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Energy losses in compound open channels

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ABSTRACT

This paper investigates energy losses in compound channel under non-uniform flow conditions. Using the first law of thermodynamics, the concepts of energy loss and head loss are first distinguished. They are found to be different within one sub-section (main channel or floodplain). Experimental measurements of the head within the main channel and the floodplain are then analyzed for geometries with constant or variable channel width. Results show that head loss differs from one sub-section to another: the classical 1D hypothesis of unique head loss gradient appears to be erroneous. Using a model that couple 1D momentum equations, called "Independent Sub-sections Method (ISM)", head losses are resolved. The relative weights of head losses related to bed friction, turbulent exchanges and mass transfers between sub-sections are estimated. It is shown that water level and the discharge distribution across the channel are influenced by turbulent exchanges for (a) developing flows in straight channels, but only when the flow tends to uniformity; (b) flows in skewed floodplains and symmetrical converging floodplains for small relative flow depth; (c) flows in symmetrical diverging floodplains for small and medium relative depth. Flow parameters are influenced by the momentum flux due to mass exchanges in all non-prismatic geometries for small and medium relative depth, while this flux is negligible for developing flows in straight geometry. The role of an explicit modeling of mass conservation between sub-sections is eventually investigated.

1. Introduction

For nearly four decades, studies on compound channel flow focused on the momentum exchange between the flow in the main channel and the flow in the floodplain, in case where the overall channel width is constant. The most investigated flow configuration was uniform flow in straight geometries. In particular, the shear layer between sub-sections, the secondary currents, the boundary shear stress and the apparent shear stress at the vertical interfaces between the main channel and the floodplain were depicted. The interaction between the flow in the main channel and the flow in the floodplain is investigated, e.g. by Knight and Demetriou [1]. Shiono and Knight [2] showed that three sources of energy losses coexist under uniform flow conditions: bed friction, momentum flux due to both turbulent exchange and secondary currents across the total cross-section. Three other flow configurations in non-prismatic geometry with constant overall channel width were also well investigated: flow in a compound channel with a diverging left-hand floodplain and a converging right-hand floodplain, usually called skewed flows [3–5], flow in meandering two-stage channels [6] or flow in a doubly meandering compound channel [7]. These former geometries highlight the role of a previous unstudied source of energy loss: the horizontal shearing located at the bank-full level in the main channel between the upper flow and the inbank flow. The last case investigated is non-uniform flow in a straight compound channel [8,9] characterized by a strong influence of the upstream discharge distribution between sub-sections on the mass transfers along a compound channel flume. When the total width of the channel is constant and the flow is non-uniform, a common characteristic between the various experiments was identified: mass transfers between flows in the main channel and the floodplains generate low variation in flow depth along the longitudinal x-axis. The streamwise variation in flow depth was even found to be negligible for a few flow configurations.

On the contrary, when the width of the overall channel is varying, the flow depth markedly vary. This was observed for flows in symmetrically converging floodplains [10], in symmetrically diverging floodplains [9,11], in a compound channel with an abrupt contraction of the floodplain [12], or in presence of a groyne set up on a floodplain perpendicularly to the main flow direction

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Nomenclature

A_i	sub-section area
B_i	sub-section width
h_i	sub-section flow depth
h^*	relative flow depth at mid-length of a prismatic channel or at mid-length of a diverging, converging or skewed reach
H_i	sub-section head
q_{in}	lateral inflow per unit length
q_{out}	lateral outflow per unit length
q_{rm}	lateral mass discharge between the right-hand floodplain and the main channel (algebraic value)
q_{lm}	lateral mass discharge between the left-hand floodplain and the main channel (algebraic value)
Q	total discharge
S_0	bed slope
S_{fi}	sub-section friction slope
S_{Hi}	sub-section head loss gradient
U_d	depth-averaged velocity in the longitudinal direction
U_i	sub-section mean velocity
U_{in}	longitudinal velocity of lateral inflow q_{in} at the interface
U_{int}	longitudinal velocity at the interface between one floodplain and the main channel
$U_{int.l}$	longitudinal velocity at the interface between the left-hand floodplain and the main channel
$U_{int.r}$	longitudinal velocity at the interface between the right-hand floodplain and the main channel
U_{out}	longitudinal velocity of lateral outflow q_{out} at the interface
x	longitudinal direction
y	lateral direction
z	water level above reference datum
α	Coriolis coefficient on the total cross-section
α_i	Coriolis coefficient in sub-section i
β	Boussinesq coefficient on the total cross-section
β_i	Boussinesq coefficient in sub-section i
δ	angle between the floodplain lateral walls and the main channel axis (x-direction)
τ_{ij}	shear stress at the vertical interface between two adjacent sub-sections i and j along x-axis (depth-averaged value)
ψ^t	coefficient of turbulent exchange

Subscripts

f	concerning floodplain
i	concerning a sub-section ($i = l$, r or m)
l	concerning left-hand floodplain
m	concerning main channel
r	concerning right-hand floodplain

[13]. In this case, the nature of mass transfers is clearly different, as they are produced by both streamwise changes in the total width of the channel and in water depth, and consequently become stronger than when the overall channel width remains constant.

As overbank flows with varying width are quite common in the field, this paper deals with head losses for flows with constant or variable channel width. The first aim of the paper is to identify the main physical processes responsible for head losses in both contexts. The second aim is to estimate the influence of the head losses on two hydraulic parameters of interest for engineers, the flow depth and the discharge in the floodplain, for various types of geometry. The last aim is to work out the influence of an explicit modeling of mass conservation at the interfaces between sub-sections in the longitudinal evolution of hydraulic parameters. For that purpose, we use 1D energy or momentum balances within a sub-section (main channel, left-hand or right-hand floodplain), which give a synthetic overview of the predominant physical phenomena.

First, we develop the equations of energy loss and head loss applied to one sub-section or to the total cross-section of a compound channel. An original result is obtained: head loss gradient is equal to energy slope on the total cross-section, but in the sub-sections, head loss gradient differs from the energy slope. Second, we analyze the streamwise evolution of the head in the sub-sections and in the total cross-section from various experimental data sets: developing flows in straight compound geometry, flows in symmetrical diverging or converging compound channels. In particular, we test the validity of a common 1D hypothesis: equal head loss gradients in the main channel and in the floodplain. The experimental profiles of head in the sub-sections are then compared to the numerical results of a 1D-improved model, the Independent Sub-sections Method (ISM). This model enables three sources of head loss to be accounted for: (1) the classical bed friction on the solid walls; (2) the momentum flux due to the turbulent exchanges generated by the shearing between sub-sections; (3) the momentum flux due to mass exchanges between sub-sections. Using the ISM simulations, we show the difference between computed head loss gradients and energy slopes in the sub-sections. Afterwards, we examine the relative weights of the three sources of head loss in the various geometries investigated. The influence of each source of head loss on discharge distribution and flow depth is quantified. Lastly, we examine the role of the mass conservation at the interfaces between sub-sections on the flow parameters.

2. Energy loss, head loss, and momentum

In this section, equations of energy loss, head loss and momentum are developed for one-dimensional compound channel flow, relying on the work of Field et al. [14] that deals with energy and momentum in 1D open channel flow.

Let us consider a fluid system in a control volume Ω bounded by a surface A_Ω presented in Fig. 1a and b. The total energy of this fluid system is denoted E, and the total energy per unit mass is denoted e [J/kg]. We assume that the gravity force is the only volume force deriving from a potential energy, and we only consider heat transfers with the solid walls, the water surface, and with the liquid interfaces between sub-sections. Under these assumptions, the total energy e is the sum of macroscopic kinetic energy, potential energy of the gravity force and of the internal energy per unit mass, and the first law of thermodynamics is written (see e.g. [15])

$$\frac{\partial}{\partial t}\iiint_{\Omega}\rho e\, d\Omega + \iint_{A_\Omega}\rho e(\vec{v}\cdot d\vec{A}_\Omega) = -\tilde{q} - \iint_{A_\Omega}\frac{p}{\rho}\rho(\vec{v}\cdot d\vec{A}_\Omega) + \iint_{A_\Omega}(\bar{\bar{\tau}}\cdot\vec{n})\cdot(\vec{v}\cdot dA_\Omega) \quad (1)$$

where $\vec{v}$ is the local velocity vector, $\tilde{q}$ is the calorific power exchanged with the exterior of Ω [J/s], p is the pressure, $\bar{\bar{\tau}}$ is the tensor of viscous and turbulent shear stresses applied to surface A_Ω, $d\vec{A}_\Omega = dA_\Omega\vec{n}$, $\vec{n}$ being the unit vector perpendicular to unit surface dA_Ω.