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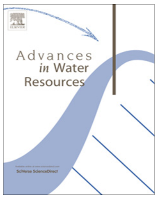

Momentum transport and bed shear stress distribution in a meandering bend: Experimental analysis in a laboratory flume

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ABSTRACT

The paper concerns the mechanisms underlying the distribution of the bed shear stress in meandering bends. Literature indicates that cross-stream circulation strongly affects the redistribution of the downstream velocity, but the feedback between them is still poorly understood. The aim of this paper is to gain some insight into how the momentum transport by cross-stream circulation contributes to the bed shear stress redistribution. Experimental analysis, based on a detailed dataset collected in a large-amplitude meandering laboratory flume, is presented. From these data an evaluation is made of the terms in the depth-averaged momentum equations and the analysis is especially devoted to terms including the momentum transport by cross-sectional motion. Results confirm that these terms exert an important role in bed shear stress estimation and, thus, they have to be adequately included in the depth-averaged models. Based on measured data, an equation expressing the interrelation between the cross-sectional momentum and the downstream velocity is also introduced.

1. Introduction

Fluvial processes encountered in natural meandering rivers have long interested engineers and researchers. As it is known, because of the irregular topography and the continuously changing plane shape, the velocity field is strongly three dimensional and cross-stream motion (i.e. motion perpendicular to channel axis) develops in each cross-section of the curved reaches (among others [12,28,33]).

Many interrelated physical processes, which are also caused by the cross-stream momentum transfer, take place in a meandering river making difficult to model the evolution of the meander wave. But, accurate specification of the spatial distribution of downstream velocity and cross-stream motion is fundamental in simulating peculiar processes involving in a natural stream.

Some researches (see as an example [6,34,39]) have highlighted that the distribution of the downstream velocity especially depends on two factors: (1) the bed topography; (2) the advective momentum transport by the cross-stream flow which develops along the curved reaches of the channel. The bed topography is mainly shaped by the bed shear stress distribution which, in turn, is determined by the distribution of the downstream velocity [13,19,37,41]. On the other side, the downstream changes in bed topography affect not only the magnitude of the bed shear stress but also the direction of the bed shear stress vector [15] and, consequently, the erosion and deposition processes.

According to Yalin [42], in meandering channels, the cross-stream motion is determined by the combination of two components: the cross-circulation motion, which is induced by the channel's curvature, and the convective component, which is due to the changing curvature of the channel. Literature [11,24,39] shows that the entity of each of these components especially depends on the channel's curvature and the width-to-depth ratio. Thus, for a given channel's sinuosity, the width-to-depth ratio is the most important parameter.

With the aid of experimental data collected in a 90° bend flume for a high value of the width-to-depth ratio ($B/h = 18$), Dietrich and Smith [14] investigated the order of magnitude of terms in downstream and cross-stream depth-averaged equations. They found that the convective accelerations, induced by channel's curvature and bed topography changes, are of the same order of magnitude as the downstream bed stress and the pressure gradient force. Other researches performed in deformed-bed meandering laboratory flumes (among others [37,41]) have also confirmed that, especially for high width-to-depth ratios, the convective accelerations play a fundamental role in the distribution of the downstream velocity.

Recent experimental results obtained both in a strongly curved channel [4] and in a large-amplitude meandering flume [39], for

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Nomenclature

B	channel width
$c = C_f^{-1/2}$	Chèzy type friction factor ($c = U/u_*$)
D_{50}	median sediment diameter
f	measured value
f_{real}	real value
F_r	Froude number
g	acceleration of gravity
h	flow depth
h_a	overall-averaged flow depth
Q	water discharge
r	transversal direction of the local reference system
r^*	transversal abscissa where the highest value of v_s occurs
R	local radius of curvature of the centerline
Re_*	roughness Reynolds number
R_h	hydraulic radius of the cross-section
R_{min}	minimum radius of curvature at centreline
s	longitudinal direction of the local reference system
S	bed slope
u_*	mean shear velocity
U	mean flow velocity
v_r	cross-stream component of velocity
v_s	downstream component of velocity
v'_j	jth instantaneous velocity fluctuation ($j = r, s$)
v^*_j	jth local deviation of the velocity component from the depth-averaged value $\langle v_j \rangle$ ($j = r, s$)
V_j	jth depth-averaged velocity component ($j = r, s$)
z	vertical direction of the local reference system
z_b	bed elevation above a horizontal plane
α_s	normalized transverse velocity gradient, $(\partial\langle v_s\rangle/\partial r)/(\langle v_s\rangle/R)$, as suggested by Blanckaert and Graf [6]
$\varepsilon(f)$	relative uncertainty of a quantity f
θ_o	deflection angle at the inflection section
ρ	water density
σ_m	root mean squared error
σ_f	standard deviation of f-series
$\sigma_{f,E}$	standard error of the mean
τ	mean shear stress
$\tau_{t,ji}$	turbulent stress component ($i = r, z, s$; $j = r, z, s$)
$\hat{\tau}_{t,ij}$	normalized turbulent stress component ($i = r, z, s$; $j = r, z, s$)
$\tau_{b,s}\tau_{b,r}$	downstream and cross-stream components of the bed shear stress

small width-to-depth ratios, have instead exalted the role of cross-stream motion in the downstream velocity and bed shear stress redistributions. It was observed, indeed, that for small width-to-depth ratios the convective behavior of flow is attenuated by cross-circulation. It should also mentioned to the fact that, along the bend, besides a main central-region circulation cell, a second counter-rotating cell was also found near the free surface in the outer-bank region [4,12,39]. Such a counter-rotating circulation cell determines a sort of buffer layer protecting the outer bank from the action of the central-region circulation cell and, thus, it could be important in finding an explanation of meander wave evolution.

From the aforementioned, it seems clear that the momentum transport by cross-circulation has to be adequately taken into account in forecasting models.

Many models for simulating hydrodynamic and morphodynamic processes in meandering rivers have been developed. Since complex and interrelated phenomena affect the meander wave evolution, the existing models are based on different approaches and/or focus on different physical mechanisms. A detailed description and comparison of some existing models, according to their hypotheses and their level of detail in simulating the various physical mechanisms involved in meandering dynamics, can be found in Camporeale et al. [9]. From the analysis performed by Camporeale et al. [9] it is clear the importance of the closure sub-model for cross-stream flow in simulating the meander wave evolution.

The point is that, although 3D numerical models (see as an example [27,29]) have been developed to simulate the cross-stream flow, 2DH models, that are based on the depth-averaged momentum and continuity equations, are still preferred for practical applications. But these models do not adequately consider the effect of the cross-stream flow.

In the past, simplified analytical models [16,33] were developed to determine the effect of cross-circulation on the downstream velocity distribution. The limitation of these models is that they were deducted in fully developed flow conditions (i.e. neglecting the terms related to the downstream variations in the flow) and, thus, they overestimate the role of cross-circulation [6]. Attempts to extend the 2DH computed flow field to the third dimension were also made either by introducing additional terms, which include the bed friction coefficient C_f, in momentum equations [22] or by applying empirical velocity distribution equations, which include geometrical control parameters like B/R (R = radius of curvature) and/or h/R [21], or by introducing geotechnical conditions for the bank stability [10]. But, these models have still limited applicability. In addition, due to the lack of data, not many comparisons with experimental data include the velocity profiles especially in complicated conditions such as flow in meandering channels.

Recently, Blanckaert and Graf [6] analyzed the order of magnitude of terms in the depth-averaged downstream momentum equation by using experimental data collected in a single section of a constant strongly curved (120°) flume for a low width-to-depth ratio ($B/h = 3.6$). Blanckaert and Graf [6] focused the attention on the developing curved flow and investigated only terms related to the cross-stream advective momentum transport and to the pressure gradient. From such an analysis, Blanckaert and Graf [6] concluded that the aforementioned terms give a contribution of comparable magnitude to the downstream bed shear stress. Based on experimental results, Blanckaert and Graf [6] presented a conceptual non-linear closure sub-model, which was previously described in details by Blanckaert and de Vriend [5], to account for the feedback between the downstream velocity and the center-region circulation cell. In a subsequent work, Blanckaert and de Vriend [7] proposed a fully non-linear hydrodynamic model which includes the aforementioned closure sub-model. This model describes the vertical structure of cross-stream flow, and its induced advective momentum transport, as a function of the friction coefficient C_f, the ratio h/R and the coefficient α_s which parameterizes the transverse distribution of the downstream velocity. On the basis of this, Blanckaert and de Vriend [7] identified $C_f^{-1}h/R$ (which is equivalent to $C_f^{-1}h/B$) as the main control parameter with respect to the velocity redistribution, and R/B as the parameter accounting for high-curvature effects. This model was also successfully applied by Ottevanger et al. [30] to simulate the flow redistribution both in a laboratory flume with flat and smooth