, S_x is the longitudinal bed slope (= tanα, here, α is the angle of inclination of the bed in the x-direction), B_g is the geometrical factor ($=\sqrt{1+S_x^2+S_y^2}$, here, S_y is the lateral bed slope), C_f is the friction coefficient, and $\overline{\varepsilon_y}$ is the y-component depth-averaged eddy viscosity. The depth-averaged eddy viscosity is estimated by following relationship:

$$\overline{\varepsilon_y} = \chi_y U_* h \quad (2)$$

where χ_y is the non-dimensional lateral eddy viscosity coefficient and U_* is the shear velocity.

In Eq.(1), F_v is the darg force due to vegetation per unit bed area, which is given by

$$F_v = \frac{\rho}{2} C_D a h_p U^2 \quad (3)$$

where C_D is the drag coefficient of vegetation, a is the vegetation density [L^{-1}], and h_p is the vegetation height. Since Eq.(1) provides the lateral distribution of the depth-averaged velocity along the width of the channel, the impact of the secondary currents cannot be considered in the present study.

2.2. Sediment transport model

The critical condition under which particles on the bank and on the bed initiate their motions is given by the following relationship:

$$\vec{F}_D + \vec{W}_g + \vec{F}_C = 0 \quad (4)$$

where $\vec{F}_D$ is the drag force providing main driving mechanism, $\vec{W}_g$ is the submerged weight of the particle tangential to the plane of the bed, and $\vec{F}_C$ is the dynamic Coulomb resistive force. Inserting expressions for each force component leads to the following relationships:

$$|\overrightarrow{u_\Delta^*}|(u_b^* - v_p^* \cos\psi) - a_c \tau_{co}^* \left(|\cos\beta| \cos\psi - \frac{\sin\alpha}{\mu_c} \right) = 0 \quad (5)$$

$$|\overrightarrow{u_\Delta^*}| v_p^* \sin\psi + a_c \tau_{co}^* \left(|\cos\beta| \sin\psi - \frac{1}{\mu_c} \frac{\sin\omega . \cos^2\alpha}{\sqrt{\sin^2\omega . \cos^2\alpha + \cos^2\omega}} \right) = 0 \quad (6)$$

In Eqs.(5) and (6), $a_c^{1/2}$ is the conductance factor ($=u_b/U_*$, here, u_b is the fluid velocity in the bedload layer), μ_C is the dynamic Coulomb friction factor, τ_{c0}^* is the critical Shields stress for the onset of particle motion on the horizontal bed, v_p^* is the dimensionless particle velocity (= $v_p/\sqrt{RgD}$), u_b^* is the dimensionless fluid velocity in the bedload layer (= $u_b/\sqrt{RgD}$), and $|\overrightarrow{u_\Delta^*}| = (u_b^* + v_p^* - 2u_b^* v_p^* \cos\psi)^{1/2}$. Also, β is the angle between the vertical axis and the normal vector to the bed plane and ψ is the angle between the direction of particle motion and longitudinal flow direction. In the present study, Newton-Raphson method is used to obtain two unknown variables, v_p^* and ψ , in Eqs. (5) and (6) with values of parameters such as $a_c^{1/2}$ = 11.9, μ_C = 0.84, and τ_{c0}^* = 0.035 from Kovacs and Parker (1994). The relationship by Kovacs and Parker (1994) is used to evaluate the vectorial volume rate of bedload transport per unit width.

2.3. Morphological model

The morphological change of the channel cross section is accounted for by solving the following Exner's equation:

$$\frac{\partial z}{\partial t} + \frac{1}{1-\lambda_p}\left(\frac{\partial q_{by}}{\partial y} + \frac{\partial q_{bx}}{\partial x}\right) = 0 \qquad (7)$$

where t is the time, z is the bed elevation, λ_p the porosity of the bottom sediment particles, and q_{bx} and q_{by} are bedload vectors in *x*- and *y*-directions, respectively. The centered finite difference scheme is used for the numerical solution of the Exner's equation. In the present study, the sliding algorithm proposed by Menendez et al. (2008) is used.

3. VALIDATIONS AND CALIBRATIONS

For validation of the flow model, the model is applied to experiments in the Flood Channel Facility, a large flume at HR Walingford, UK (Ervine et al., 2000). The data set was obtained from large-scale straight channel (SERC-Series A (A02). The discharge was Q = 0.3832 m^3/s with a flow depth of h = 0.197 m. The slope of the channel was 0.001027 with roughness coefficients of n = 0.012 for both main channel and floodplain.
Figure 1 shows the lateral distribution of the depth-averaged velocity in the compound channel. A value of χ_y = 0.16 is used for computations. Good agreement between the computed profile and measured data are observed. Slight over-prediction and under-prediction of the numerical model are seen at the channel center and interface, respectively.

Now, the model is applied to a dataset RUN 17 of Ikeda's (1981) experiments. Ikeda (1981) observed a morphological process resulting from erosion of the bank in a flume that is 15 m long and 0.5 m wide. He built a trapezoidal channel with well-graded sands whose mean diameter is 1.3 mm. Figure 2 show the morphological change of the channel cross section after 1 hr. For comparisons, both measured data of Ikeda (1981) and simulated results by Kovacs and Parker (1994) and Menendez et al. (2008) are given. It can be seen that the proposed numerical model predicts the overall morphological process well. However, more erosion in the upslope part of the bank is noticed, resulting less deposition on the downslope part of the bank and channel bottom. A similar trend is also observed in the computed profile by Kovacs and Parker (1994).

In order to calibrate non-dimensional eddy viscosity for vegetated flows, the flow model is applied to laboratory experiments of Jordanova and James (2003). The case simulated numerically herein is Case A1, whose flow conditions are flow depth of 0.043 m and unit discharge of 0.0065 m^2/s in a 0.38 m wide rectangular channel. Cylinders were planted on the bottom of the channel to mimic emergent vegetation. Figure 3 shows the lateral distribution of the depth-averaged velocity for different values of non-dimensional eddy viscosity. It can be seen that higher values of χ_y induces the velocity distribution smoother in the vicinity of the sidewall. For Case A1. the discharge is best matched when χ_y = 0.067 is used. More numerical experiments were performed, yielding the average value of χ_y = 0.061, which is much smaller than the value for the plain open-channel flows.

4. APPLICATIONS

In order to see the impact of floodplain vegetation on the morphological process, the compound channel flow depicted in Figure 4 is numerically simulated. It is assumed that the channel is covered by uniform sands of D = 0.5 mm, resulting Manning's roughness coefficient of n = 0.0134 from Strickler's law. The discharge of Q = 0.122 m^3/s is conveyed at a slope of 0.001. For vegetative condition, rigid cylinders whose diameter is 0.012 m are assumed to planted uniformly on the bottom at a vegetation density of 2.4 m^{-1}. For non-dimensional eddy viscosity, values of 0.061 and 0.16 are used for vegetative and non-vegetative beds, respectively.

Figure 5 compares lateral distributions of the unit discharge with and without vegetation on the floodplain. It can be seen that floodplain vegetation moves the discharge to the main channel.

Quantitatively, 11% of the total discharge is shifted due to floodplain vegetation. It is expected that the retarded flow in the floodplain slows down the morphological change after planting vegetation on the floodplain. Figure 6 shows the morphological change of the channel cross section after 10 min. The channel cross sections with and without floodplain vegetation are compared. Vegetation on the floodplain induces less widening (or erosion) of the sidewalls of both floodplain and main channel, thus less deposition of the particles on the main channel.

5. CONCLUSIONS

The present paper presents a numerical model that can simulate the morphological process of a straight open-channel. The model comprises hydrodynamic, sediment transport, and morphological components. The lateral distribution method is used for the flow, and the sediment transport formulation by Kovacs and Parker (1994) is used for the bedload transport. In order to account for the morphological change, Exner's equation is solved with the help of sliding algorithm by Menendez et al. (2008).

The model is validated by applications to a compound channel flow and a morphological process of a trapezoidal channel. Then, calibration of the non-dimensional eddy viscosity is performed by applying the model to open-channel flows through emergent vegetation. A value of 0.061, smaller than that for the plain open-channel flow, is obtained for the flow with vegetation. Then, the compound channel flow with vegetation on the floodplain is simulated numerically. Floodplain vegetation is observed to move the discharge from the floodplain to the main channel. This induces less erosion and sedimentation in the floodplain and main channel, respectively.

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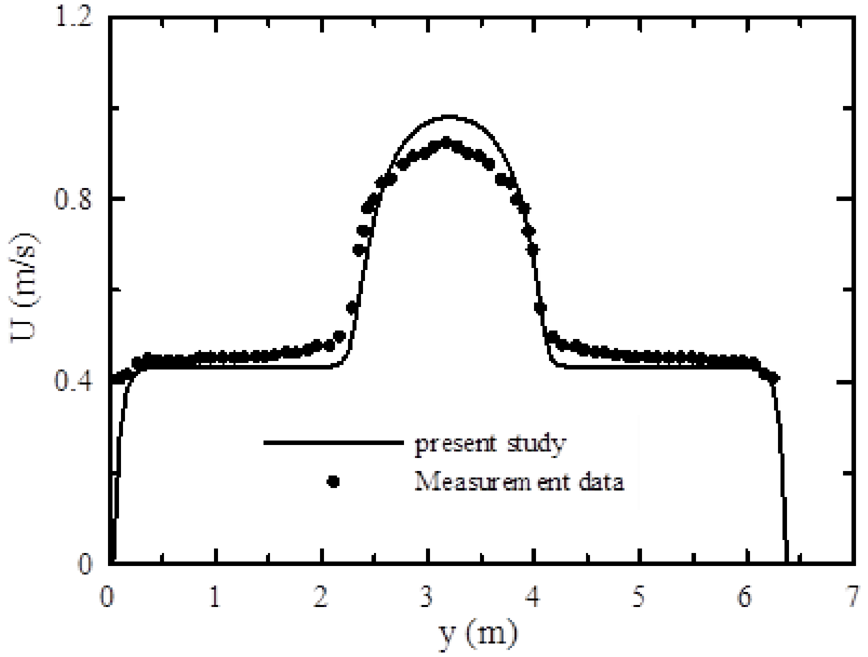

Figure 1. Lateral distribution of depth-averaged velocity in the compound channel

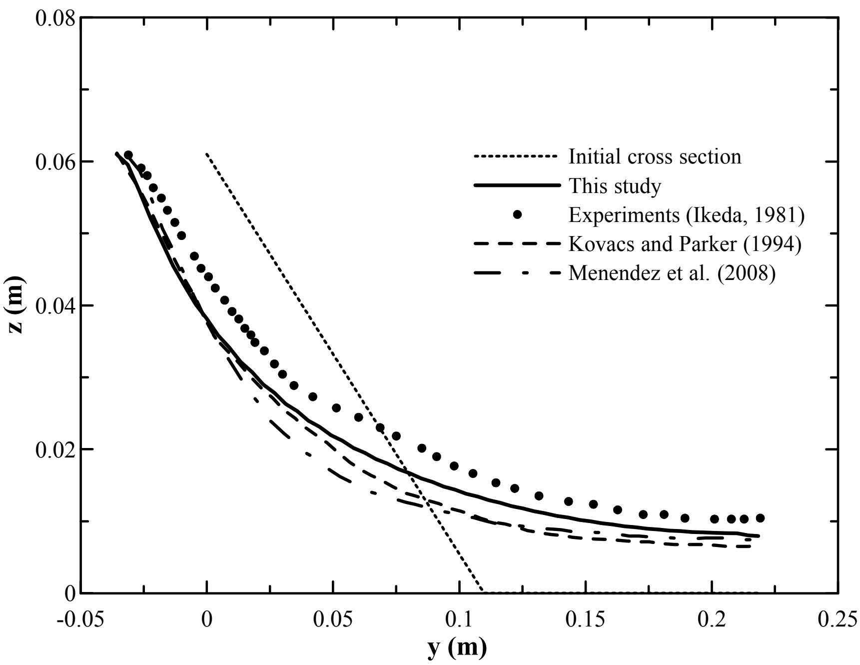

Figure 2. Morphological change of the trapezoidal channel after 1 hr

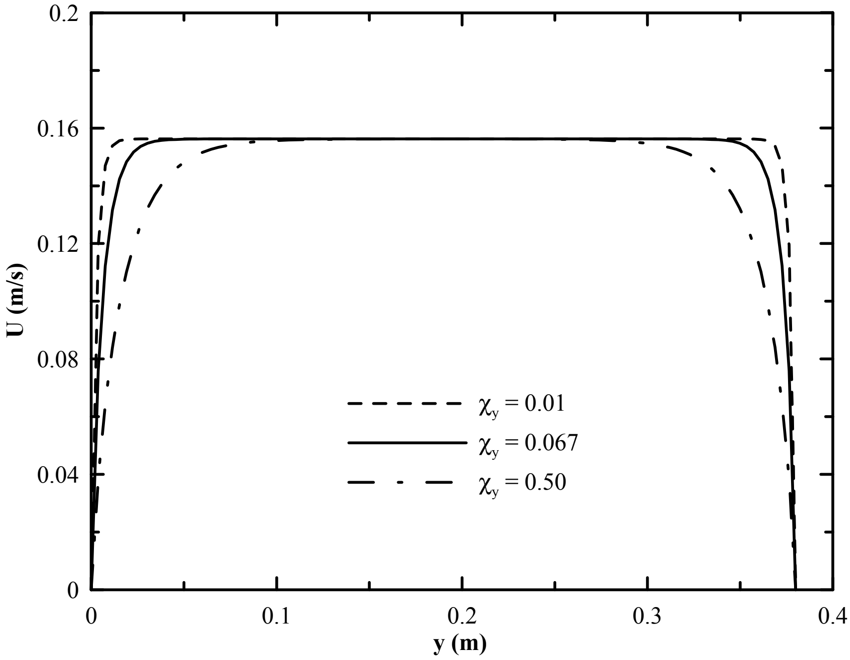

Figure 3. . Lateral distribution of depth-averaged velocity for different non-dimensional eddy viscosities

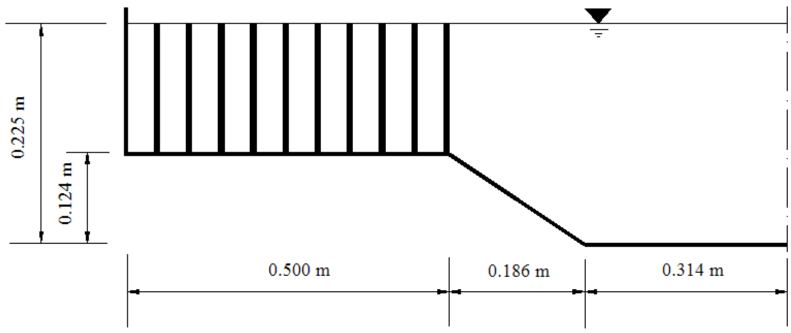

Figure 4. Cross section of compound channel with vegetated on floodplain

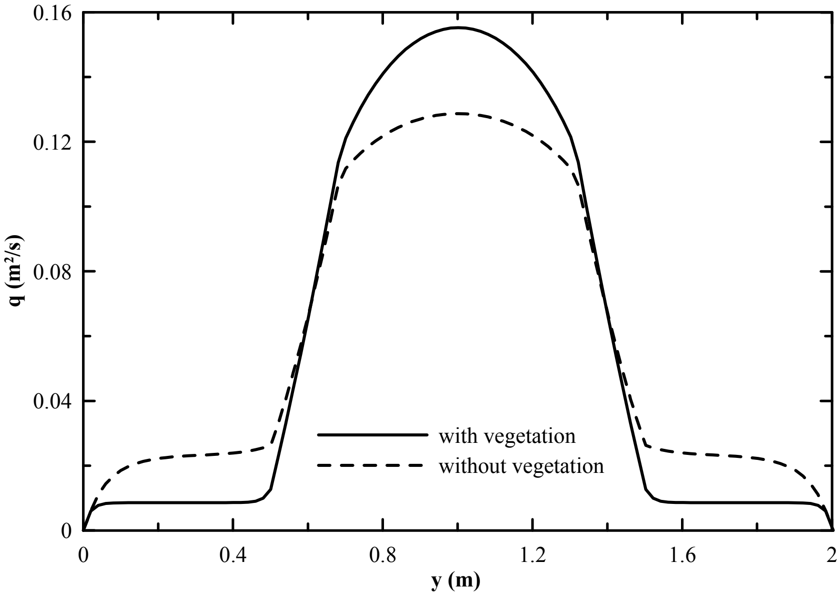

Figure 5. . Lateral distribution of unit discharge with and without vegetation on floodplain

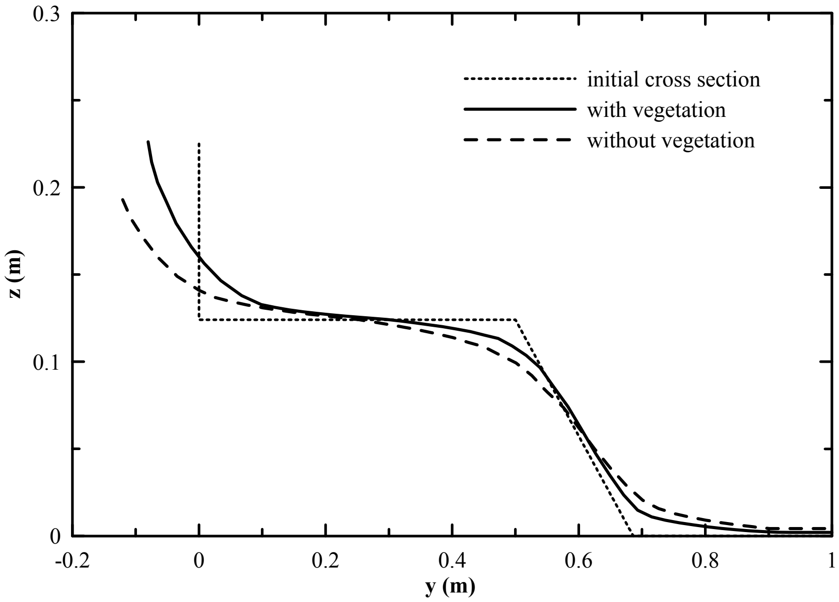

Figure 6. Morphological change after 10 minutes