Available online at www.sciencedirect.com

SCIENCE DIRECT®

Advances in Water Resources 28 (2005) 939–949

Advances in Water Resources

www.elsevier.com/locate/advwatres

Wind effect in turbulence parametrization

M. Colombini *, A. Stocchino

Dipartimento di Ingegneria Ambientale, Università di Genova, Italy

Received 29 April 2004; received in revised form 26 January 2005; accepted 9 February 2005
Available online 10 May 2005

Abstract

The action of wind blowing over a closed basin ultimately results in a steady shear-induced circulation pattern and in a leeward rising of the free surface—and a corresponding windward lowering—known as wind set-up. If the horizontal dimensions of the basin are large with respect to the average flow depth, the occurrence of local quasi-equilibrium conditions can be expected, i.e. the flow can be assumed to be locally driven only by the wind stress and by the opposing free surface gradient due to set-up. This wind-induced flow configuration shows a strong similarity with turbulent Couette–Poiseuille flow, the one dimensional flow between parallel plates generated by the simultaneous action of a constant pressure gradient and of the shear induced by the relative motion of the plates. A two-equation turbulence closure is then employed to perform a numerical study of turbulent Couette–Poiseuille flows for different values of the ratio of the shear stresses at the two walls. The resulting eddy viscosity vertical distributions are analyzed in order to devise analytical profiles of eddy viscosity that account for the effect of wind. The results of this study, beside allowing for a physical insight on the turbulence process of this class of flows, will allow for a more accurate description of the wind effect to be included in the formulation of quasi-3D and 3D models of lagoon hydrodynamics.

Keywords: Wind-driven flow; Couette–Poiseuille flows; Eddy viscosity; Shallow water; Two-equation turbulence closure

1. Introduction

Water quality modelling in natural or artificial water bodies like lakes, reservoir, estuaries and coastal zone requires the prior knowledge of the circulation flow. The transport of a passive or active pollutant can be described with sufficient accuracy if the hydrodynamics is known. The simulation of more complex phenomena, like sediment transport, involves the evaluation of the shear stress acting on the bed, which in turn is able to modify the shape of the domain in which the flow itself evolves.

Mathematical models based on the shallow-water approximation have quite a long tradition for the solution of this class of flows, due to the sharp separation between the vertical and the horizontal spatial scales that allows for solving the problem in terms of the depth-averaged horizontal velocity components, disregarding the role of the vertical velocity.

However, the knowledge of the vertical velocity and, more important, of the vertical profiles of the horizontal velocities has soon become a pressing need for the study of some practical engineering problems, like the oil-spill movement or the transport of a passive contaminant or the suspended sediment dynamics, which strongly depend on the vertical structure of the flow. Apparently the only answer to these problem is the solution of the full set of the 3D Reynolds equation, a task that however, even nowadays, can be prohibitive in terms of computer time.

In an attempt to reconcile the requirement of a more detailed solution with the slenderness and robustness of 2D models, a new generation of numerical models,

---

* Corresponding author. Address: DIAM, Via Montallegro 1, 16145 Genova, Italy. Fax: +39 10353 2478.
E-mail addresses: col@diam.unige.it (M. Colombini), jorma@diam.unige.it (A. Stocchino).

0309-1708/$ - see front matter © 2005 Elsevier Ltd. All rights reserved.
doi:10.1016/j.advwatres.2005.03.002

which can be identified as a whole as quasi-3D (Q3D), appeared in the late 80s [10,23a]. These models are characterized by a primary module solving the 2D shallow water equation coupled to a secondary module that is fed with the local values of the averaged horizontal velocities and flow depth and, through the identification of a suitable vertical structure of the flow, allows for the determination of some quantities (namely the bed shear stress), which are then fed back to the main module [8]. In a way, even standard 2D models can be thought as Q3D models, since the usual choice of modelling the bed shear stress as proportional to the square of the depth-average velocity through a friction Chezy coefficient is consistent with the assumption of a vertical logarithmic profile of the velocity and of a parabolic vertical structure of the eddy viscosity.

A realistic 3D flow can thus be obtained at a much less computational cost with respect to conventional 3D models. Of course, simplifying assumptions have to be made about the vertical structure of the flow, but the two dimensional imprint of this class of flows is retained. Moreover, a rigorous derivation of the shallow water equations shows that, in the process of averaging the 3D Reynolds equations, new "stresses" appear that require a suitable closure hypothesis to be modelled. In fact, similarly to the appearance of Reynolds stresses in the averaging of Navier–Stokes equation, the nonlinearity of the advective terms produces the so-called "dispersive stresses" that are related to the vertical nonuniformity of the horizontal velocities. Dispersive stresses, together with the depth-averaged values of the Reynolds stresses acting on vertical planes, are usually disregarded in conventional 2D models, or, at most, they are modelled as a whole introducing a diffusive 'viscous' term. However, the presence of such a term is justified more on the ground of numerical instability control than on a physical basis. The a priori knowledge of the vertical profiles of velocity and eddy viscosity allows for a rigorous derivation of all the unknown stresses in the shallow water equations [5].

Many Q3D models have been formulated for the case of wind-driven circulation flow. Wind and tide are the main causes of circulation flow in small basins but while 2D models proved successful in the modelling of tide-generated flow, the numerical predictions of wind-induced circulation pattern and of the so-called set-up were not as satisfactory [15].

The success of standard 2D models in modelling tide-generated flow can be ascribed to the fact that in this case a condition of local equilibrium holds such that the logarithmic vertical profile of the horizontal velocities can be confused with its depth-averaged value and the bed shear stress quadratically depends on the depth-averaged velocity through a friction coefficient. The actual occurrence of this local equilibrium is ensured by the slow variation of all the quantities (and in particular of the free surface slope) in the horizontal directions when scaled with the local flow depth.

However, both theoretical analyses and field or laboratory measurements show that the way velocity profiles develop for the case of tidal and wind-induced circulation is remarkably different. In particular, flow reversal can be often detected along the vertical in the latter. If this is the case, the displacement of the local velocity with respect to its depth-averaged value can be large and dispersive stresses cannot be assumed to be negligible. Moreover, the quadratic dependence of the bed shear stress from the depth-averaged velocity through a friction coefficient, widely adopted in the simulation of shallow flows in the absence of wind, cannot be simply generalized to wind-driven flows.

Purpose of the present paper is to investigate the vertical structure of wind-driven flows and in particular to propose a new analytical relationship for the vertical profile of the eddy viscosity aiming at the formulation of a new quasi-3D model for flow generated by both wind and tide. As for the case of tide-generated flow, local equilibrium condition are sought and analyzed in terms of self-similar vertical profiles of eddy viscosity and velocity.

The next section is therefore devoted to the analysis of local equilibrium condition and of the analogy between these equilibrium profiles and flows of the Couette–Poiseuille (C–P) family. Then, in Section 3 the problem of turbulent C–P flow is formulated and the turbulent closure model adopted is presented. A comparison of the numerical results with the experimental data on C–P flows of El Telbany and Reynolds [4] is attempted in the following section, showing that the numerical model perform well for this flow configuration. Then, in Section 5 a discussion of the results in terms of eddy viscosity profiles is presented, together with some proposals for an analytical interpretation of the numerical results.

2. The Couette–Poiseuille flow analogy

In our search of self-similar profiles we focus on unidimensional wind-driven flows slowly varying in the longitudinal direction. A typical example is the so-called countercurrent flow, the kind of flow that shows up in a long and narrow (with respect to flow depth) closed channel where a constant wind is blown in the longitudinal direction.

This simple flow reproduces many features of 2D wind-driven flows, namely the formation of a set-up of the free surface in the wind direction, and it has been therefore widely studied both experimentally [2,7,20] and theoretically [10,19,23a,23b].

Nevertheless, for the purpose of identifying self-similar configurations, the countercurrent flow can be an