Analysis of flow characteristics in a compound channel: comparison between experimental data and 1D numerical simulations

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Abstract

The common configuration of rivers is a main channel flanked by floodplains. During flood events, the main channel is not enough to discharge the flow and the floodplains are submerged. The momentum transfer due to the difference of the velocities between the sub-sections generates a complex 3D flow structure. For the study of the influence of this structure in flow modeling, measurements of the velocities in a prismatic compound channel have been made. Seven 1D methods to compute the sub-section and total discharges were applied. Comparisons between experimental data and modeling reveal good agreement when simple models that indirectly take into account the momentum transfer are applied.

Introduction

The present paper presents a study of the flow in a compound channel. This configuration has extreme importance because in many cases the main channel of the rivers is not enough to discharge the total flow, mainly during flood events. In these cases, the flow inundates the surrounding fields, called the floodplains. Therefore, the common configuration of the rivers during floods is a compound channel flow, where one can observe the interaction between the main channel and the floodplain flows.

The traditional method to study the flood inundation is based in an old approach that simply divides the total cross section with vertical divisions in the interface of the main channel and the floodplains. Besides that, new

1D approaches can take into account the interaction between the flows in each subsection.

This paper intends to improve the knowledge of the flow in compound channels. So, experimental results were compared with 1D modelling of the flow in this type of channel. The data showed in the present paper corresponds to an upgrade of the work presented in [1].

Theoretical background

The water depths in a single channel are accurately estimated since the equation proposed by Antoine de Chézy [2]. This is not the case for compound channels, because of the velocity gradient between the flows in the main channel and in the floodplains, where the water depth is lower and, in many cases, the roughness is higher. This gradient generates a mixing layer in the interface which creates a 3D flow structure (*cf.* Fig. 1).

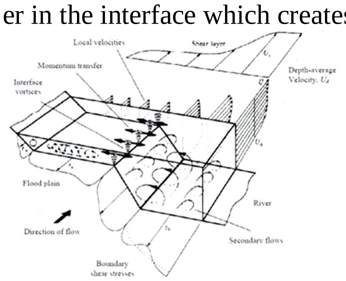

Fig. 1. Flow structure in a compound channel [3].

The discharge capacity of the main channel reduces and the floodplain capacity increases, generating a global loss in the total discharge capacity.

The 2D and 3D methods include some of the characteristics of compound channels. In engineering, due to the amount of data required and the processing time, 1D methods are often preferred. Still, the momentum transfer should be taken into account in 1D modeling [4].

Since [5] presented the first evidences of the flow characteristics in compound channels that there have been attempts to modelling it. [6] referred the difficulty of the developed formulas to be applied universally as, in many cases, they had been set based on a reduced amount of data.

Modelling the flow in a compound channel as a simple channel by applying a formula of resistance to flow does not take into account the subsection velocity differences. [7] suggested the division of the channel in subsections where velocity and roughness could be considered as uniform. This method, called the Divided Channel Method, is still widely used in commercial models as HEC-RAS [8], ISIS [9], SOBEK and Mike 11 [10].

As pointed out in [9] this treatment of a compound channel assumes that there is no interaction between the subdivided areas despite the existence of mean velocity discontinuities at the assumed internal boundaries. Therefore the simple division of the channel in subsections is not appropriate for modelling the discharge in compound channels [6].

Different methods had been proposed with the attempt to model the interaction processes that occur in this type of flows, including the mass and momentum transfer.

According to [9], these methods can be divided into 5 groups: i) methods that change the sub-area wetted perimeters; ii) methods that made discharge adjustments (with the experimental data, for example); iii) methods that include apparent shear stresses on the sub-area division lines; iv) methods where the lines are located at zero shear stress; v) methods that combine different divisions of the channel.

In this work, seven methods were used to modeling the flow in the compound channel. Its computation procedures are presented in the Annex 1. Firstly, we used the two traditional methods called Single Channel Method (SCM) and Divided Channel Method (DCM).

From the groups presented before, we used the Coherence Method (CM) and the Debord Method (DM) from the group ii), the Exchange Discharge Method (EDM) and the Interacting Divided Channel Method (IDCM) from the group iii) and the Weighted Divided Channel Method (WDCM) from the group v).

Experimental component

The channel used in the present work is located in the Fluvial Hydraulics Pavilion of the National Laboratory for Civil Engineering, in Lisbon. The channel has about 10 m length and 2 m wide. The slope of the channel is $1,1 \times 10^{-3}$ m/m. The cross-section is symmetrical and it is composed by a 0.4 m wide and 0.1 m high main channel, flanked by two floodplains 0.7 m wide. The transition between the subsections is made by banks with 45º slope. The channel bottom is made of polished concrete. Fig. 2 shows a photograph of the channel and a schematic cross-section.

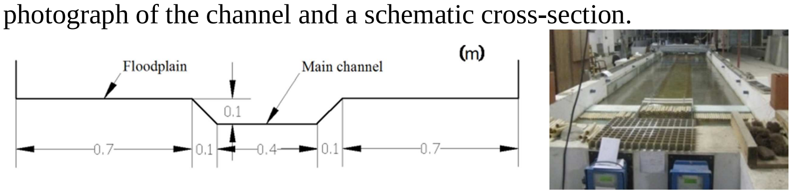

Fig. 2. Compound channel.

Following the recommendations of [12], separate inlets were available in order to avoid the mass transfer between subsections. The discharges for the main channel and floodplains were monitored by two flowmeters and controlled by two different valves. Honeycomb diffusers and polystyrene plates were located at the beginning of the flume to stabilize the flow.

The flow regime is subcritical and the water depths were controlled by three horizontal axis tailgates located at the downstream end of the channel. It was possible to define two different water levels, one for the main channel and the other for the floodplains.

Water levels were measured with three hydrometers, two of them fixed at the upstream and downstream sections of the flume and the other is located in a movable trolley.Velocity measurements were made using a Pitot tube with a 3.2 mm diameter. The difference between static and dynamic pressures was measured with a differential pressure transducer.

Experimental procedure

For the presented compound channel, the distribution of the discharge between the main channel and the floodplains was not known. The procedure used to obtain an uniforme flow starts with the distribution given by the Weighted Divided Channel Method [13]. With this first discharge distribution, the water levels were controled with the tailgates in order to achieve an uniform water depth along the channel. Reached the uniformity, the discharge distribution at the downstream section is compared with the upstream distribution. If the upstream and downstream distributions match unless 0.1 l/s, the uniform regime has been achieved. Otherwise the measured discharge distribution is imposed upstream and the procedure is repeted (normally 2 or 3 iterations).

The velocities were measured in 45 verticals with 5 or 6 points each for the floodplains and main channel, respectively (*cf.* Fig. 3).

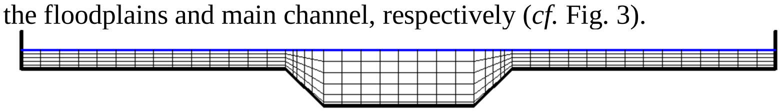

Fig. 3. Mesh for the velocity measurements.

For each vertical, the depth-averaged velocity was computed from the velocity measurements in 5 or 6 points using the following equations.

$$U_{fp}^{ave} = \left(7{,}5 \times U_{bot} + 15 \times U_{20\%} + 20 \times U_{40\%} + 20 \times U_{60\%} + 30 \times U_{80\%}\right)/100 \qquad (1)$$

$$U_{mc}^{ave} = \begin{pmatrix} 2{,}5 \times U_{bot} + 10 \times U_{10\%} + 15 \times U_{20\%} + 20 \times U_{40\%} + \\ + 20 \times U_{60\%} + 30 \times U_{80\%} \end{pmatrix}/100 \qquad (2)$$

In which $U_{\#\%}$ stands for velocity measured at a height equal to #% of the water depth; U^{ave} for average velocity; *"mc"* for main channel; *"fp"* for floodplains and *"bot"* for bottom. The eqs. (1) and (2) were obtained using measurements of vertical profiles of velocity with 18 points. For these profiles the average velocity was calculated and compared with several equations assuming the knowledgement of the velocity at these 5 or 6 points. The best results were obtained with these equations.

Analysis of results

Results

Four different tests have been made corresponding to relative depth, h_r (relationship between water depths in the floodplain and in the main channel) approximately equal to 0.1; 0.15; 0.2 and 0.3. The discharge distributions are shown in Table 1. The average velocity distributions are presented in Fig. 4.

Table 1. Results of the discharge distributions.

Relative depth, h_r (-)	Flooplains discharge (l/s)	Main channel discharge (l/s)	Total discharge (l/s)
0.1	3.2	34.5	37.7
0.15	6.2	38.6	44.8
0.2	11.2	42.2	53.4
0.3	27.4	53.3	80.7

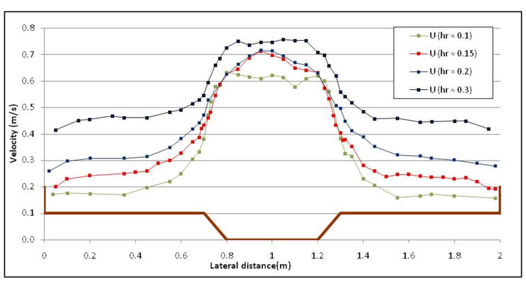

Fig. 4. Velocity distribution in the cross section.

Comparison between experimental data and 1D modeling

The results from the 1D methods presented in the Annex 1 were compared with the results from the experimental tests. This comparison covered the total discharge and the sub-section discharges. Indeed, as refereed by [9], it is essential to perform the analysis for each subsection. The assessment of the accuracy by each method is based on the calculation errors computed by Eqs. (3) to (5).

$$\text{Error}_{mc}\ (\%) = 100 \times \left(Q_{mc}^{Measured} - Q_{mc}^{Calculated} \right) / Q_{mc}^{Measured} \quad (3)$$

$$\text{Error}_{fp}\ (\%) = 100 \times \left(Q_{fp}^{Measured} - Q_{fp}^{Calculated} \right) / Q_{fp}^{Measured} \quad (4)$$

$$\text{Error}_{Total}\ (\%) = 100 \times \left(Q_{Total}^{Measured} - Q_{Total}^{Calculated} \right) / Q_{Total}^{Measured} \quad (5)$$

In which $Q^{Measured}$ stands for measured discharge and $Q^{calculated}$ for the discharge calculated by one 1D method.

In Table 2 the errors obtained for each subsection and for the entire channel by each method are presented. The results of the Table 2 are presented graphically in Fig. 5.

Table 2. Errors obtained by applying the different 1D methods.

Method	SCM	DCM	CH	DM	EDM	IDCM	WDCM
Relative depth (-)	Errors in the main channel discharge evaluation (%)						
0.10	38.1	-10.6	-2.9	-5.7	13.2	-3.1	-2.0
0.15	36.3	-8.2	1.1	-0.7	15.8	1.5	2.4
0.20	31.6	-10.4	0.7	-0.3	13.9	1.8	2.5
0.30	22.3	-13.9	-2.0	-2.5	9.1	2.3	2.0
Relative depth (-)	Errors in the floodplain discharge evaluation (%)						
0.10	-94.6	6.3	-1.2	-6.8	-42.7	-12.9	-6.3
0.15	-58.2	11.1	5.2	-1.9	-25.4	-6.2	-0.8
0.20	-34.4	14.8	10.1	2.7	-12.8	-0.8	3.4
0.30	-19.1	11.2	11.2	2.9	-7.3	-2.6	-0.7
Relative depth (-)	Errors in the total discharge evaluation (%)						
0.10	26.8	-9.2	-2.8	-5.8	8.5	-3.9	-2.3
0.15	23.2	-5.5	1.6	-0.9	10.1	0.4	2.0
0.20	17.8	-5.1	2.7	0.3	8.3	1.2	2.6
0.30	8.2	-5.4	2.3	-0.7	3.5	0.6	1.1

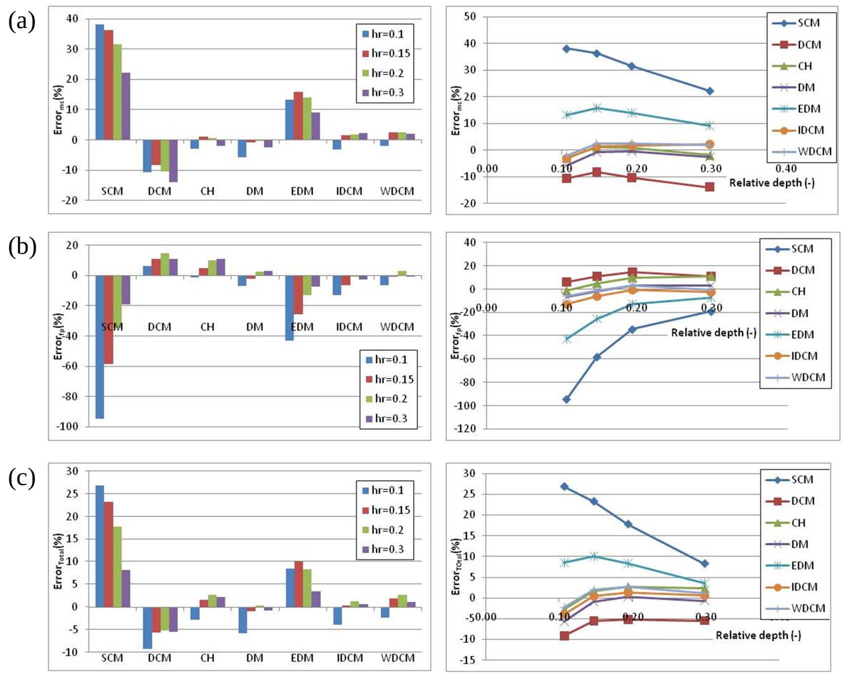

Fig. 5. Error in the calculation of the discharges (a) Main channel; (b) Floodplain and (c) Total.

From these results, it can be seen that the SCM, assuming an average velocity for whole cross section tends to underestimate the total discharge. The opposite happens with the results obtained with DCM. The simple division of the channel, without considering the interaction between the subsections, leads to an over estimation around 10%. The overestimation occurs also for the calculation of the discharge in the main channel and the opposite in the computation of the discharge in the floodplains. This result is due to the non consideration of the deceleration that the flow of floodplains causes in the main channel flow and vice versa.

With the exception of EDM, all proposed methods improve the results obtained with DCM for total and sub-section discharges. For the calculation of the total discharge, the method with better performance is the Coherence Method, with errors below 2%.

The WDCM is the method that shows a better overall performance presenting errors around 2% for the majority of the situations and for the three flow discharges studied.

As the water depth becomes higher, the results of almost all methods improve, revealing a gradual reduction of the interaction between subsections, i.e. a reduction of the effect of large-scale vortices in the momentum transfer.

Conclusions and recommendations

In this paper an experimental study of the flow in a compound channel was presented. The collected data was used to evaluate the performance of several 1D methods available in the literature.

The modelling of the flow was done using 1D methods and the results were compared with the experimental data. The results point out that when the flow overflows the main channel and inundates the floodplains, the effects of the interaction between the main channel and floodplains should be taken into account. Errors when one uses a simple division of the channel are up about 10%. With a greater range of data, [14] points to average errors of around 20%. The errors in the flow distribution between main channel and floodplains are higher and show the need to examine individually the subsection discharge. A relevant aspect is the fact that DCM, commonly used in commercial models, overestimates the discharge for a given water depth, which goes in the opposite direction of safety. Alternative methods to DCM take into account the interaction between the discharges in each subsection namely the momentum transfer and improve the results of both the calculation of the total and sub-section discharges. For performed tests, the CH and the WDCM showed the better performance. For this reason and because they are simple to implement, their use in engineering case studies should be assessed when the channel or river has a compound configuration.

Acknowledgments

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ANNEX 1. 1D METHODS

Single Channel Method (SCM)

This method does not divide the channel and considerer it as a single channel assuming an average velocity for the whole channel. Using a global roughness coefficient, this method computes the total flow through a flow resistance equation (*e.g.* Manning-Strickler).

$$Q = K\,R^{2/3} A\,S_0^{1/2} \tag{6}$$

In which Q stands for the discharge; K for the roughness coefficient; R for the hydraulic radius; A for the cross section area and S_0 for the slope of the channel.

Divided Channel Method (DCM)

This method proposes the division of the channel in three sub-sections, namely the main channel and the lateral floodplains. The typical division is through vertical lines, where the total flow is given by the sum of sub-section discharges (*cf.* Eq. 7).

$$Q = \sum_i Q_i = \sum_i K_i R_i^{2/3} A_i S_0^{1/2} \tag{7}$$

where the index i indicates each subsection.

Coherence Method (CM)

The Coherence Method was developed by [15] and it improves the results of the DCM, making it the most appropriate for compound channel flows. This method uses two coefficients for the adjustment of the sub-section discharges. The coherence (COH) is the relationship between the discharge given by the SCM and the DCM (*cf.* Eq. 8).

$$COH = \frac{Q^{SCM}}{Q^{DCM}} \tag{8}$$

The closer to 1 is this coefficient, the more appropriate is to treat the channel as a single one. When this coefficient is significantly less than 1 it is necessary to apply a different coefficient, called DISADF in order to correct the discharge in each subsection. An analysis of the experimental results has split the flow in 4 regions according to the relative depth of each one (*cf.* Fig. 8).

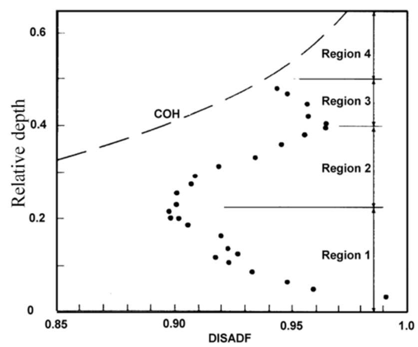

Fig. 8. DISADF coefficient.

[15] present the formulas for computing the DISADF in each flow region. The discharge is then obtained by the following equations.

$$Q = Q^{DCM} - DISDEF \quad \text{For flow region 1} \tag{9}$$

$$Q = Q^{DCM} \times DISADF \quad \text{For flow region 2 to 4} \tag{10}$$

Where DISDEF is a factor called discharge deficit which calculation procedure can be found, for example, in [16].

Debord Method (DM)

The Debord Method (Formulation simplifiée Debord in the original french designation) proposes the correction of the results obtained by the DCM [17]. The basis of the correction is a set of experimental tests conducted with 16 different configurations. In those tests, the flow in the compound channel was compared with the flow in the independent sections (vertical separations were placed in the interface). [17] concluded that the relationship between these flows depends mainly on the relationship between the roughnesses of each subsection. This method models the discharge in each subsection with the Eqs. (11) and (12).

$$Q_{mc} = \varphi K_{mc} R_{mc}^{2/3} A_{mc} S_0^{1/2} \tag{11}$$

$$Q_{fp} = \sqrt{1 + \frac{A_{mc}}{A_{fp}}\left(1 - \varphi^2\right)}\, K_{fp} R_{fp}^{2/3} A_{fp} S_0^{1/2} \tag{12}$$

In which φ stands for the experimentally coefficient given by:

$$\varphi = \varphi_0 = 0{,}9\left(K_{mc}/K_{fp}\right)^{1/6} \quad \text{for } \mathrm{R_{lc}/R_{lp}} > 0{,}3 \tag{13}$$

$$\varphi = \frac{1}{2}\left[\left(1-\varphi_0\right)\cos\left(\frac{\pi\; R_{fp}/R_{mc}}{0{,}3}\right) + \left(1+\varphi_0\right)\right] \quad \text{for } 0 < \mathrm{R_{lc}/R_{lp}} \le 0{,}3 \tag{14}$$

Exchange Discharge Method (EDM)

This method is based on the concept of the apparent shear stress. The basis of this method is the integration in the cross section of the equation of momentum conservation. After some simplifications and mathematical operations this equation could be written for the main channel and for the floodplains as showed in Eq. 15 and 16.

$$\rho \cdot g \cdot A_{mc} \cdot S_o + \left(h_{\text{int},rig} \cdot \tau_{\text{int},rig} + h_{\text{int},lef} \cdot \tau_{\text{int},lef}\right) - \tau_o \cdot P_{mc} = 0 \qquad \text{Main channel} \qquad (15)$$

$$\rho \cdot g \cdot A_{fp} \cdot S_o - h_{\text{int}} \cdot \tau_{\text{int}} - \tau_o \cdot P_{fp} = 0 \qquad \text{Floodplains} \qquad (16)$$

In which ρ stands for the density of water; g acceleration due to gravity; h_{int} – interface height; τ_{int} – Boundary shear stress; τ_0 – Apparent shear stress; P – wet perimeter; "rig" – right; "lef" – left.

Modelling the boundary shear stress it is only necessary to know the value of the apparent shear stress to calculate the rating curve of a compound channel.

EDM models the "momentum transfer due to turbulence" through a model similar to the mixing layer model [18], obtaining Eq. (17) for apparent shear stress.

$$\tau_{\text{int}} = \frac{1}{2}\psi\rho\left(U_{mc} - U_{fp}\right)^2 \qquad (17)$$

In which ψ stands for an experimental parameter and U stands for average velocity in a single subsection.

EDM also models the momentum transfer associated with the geometry (including enlarging or converging main channels), what is outside the scope of this work.

Interacting Divided Channel Method (IDCM)

This method was developed by [10] and it is also based in the apparent shear stress concept (Eq. 15 and 16). This method uses the formulation of [19] to model the momentum transfer in the interface, obtaining the Eq. (18).

$$\tau_{\text{int}} = \frac{1}{2}\gamma\rho\left(U_{mc}^2 - U_{fp}^2\right) \qquad (18)$$

In which γ corresponds to a coefficient, having been obtained from experimental results collected in literature ([10] suggest 0.02).

Weighted Divided Channel Method, WDCM

The Weighted Divided Channel Method was developed by [13] and it is based on the observation of the velocity distributions in the main channel and floodplains. This method consists in a correction of the DCM in order to integrate the effects caused by the momentum transfer by a weighting in the results of velocities obtained with vertical and horizontal divisions between the subsections. The equations for the main channel and floodplains are presented below.

$$U_{mc} = \xi U_{mc}^{DCM-V} + (1-\xi) U_{mc}^{DCM-H} \tag{19}$$

$$U_{fp} = \xi U_{fp}^{DCM-V} + (1-\xi) U_{fp}^{DCM-H} \tag{20}$$

In which *"DCM-V"* stands for the results of DCM with vertical divisions; *"DCM-H"* with horizontal divisions and ξ for the weighting coefficient for the WDCM (from the experiments of the authors for equal roughness of the subsections the value of this coefficient is 0.5).