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Experimental analysis of the effect of vegetation on flow and bed shear stress distribution in high-curvature bends

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ABSTRACT

The cross-sectional circulation, which develops in meandering bends, exerts an important role in velocity and the boundary shear stress redistributions. This paper considers the effect of vegetation on cross-sectional flow and bed shear distribution along a high-curvature bend. The analysis is conducted with the aid of data collected in a large-amplitude meandering flume during a reference experiment without vegetation and an experiment with vegetation on the bed. The results show that the presence of vegetation modifies the curvature-induced flow pattern and the directionality of turbulent structures. In fact, in the presence of vegetation, the turbulent structures tend to develop within and between the vegetated elements. The pattern of cross-sectional flow, modified by the presence of vegetation, affects the bed shear stress distribution along the bend so that the core of the highest value of the bed shear stress does not reach the outer bank.

1. Introduction

The prediction of planform evolution of meandering rivers is fundamental not only because of hazards associated with it but also because of the remarkable implications in the ecosystem dynamics of surrounding areas. Understanding of flow dynamics in high-curvature bends, especially close to the outer bank that is most vulnerable to erosion, is of particular importance. Recent studies (among others Sekely et al., 2002; Wilson et al., 2008; Palmer et al., 2014) have also highlighted that the bank erosion can be considered as one of the most important contributions to watershed sediment loads. Natural rivers present a large variety of forms and variable bed and bank roughness. Field studies (Hooke, 2003) reveal that the migration rate of high-curvature bends exhibits large variance, and some bends present stability or low activity while others tend to be transformed into braided channels.

As the literature indicates, the flow pattern in high-curvature bends is mainly affected by i) bed topography, which determines the so-called topographical steering of flow (see as an example Dietrich and Smith, 1983; Blanckaert, 2010). This is owing to the fact that the development of the point bar at the inner bank leads to an asymmetrical cross section and determines higher depth-averaged velocity in the deeper part of the cross section. ii) The curvature-induced cross-sectional flow (see also Table 1), which can be considered as the combination of the cross-circulation (induced by the channel curvature) and the convective component (induced by the variation of the channel curvature; Yalin, 1992); and (iii) the additional counter-rotating circulation cell, which often develops in the upper part of the outer-bank region. According to recent research (among others Blanckaert and de Vriend, 2004; Termini and Piraino, 2011; Termini, 2015a) such a counter-rotating cell allows the bank shear stress to maintain low values in the outer side of the bend protecting the outer bank from the action of the central-region circulation cell. Consequently, such a counter-rotating cell could play an important role with respect to the stability of the outer bank and thus could be crucial to analyze the variations of migration rates of meander bends.

Although a considerable amount of research has been conducted in order to analyze the aforementioned processes, understanding of their relative importance, for different geometric and roughness conditions, and their role in meander migration is still incomplete.

Literature also shows that vegetation covering the bed and banks of natural rivers alters the local roughness and the banks strength (among others Ikeda and Izumi, 1990; Jang and Shimizu, 2005). Thus, especially in recent years, researchers have devoted much attention to the identification of the effect of the vegetation on river morphodynamics (among others Bendix and Hupp, 2000; Jang and Shimizu, 2005; Perrucca et al., 2006, 2007; Güneralp and Rhoads, 2011; Schnauder and Sukhodolov, 2012). From these studies, vegetation clearly affects the turbulence structure of flow, the secondary current strength, and the boundary shear stress characteristics (see also Hickin, 1984; Thorne, 1990; Yang et al., 2007; Corenblit et al., 2009). But how the variations of planform characteristics of the bend may be controlled by vegetation remains poorly understood.

The interactions between flow and vegetation are complex and depend on plant characteristics (morphology, stiffness, concentration, distribution, etc.) and on flow characteristics (velocity, turbulence

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Table 1

Explanation of adopted definitions on cross-sectional flow.

Definition	Explanation
Curvature-induced cross-sectional flow	Flow component perpendicular to the channel axis, which is induced by the channel's curvature
Cross-circulation	Cross-sectional flow component (with circulatory motion) induced by the curvature and results from the interaction between the outward centrifugal force and the inward pressure gradient
Central- region circulation cell	The cross-circulation gives rise to a circulation cell in the central-region of the cross section. This causes near-bed velocities that are directed inward
Outer-bank circulation cell	Additional counter-rotating circulation cell that forms near the surface at the outer bank
Convective component	Cross-sectional flow component caused by the downstream variation of the channel's curvature
Momentum transport by cross-circulation	Advecting momentum transport by the central-region circulation cell
Downstream component of the vorticity vector *ws*	This term allows us to mark the circulation part of the cross-sectional motion
Downstream velocity non-uniformity	This term indicates the cross-sectional nonuniformity of the downstream velocity

intensity, etc.). Moreover, it is clear from literature (among others Ghisalberti and Nepf, 2002; Carollo et al., 2005; Okamoto and Nezu, 2010) that the effect on flow between rigid and flexible vegetation is different. In particular, recent researches show (see as an example Meftah and Mossa, 2015; Malcangio and Mossa, 2016) that the hydraulic behavior of rigid elements is similar to that of a fixed bed formed by elements of known geometry in large-roughness conditions. On the contrary, flexible vegetation oscillates in the flow changing position and configuration (erect, gently swaying, prone, etc.) depending on flow conditions and stem stiffness (Carollo et al., 2002, 2005; Meftah et al., 2015).

Some research has focused on flow-vegetation interactions in straight flumes (among others Nepf. and Vivoni, 2000; Ghisalberti and Nepf, 2002; Carollo et al., 2002), but no systematic research has been conducted to investigate flow-vegetation interactions in curved flows.

Considering the aforementioned, the present paper reports on an investigation of flow-vegetation interactions in a high-amplitude meandering bend. It focuses on the effects of vegetation on the cross-sectional flow and the bed shear stress patterns along the bend. Attention is restricted to the case of submerged flexible vegetation. According to Nikora et al. (2008), such a behavior is characteristic of aquatic vegetation, which includes submerged plants on streambed. The present research also has been motivated by the fact that there has been a growing interest in understanding the hydraulic behavior of aquatic plants, across a wide range of species, and their effect on flow characteristics. Nikora et al. (2008) observed submerged aquatic plants in five small New Zealand streams, in a wide range of flows and vegetation species. Miler et al. (2012) highlighted that abundant aquatic vegetation can be found on the bed in lowland rivers. In a subsequent work, Miler et al. (2014) investigated the differences in biomechanical and morphological characteristics between species of aquatic vegetation in small rivers, in a gradient of hydraulic habitats ranging from high to low flow velocities, and in lakes. Schnauder and Sukhodolov (2012) analyzed the effects of aquatic flexible vegetation on flow and turbulence along a meandering bend of the Tollense River in Germany.

The present analysis is conducted by means of laboratory experiments carried out in a meandering flume without and with vegetation on the bed. In a previous work, Termini and Piraino (2011) examined the cross-sectional flow pattern in absence of vegetation and for different hydrodynamic conditions. The present paper explores the effect of vegetation by comparing cross-sectional flow, turbulence, and bed shear stress distribution obtained in a reference experiment without vegetation with those obtained in an experiment with vegetation on the bed. Thus, the present paper has the following objectives: (i) to investigate cross-sectional flow and turbulence patterns in the presence of vegetation, and thus to gain new insights into flow-vegetation interactions, in a high-curvature meander wave; and (ii) to explore the influence of vegetation on the bed shear stress distribution along the meander wave.

The paper is organized as follows: Section 2 describes the experimental apparatus and summarizes results presented in previous works (Termini, 2009; Termini and Piraino, 2011) and performed in the same meandering flume as that considered in this work; Section 3 presents the experimental results; finally, conclusions are drawn in Section 4.

2. Material and methods

2.1. Experimental apparatus and data

Experiments were carried out in a laboratory flume at the Dipartimento di Ingegneria Civile, Ambientale, Aereospaziale, dei Materiali (DICAM), University of Palermo, Italy. The experimental apparatus was presented in details in previous works (Termini, 2004, 2009; Termini and Piraino, 2011). Thus, only essential information is reported here.

The centerline of the meandering flume follows the sine-generated curve (Langbein and Leopold, 1966) in agreement with the prevailing literature's approach (among others Whiting and Dietrich, 1993; Da Silva et al., 2006; Termini, 2009). The channel (see Fig. 1A) is characterized by a deflection angle at the inflection section of 110° (minimum radius of curvature at centreline $R_{min} = 0.97$ m); the channel is of constant width, $B = 50$ cm, and the banks are of Plexiglas strips. The bed was of quartz sand ($d_{50} = 0.65$ mm and geometric standard deviation $\sigma_g = 1.3$) and follows the equilibrium topography obtained at the end of a mobile-bed run (see details in Termini and Piraino, 2011) carried out with flow discharge $Q = 0.012$ m^3/s and initial conditions described in Table 2. This paper reports on an experiment labeled as run 1 in Termini and Piraino (2011) that is used as a reference experiment without vegetation (hereon indicated as *NV*-run) in the present work. This *NV*-run was conducted over the deformed-bed and under the same hydraulic conditions as the aforementioned mobile-bed run. After having covered the deformed-bed with real herbaceous (flexible) vegetation (*Festuca arundinacea*), another experiment (hereon indicated as *V*-run) was conducted with the same flow discharge as that of *NV*-run. Fig. 1B shows a sketch-view of the vegetated-bed. The bent vegetation height *kv* was about equal to 2.6 cm. A concentration of 200 stems/dm^2 was used. According to Carollo et al. (2002), the stem concentration was measured by counting the number of stems holding to five steel cylinders (internal diameter 4.5 cm).

During both runs, measurements of flow velocity components and water depth were carried out in sections selected along the channel. In this work, attention is restricted to sections included in channel reach A–E (see Fig. 1A), that is between two consecutive inflection sections. The velocity measures were carried out by using the Acoustic Doppler Velocity Profiler (DOP 2000, by Signal Processing s.a.), based on Doppler effect. This instrument consists of a probe that allows us to measure the instantaneous velocity profile along the probe direction. To collect the data used in the present work, three probes with emission frequency of 4 Mhz were used. The distance between the centre of adjacent sampling volumes was 0.75 mm. During the *NV*-run, each probe was oriented according to a direction inclined at a known angle α ($\pm 60°$) with respect to the horizontal direction, and the system of the three probes moved automatically in a transverse direction with a spatial step of 1.5 mm by means of a one-dimensional motion control system by MICOS s.r.l. (Termini and Piraino, 2011). During the *V*-run, the three probes (the first pointing in the vertical direction; the second and third sloping at angle α and pointing in the transversal direction and in the longitudinal direction, respectively) moved automatically by the help of the three-dimensional automatic position system that uses the language of LabView for control applications. The spacing of