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Impact of topographic obstacles on the discharge distribution in open-channel bifurcations

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SUMMARY

When simulating urban floods, most approaches have to simplify the topography of the city and cannot afford to include the obstacles located in the streets such as bus stops, trees and parked cars. The aim of the present paper is to investigate the error made when neglecting such singularities in a simple flooded 3-branch crossroad configuration with a specific concern regarding the error in discharge distribution to the downstream streets. Experimentally, the discharge distribution for 14 flows in which nine obstacles occupying 1/6 of the flow section are introduced one after the other is measured using electromagnetic flow-meters. The velocity field for one given flow is obtained using horizontal-PIV. Additionally, all these flows are computed using a CFD methodology. It appears that the modification in discharge distribution is mostly related to the location of the obstacles with regards to the intersection, the location of the separating interface and is strongly impacted by the Froude number of the inflow while the influence of the normalized water depth remains very limited. Overall, the change in discharge distribution induced by the obstacles remains lower than 15% of the inflow discharge even for high Froude number flows.

1. Introduction

When an urban flood occurs, streets generally carry most of the flow from the upstream to downstream part of the city, especially when the area is densely urbanized (Mignot et al., 2006). Flow in the streets is mostly 1D with mean velocities parallel to the building façades. However, in crossroads several flows collide and/or separate and the flow pattern becomes complex (see Mignot et al., 2008) especially when artificial topographies create additional flow structures such as wakes, recirculation zones and secondary flows. Bazin et al. (2012) have studied the impact of obstacles on a junction flow where two subcritical flows collide. They observed that this impact depends on the location of the obstacles and may (i) strongly modify the local velocity distribution and (ii) the extensions of a recirculation zone. Moreover, the authors observed that if an obstacle is located within a recirculation zone, the impact of the obstacle is strongly damped.

Within street bifurcations, with a single inflow separating into two outflows, artificial topographies can also affect the flow distribution reaching the downstream streets. The aim of the present paper is thus to investigate (i) the impact of obstacles on the local flow characteristics in bifurcation flows and (ii) the consequences of such modifications of the flow pattern on the modification of flow distribution to the downstream branches. The selected artificial topographies are squared emerging obstacles which would represent trees, bus-stop or any other impervious urban furniture located near crossroads.

The general pattern of a steady subcritical 3-branch bifurcation without obstacle is described by Neary et al. (1999). A three-dimensional recirculating region develops in the lateral branch and secondary flows appear in both outlets. The principal challenge in such separating flow lies in the prediction of flow distribution from the incoming towards both outgoing flows. A review of analytical models developed to access such prediction is given by Rivière et al. (2007). The models are based on the momentum conservation law (see for instance Ramamurthy et al., 1990), but Rivière et al. (2006) showed that this balance alone does not permit to calculate the flow distribution, and that additional equations must be introduced. These authors proposed an improved relationship based on (i) the momentum conservation law from Ramamurthy et al. (1990), (ii) suitable stage-discharge relationships for the downstream controls in the outflow channels and (iii) an empirical correlation obtained through experimental data. This approach

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proved to accurately predict the flow distribution in three-branch bifurcations in ideal conditions: 90° angle, smooth walls and identical horizontal rectangular sections in each branch. Riviere et al. (2011) then generalized the results to 4-branch intersections.

Nevertheless, when singularities are introduced near or in the bifurcation, the flow pattern can be strongly affected and this analytical model obviously does not apply. The question raised by the present paper is to what extent an introduction of single or pairs of obstacles in the vicinity of the intersection affects the discharge distribution. Nine configurations of simplified square-shaped obstacles of typical size equal to 1/6 of the channel width are tested here. Their impact on the flow pattern and the downstream flow rates is analyzed for 14 flow configurations divided in three series.

For practical reasons, velocity field for all flow configurations with all obstacles could not be measured experimentally. The selected approach is rather based on a mix of experimental measurements and 3D calculations. After verification of their accuracy, these calculations are considered reliable enough to support the experimental investigation. In the first and second sections we describe the experimental and numerical methodologies respectively along with the selected flow and obstacle configurations. In a third section, we describe the impact of the obstacles on the flow pattern and discharge distribution and finally discuss the impact of the base flow (before introducing obstacles) characteristics on such results.

2. Experimental methodology

2.1. Experimental set-up

The experiments were performed in the channel intersection facility at the Laboratoire de Mécanique des Fluides et d'Acoustique (LMFA) at the University of Lyon (Insa-Lyon, France). The facility consists of three horizontal glass channels 2 m long and $b = 0.3$ m wide each. The channels intersect at 90° with one upstream branch (with the flow rate Q_u), one downstream branch (flow rate Q_d) aligned with the upstream one and one lateral branch (flow rate Q_b). The upstream branch is connected to a large upstream storage tank where the flow is straightened and stabilized by passing through a honeycomb. The flow separates in the bifurcation and is finally collected by the downstream and lateral tanks. The lateral tank is connected to the downstream tank and the lateral discharge Q_b is measured using an electromagnetic flow-meter (see Fig. 1). When pumped from the downstream tank to the upstream tank, the upstream flow-rate Q_u is measured using a second electromagnetic flow-meter. In order to control the flow conditions, PVC channels (length 60 cm) fitted with sharp crested weirs are added to the ends of the two exit channels so that $L_d = L_b = 2.6$ m while $L_u = 2$ m. A more detailed description of the experimental set-up can be found in (Riviere et al., 2011).

For each flow configuration, the three boundary conditions to be set are: the upstream flow rate Q_u and the height of the sharp crest weirs C_d (for the downstream branch) and C_b (for the lateral branch). The stage discharge relationship (h_n, C_n, Q_n, $n = b$ or d) is calibrated experimentally for each weir: h_b and h_d are measured using a digital point gauge at a length equal to two channel width upstream from the weirs. Similarly, the upstream water depth h_u used to characterize the upstream velocity and Froude number is measured one channel width upstream from the entry section of the bifurcation (see Fig. 1). A point gauge is used to measure backwater curves in the main and the branch channel for most flow configurations.

Upstream water depth h_u ranges from 25 to 71 mm and discharge Q_u from 1.6 to 7.0 L/s. The corresponding Reynolds number ranges between 18,000 and 65,000 and the corresponding Froude number from 0.23 to 0.69. Moreover, the roughness height k_s was measured using a roughness meter which revealed that the maximum roughness is smaller than 1 μm and the average roughness smaller than 0.1 μm. Given the hydraulic diameter, ranging from $D_h = 0.08$ m to 0.2 m, the maximum relative roughness k_s/D_h is estimated to about 10^{-5}, corresponding to a hydraulically smooth regime in the Moody diagram.

2.2. Dimensional analysis and flow series

Dimensional analysis is applied to the present flow configuration. The 13 variables to be included in the dimensional analysis of discharge distribution law without obstacle are the channel width b and roughness k_s, the acceleration due to gravity g, the three flow rates and associated water depths Q_u and h_u, Q_b and h_b, Q_d and h_d, the two weir crest heights C_d and C_b and finally the fluid density ρ and dynamic viscosity μ.

Five available straightforward equations are:

– The mass conservation, which yields $Q_u = Q_b + Q_d$, permitting to remove the Q_d parameter.

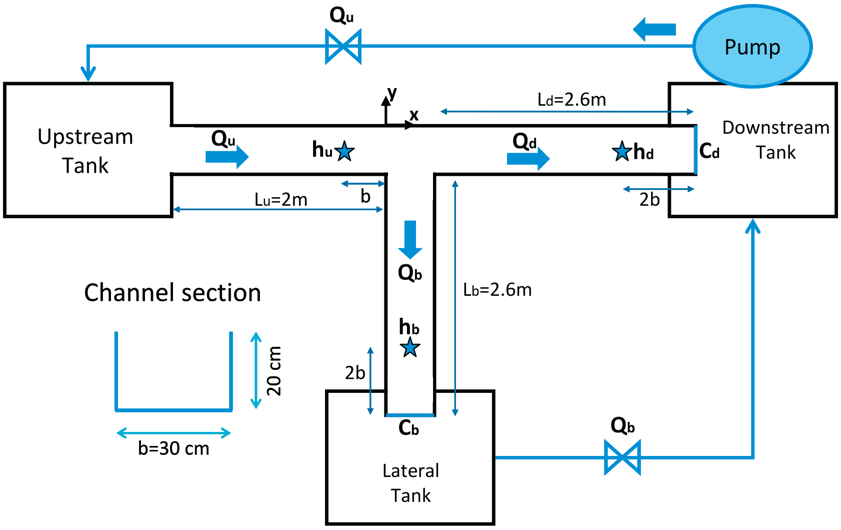

Fig. 1. Scheme of the experimental set-up.