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Turbulence anisotropy in a compound meandering channel with different submergence conditions

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ABSTRACT

The understanding of the physical processes related to flows on compound meandering channels is a challenge given their highly 3D and complex characteristics. Three-dimensional ADV measurements were made in three cross-sections on a 1:20 physical Froude model of a real reach in River Mero (A Coruña) for bankfull flow and flood conditions. General characteristics and processes within the flow are herein described and characterized, such as momentum and mass exchange between the main channel and the floodplains. Time-averaged velocities and Reynolds stresses are presented and discussed. The spatial distribution of turbulence in several positions along a meander bend is analyzed in this paper. The characterization of the turbulent field in these 3D complex flows highly depends on the used reference system, and the intense local variation of turbulence makes a global and fixed coordinate system of petty use. An independent technique, regardless the coordinate system of the measurements, is thus the best way to analyze these flows. The anisotropy invariants technique was used to analyze the evolution of the magnitude and nature of anisotropy along the meander. The degree and nature of anisotropy was identified, and their relation to flow structures, such as vortices in the contact between the main channel and the floodplains, was analyzed using the quadrant analysis technique.

1. Introduction

River management represents a challenge from an engineering, environmental and social point of view. In particular, floodplains are among the most productive and diverse ecosystems in the world due to the regular deposition of nutrient rich sediments [28]. The environmental value of these ecosystems is unquestionable given their high biodiversity and their role on water purification and on the fixation of soil and nutrients. Furthermore, floodplains can be seen as natural systems providing food availability and flood protection. The capacity to act as a natural protection against floods is conditioned and intrinsically related to the local hydrodynamics, erosion and sedimentation processes and to the global resistance of the river reach. Flow properties, more specifically related to turbulent phenomena, need a good physical understanding so engineers can address such important issues such as flood management, morphology evolution and spreading of pollutants in river flows [27]. The physical processes underlying the formation of meanders have been the subject of intensive and detailed research (i.e. [6,7,24]), although the theoretical developments taking into account compound meandering channels are still scarce.

Compound meanders usually appear in the final, low reaches of rivers. Their hydrodynamics are commonly characterized by the existence of two flow layers associated to the main channel and the floodplains. The floodplain flow plunges into the main channel along the inner margin of the bend and the water in the main channel is ejected towards the floodplain in the outer part of the curve [20]. Coherent vortices developed at the boundary between these two regions [18] enable momentum exchange and induce extra friction of turbulent nature [17]. Also, vertical vortices appear in the contact between main channel and floodplain [19]. Hence, the turbulent pattern is also characterized by a vertically two-layer structure around the main channel–floodplain interface, as stated by Carling et al. [4]. These turbulent processes produce changes in the morphology of the channel bed, such as dunes and bars [30] that modify the flow dynamics. Their magnitude and orientation are directly related to the flow resistance and sediment transport processes.

The flow in compound meandering channels is hence tridimensional, and reorientation occurs along vertical and transverse directions. Some authors have analyzed the hydrodynamics of

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curved channels [1,3,25] and straight compound channels [11,12]. However, the experimental studies focused on compound meandering morphologies are scarce [21,22] and refer to simplified sinusoidal channels. This work analyzes a river reach with real planform and transversal morphology, geometry features that add complexity to the flow.

This paper is focused on a real case of a compound meandering reach in River Mero (A Coruña), where natural bed irregularities and roughness heterogeneity add complexity to the hydrodynamic pattern. Laboratory measurements are performed intensively in key cross-sections of a physical scaled model of this river reach. The studied area is paradigmatic from a compound meandered channel flows and real features were introduced in the scale model. A scale model of a real case, although reduces the generalization of the research results, induces extra complexity which needs to be adequately tackled.

The shear stresses and turbulence patterns are analyzed in detail. The existence of turbulent structures with particular orientations may be related to hydrodynamic patterns, such as the preferred flow direction, the existence of vortices in the shear layer formed between different water masses or the presence of solid or hydrodynamic boundary conditions.

Reference frames based on the channel geometry may be too rigid to analyze flow features with this degree of re-orientation and tridimensionality. Other systems, related for example to the local flow velocity, can vary too much along the model [14]. To overcome these limitations, the technique of the anisotropy invariants proposed by Lumley and Newman [13] provides a methodology to analyze the turbulence which is irrespective of the reference system. It allows the characterization of its spatial distribution in terms of anisotropy degree and nature. Smalley et al. [23] applied this technique to velocity measured in near-wall turbulent boundary layers with different values of roughness and concluded. The only reported results of the application of this methodology to flow in complex morphologies are the presented by van Balen [26], applied to numerical results from simulations of the flow in sharp open-channel bends. Finally, the quadrant analysis technique is used here in order to link the anisotropy results to the existing hydrodynamic pattern.

The objective of this paper is to characterize the hydrodynamics and the turbulence pattern in a real compound meandering channel. This is accomplished by using the anisotropy invariants and the quadrant analysis techniques. The preliminary application of this methodology to previous results in some specific locations obtained in the same physical model can be found in Mera et al. [15].

2. Theoretical framework

A first description of the flows studied in this paper is made by computing and analyzing time-averaged velocities and Reynolds stresses. Standard Reynolds decomposition, followed by application of time-averaged operators, implies the appearance of Reynolds stresses (extra sinks) in the momentum conservation equations which are later shown and commented in this document.

By far less common on the analysis of fluvial flows is the use of the so-called Lumley triangle technique, which is thus hereinafter described in detail. This technique, proposed by Lumley and Newman [13], is based on the analysis of the anisotropy tensor b_{ij}, which is the result of decomposing the Reynolds stress tensor into an isotropic and a non-isotropic term:

$$b_{ij} = \frac{\overline{v'_i v'_j}}{2 \cdot k} - \frac{\delta_{ij}}{3} \tag{1}$$

where v'_i is the instantaneous velocity fluctuation in the direction i, δ_{ij} is Kronecker's delta function and k is the turbulent kinetic energy of the flow defined as

$$k = \frac{1}{2}\left(\overline{v'^2_1} + \overline{v'^2_2} + \overline{v'^2_3}\right) \tag{2}$$

Lumley's theory is based on the analysis of the anisotropy tensoŕs invariants. b_{ij} has two non-null independent invariants, which are [5,13]

$$II = -b_{ij}b_{ji} \tag{3}$$

$$III = b_{ik}b_{kj}b_{ji} \tag{4}$$

Plotting III against $-II$, the domain of both invariants is reduced to the interior of a curved triangle, as shown in Fig. 1. The limits of this triangle define several characteristic states of the turbulence. The origin of the graph ($-II = 0$, $III = 0$) corresponds to 3D isotropic turbulence, where the three normal stresses are equal. The transition from 3D to 2D and/or to 1D turbulence is delimitated by two characteristic types of turbulent structures: pancake-shaped turbulence corresponding to a situation where two of the fluctuation components are equally distributed and with considerably higher amplitude than the third; and cigar-shaped structures where two of the turbulence components, and hence normal stresses values, are similar with the third component substantially higher. These two types of structures of turbulence can be interpreted as transition states, the former from 3D to 2D turbulence – if the lowest component vanishes – and the latter from 3D to 1D turbulence – if the cigar-shaped structure is extremely stirred and becomes a line. The upper boundary and vertex correspond to isotropic 2D and 1D turbulence, respectively, and the areas far and within from the mentioned limits represent general tridimensional turbulent conditions. Any turbulence state must be within the limits of the Lumley plots, and it can be said that $-II$ represents the degree of anisotropy, while III indicates its nature. Another variable evaluating the flow anisotropy is the parameter $J = 1–9(0.5II–III)$ proposed by Jovanović [10], which indicates a two-component turbulence when it is close to zero and isotropic turbulence if $J = 1$.

3. Materials and methods

This work makes use of a physical scale model of a real meander in river Mero (Cambre, NW of Spain, see location and details in Fig. 2). The reach herein analyzed consists of two consecutive low-radius bends contained by protection embankments in both margins. Main channel width ranges from 12 to 14 m, while its mean depth is approximately 2.5 m and its longitudinal slope is 0.0015. Floodplains of the river reach under analysis are commonly flooded to when a compound meandered flow happens. The roughness of the reach is defined by two characteristic areas, corresponding to the main channel and the vegetated floodplains.

The results presented in this work are based in the measurements carried out in a physical model of the described meander

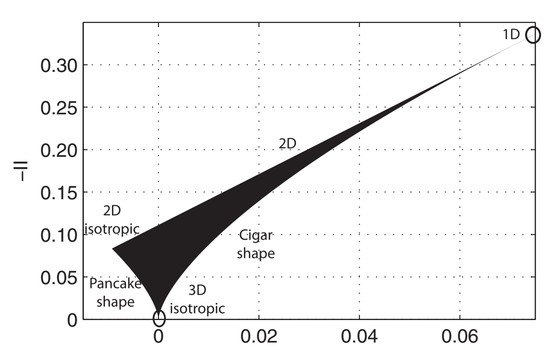

Fig. 1. Lumley-triangle, adapted from Lumley and Newman [13].