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Improvement of the Lateral Distribution Method based on the mixing layer theory

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ABSTRACT

The accurate prediction of depth-averaged streamwise velocity, boundary shear stress and lateral shear stress are important requisites for the estimation of the flow depth associated with flood events in compound river channels composed of main channel and floodplain. This engineering problem may be tackled through the analytical solution of the depth-averaged momentum equation. Under uniform flow, this solution relies on the calibration of three descriptors of the bottom friction, secondary currents and lateral shear stress. In this paper, the analytical solution materialized in the Lateral Distribution Method is revisited through the consideration of a new panel division. Accurate measurements of streamwise and spanwise velocities as well as of boundary shear stress are used to obtain new predictors of the coefficients describing the effects of bottom friction, secondary currents and lateral shear.

The new lateral division of the compound channel into four panels is physically based on the mixing layer width, which is computed by an iterative procedure easily implemented in practical applications.

1. Introduction and framework of analysis

During floods, rivers frequently acquire a compound channel configuration, which induces important flow interactions between the main channel and the floodplain. The velocity gradient between these flows generates large-scale vortices of quasi-vertical axes (cf. [1]). Depending on the flow depth, one or two longitudinal vortices may also develop near the interface between the main channel and the floodplain due to turbulence anisotropy originated at the fixed boundaries and the interface [2]. The two vertical structures constitute a complex 3D flow structure where momentum transfer between the main channel and the floodplains can easily be identified [3].

In compound channels, the accurate prediction of the lateral distributions of the streamwise velocity and boundary shear stress is rather important. For this reason, several contributions can be found in the literature on the modeling of the compound channel flows. Shiono and Knight [4] derived one analytical solution of the depth-averaged momentum equation for steady uniform flow in the streamwise direction. They have assumed that viscous shear stresses are negligible in comparison with the turbulent shear stresses and that the time averaged vertical velocity is null. Their solution reads:

$$\rho g h s_0 - \tau_0\sqrt{1+1/s_y^2} = \frac{\partial}{\partial y}[h(\rho UV - \tau_{xy})] \tag{1}$$

where ρ = water density, g = gravity acceleration, h = flow depth, s_0 = longitudinal bottom slope, τ_0 = boundary shear stress, s_y = slope of the main channel lateral-bank (1:s_y = vertical:horizontal), y = lateral position, UV = depth-averaged product of the streamwise and spanwise velocities, respectively, and τ_{xy} = depth-averaged lateral shear stress.

Shiono and Knight [5] added closure models for the boundary shear stress and for the transverse derivative term of the shear stress due to the secondary currents (ρUV) and of the depth-averaged lateral shear stress (τ_{xy}); they also assumed the eddy viscosity approach, according to which:

$$\tau_{xy} = \rho\lambda u_* h\frac{\partial U}{\partial y} \tag{2}$$

where λ = dimensionless eddy viscosity coefficient and $u_* = (\tau_0/\rho)^{1/2}$. Assuming $u_* = (f/8)^{1/2}U$, where f = Darcy–Weisbach friction coefficient, they reduced Eq. (1) into the following ordinary differential equation:

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$$\rho g h s_0 - \frac{1}{8}\rho f U^2\sqrt{1+\frac{1}{s_y^2}} + \frac{\partial}{\partial y}\left(\rho\lambda h^2 (f/8)^{1/2} U\frac{\partial U}{\partial y}\right) = \Gamma \quad (3)$$

Here $\Gamma = \rho\frac{\partial}{\partial y}(hUV)$ = secondary current coefficient.

The analytical solution of the momentum equation proposed by Shiono and Knight [5] has been analyzed by several researchers while other analytical solutions have been suggested (e.g. Lambert and Sellin [6] and van Prooijen et al. [7] for uniform flows; Ervine et al. [8] for straight, skewed and meandering overbank flows). In the sequence of the work by Shiono and Knight [5], Abril and Knight [9] have shown that the analytical solution of Eq. (3) is more sensitive to changes of the friction coefficient, f, and of the secondary currents coefficient, Γ, than to those of the dimensionless eddy viscosity coefficient, λ. Omran et al. [10] highlighted the meaning of the secondary flow term in rectangular prismatic channels. These authors revealed that the secondary cells are dependent on the aspect ratio pointed out the difficulty in determining these features.

The analytical solution suggested by Shiono and Knight [5] can be implemented if the channel is adequately divided into panels where the coefficients may be described adequately and appropriate boundary conditions at the limits between panels are correctly specified. These conditions depend on the type and number of panels used in the division. Shiono and Knight [5] proposed the division of the compound channel into three panels: the main channel, the transition region (above the side slope of the main channel) and the floodplain.

For adjacent panels i and $i+1$, the boundary conditions must guarantee continuous depth-averaged velocity distribution in the spanwise direction, which implies $U_i = U_{i+1}$, $\partial U_i/\partial y = \partial U_{i+1}/\partial y$ and $(h\tau_{xy})_i = (h\tau_{xy})_{i+1}$. The no-slip condition holds for the lateral position at a solid lateral wall, $U_i = 0$. If the channel is symmetric, the lateral gradient of the depth-averaged velocity, $\partial U_i/\partial y$, is zero, in the symmetry axis.

The division of the compound channel must account for the turbulent structure of the flow and the influence of the mixing layer in the region near the interface, where vortices of quasi-vertical axis develop. Defining U_h and U_l as the depth-averaged streamwise velocities out of the mixing layer (corresponding to the higher and lower velocity *plateaus*, respectively) that develops near the interface between the main channel and the floodplain (cf. Fig. 1), one can also define the lateral position, y_α, where the local depth-averaged streamwise velocity, U_α, reads:

$$U_\alpha = U_l + \alpha(U_h - U_l) \quad (4)$$

for $0 < \alpha < 1$. The mixing layer width, δ, is defined herein according to Pope [11] for plane unbounded mixing layers:

$$\delta = |y_{0.9} - y_{0.1}| \quad (5)$$

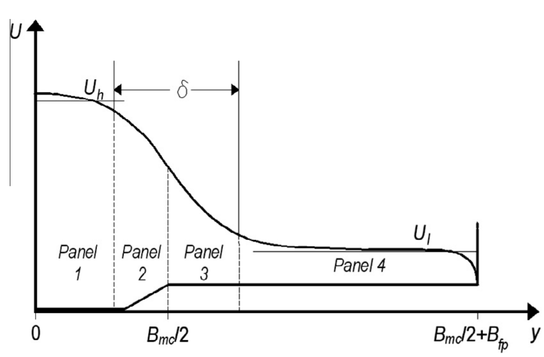

Fig. 1. Definition of plane unbounded mixing layer width, δ. (B_{fp} = floodplain width, B_{mc} = main channel width, U_l and U_h = average streamwise velocities outside the mixing layer in the lower and higher velocity regions).

Preliminary tests carried out in this study have shown that the mixing layer does not extend into the deepest region of the main channel, but it normally extends into the floodplain as schematically shown in Fig. 1, where a new panel division is conceptually presented. The main difference of the new division arises in the floodplain, where, instead of a single panel, a division in two panels, one where the mixing layer influence is felt (Panel 3) and another one where that influence is negligible (Panel 4), is proposed.

In the present paper, the analytical solution of the depth-averaged streamwise momentum equation proposed by Shiono and Knight [5], herein called Lateral Distribution Method (LDM), is analyzed in the framework of the new panel division. An iterative procedure derived from the plane unbounded mixing layer theory (cf. Pope [11]) is adopted to fix the limits of the panels. Measurements of streamwise and spanwise velocities and longitudinal boundary shear stresses taken for nine uniform flows in a straight compound channel with two floodplains roughnesses are used to derive new predictors of the Darcy–Weisbach friction coefficient, f, the dimensionless eddy viscosity coefficient, λ, and the secondary current coefficient, Γ. The new division and the new coefficients are validated through independent experimental data of Zeng et al. [12].

2. Experimental study

2.1. Experimental setup and measuring equipment

The experiments were carried out in a 10 m long and 2 m wide symmetrical compound channel located at the National Laboratory for Civil Engineering in Lisbon, Portugal. According to Fig. 2, its cross section consists of two equal rectangular floodplains (floodplain width B_{fp} = 0.7 m) and one trapezoidal main channel (bank full height, h_b = 0.1 m, main channel width, B_{mc} = 0.6 m, and 45° lateral bank slope, s_y = 1). In Fig. 1, h_{fp} and h_{mc} are the floodplain and the main channel flow depths, respectively.

The channel bed is made of polished concrete and its longitudinal slope is s_0 = 0.0011 m/m. Six experiments were performed for the original polished concrete bottom (smooth boundary), while another three were run with synthetic grass on the floodplains (rough boundary). Preliminary tests for the characterization of the bed roughness indicated that Manning's coefficient is n = 0.0092 m$^{-1/3}$ s for the polished concrete and n = 0.0172 m$^{-1/3}$ s for the synthetic grass.

Separated inlets for the main channel and for the floodplains were installed by adopting the suggestion of Bousmar et al. [13]. For each inlet, the flow discharge was controlled with a valve and monitored through an electromagnetic flow meter to the accuracy of ±0.3 l/s. At the downstream end of the flume, independent tailgates for each sub-channel were used to adjust the water levels in the flume.

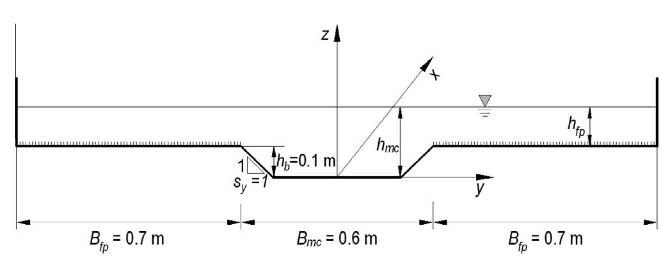

Fig. 2. Schematic representation of the compound channel. (B_{fp} = floodplain width, B_{mc} = main channel width, h_{fp} and h_{mc} = water depth in the floodplain and in the main channel, h_b = bankful depth and, s_y = slope of the main channel lateral-bank).