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Free surface profiles in river flows: Can standard energy-based gradually-varied flow computations be pursued?

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SUMMARY

Is the energy equation for gradually-varied flow the best approximation for the free surface profile computations in river flows? Determination of flood inundation in rivers and natural waterways is based on the hydraulic computation of flow profiles. This is usually done using energy-based gradually-varied flow models, like HEC-RAS, that adopts a vertical division method for discharge prediction in compound channel sections. However, this discharge prediction method is not so accurate in the context of advancements over the last three decades. This paper firstly presents a study of the impact of discharge prediction on the gradually-varied flow computations by comparing thirteen different methods for compound channels, where both energy and momentum equations are applied. The discharge, velocity distribution coefficients, specific energy, momentum and flow profiles are determined. After the study of gradually-varied flow predictions, a new theory is developed to produce higher-order energy and momentum equations for rapidly-varied flow in compound channels. These generalized equations enable to describe the flow profiles with more generality than the gradually-varied flow computations. As an outcome, results of gradually-varied flow provide realistic conclusions for computations of flow in compound channels, showing that momentum-based models are in general more accurate; whereas the new theory developed for rapidly-varied flow opens a new research direction, so far not investigated in flows through compound channels.

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1. Introduction

Discharge hydrographs from heavy rainfall events are conveyed as a free surface flow through natural waterways and rivers, which are normally compound channels. The cross-sections of these channels are complex and can be divided into a main channel and the flood plains, with a large variation of hydraulic roughness between them (Sturm, 2001). The computation of free surface levels in natural channels is an important procedure and is required to demarcate the flow inundation areas as a function of the return period of peak flood (Chow et al., 1988; Brutsaert, 2005). The accuracy in flow profile predictions relies on hydraulic computations based on one-dimensional gradually-varied flow models (Chow et al., 1988). Programs like HEC-RAS (Hydrologic Engineering Center-River Analysis System) are used to compute one-dimensional gradually-varied flow in natural channels by using the energy equation (Sturm, 2001; Chaudhry, 2008). A decisive aspect in these computations is the selection of an appropriate method to calculate the discharge taking into account the variation of hydraulics roughness within the cross-section. The HEC-RAS program, for example, subdivides the channel cross-section with vertical planes and turbulent stresses are neglected along the division lines. This is a traditional approximation in open channel flows (Chow, 1959; Montes, 1998; Sturm, 2001; Chaudhry, 2008). However, in the past 30 years, a large number of studies analyzed the discharge prediction method for compound channel sections. Most of them argued that the subdivision method is not accurate for the discharge prediction. The strong lateral velocity gradients and turbulence result in a significant linear momentum transfer between the main channel and the flood plains (Sellin, 1964; Myers, 1978; Rajaratnam and Ahmadi, 1981; Wormleaton et al., 1982; Knight and Demetriou, 1983; Shiono and Knight, 1991; Knight and Abril, 1996; Lambert and Sellin, 1996; Bousmar and Zech, 1999; Khatua et al., 2011). Prinos (1985) and Chatila and Townsend (1996) compared the methods based on virtual plane divisions between the main channel and the floodplains. The interaction between the flood plain and the main channel

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Nomenclature

A	total flow area (m^2)
A_h	$\partial A/\partial h$ (m)
A_{hh}	$\partial^2 A/\partial h^2$ (–)
a_i	subsection flow area (m^2)
b_1	main channel bottom width (m)
b_2	floodplain bottom width (m)
E	specific energy (m)
f	friction factor (–)
F_α	compound channel Froude number based on specific energy (–)
F_β	compound channel Froude number based on specific momentum (–)
F_c	compound channel Froude number (–)
g	gravitational acceleration (m/s^2)
h	maximum flow depth in compound section (m)
h_c	critical depth (m)
I	moment of inertia of cross-section (m^4)
K	total conveyance (m^3/s)
k_i	subsection conveyance (m^3/s)
Q	total discharge (m^3/s)
Q_u	upper discharge for multiple critical depths (m^3/s)
n	Manning coefficient ($m^{-1/3}$ s)
n_i	subsection Manning coefficient ($m^{-1/3}$ s)
n_1	main channel Manning coefficient ($m^{-1/3}$ s)
n_2	floodplain Manning coefficient ($m^{-1/3}$ s)
n_e	equivalent Manning coefficient ($m^{-1/3}$ s)
P	total wetted perimeter (m)
p_i	subsection wetted perimeter (m)
p	pressure (Pa)
R	hydraulic radius (m)
r_i	subsection hydraulic radius (m)
S	specific momentum (m^3)
S_0	channel slope (–)
S_e	gradient of dissipated energy (–)
S_f	friction slope (–)
t	time (s)
T	total top width (m)
t_i	subsection top width (m/s)
U	mean flow velocity (m/s)
U_c	mean flow velocity in main channel (m/s)
U_f	mean flow velocity in flood plain (m/s)
u_i	subsection flow velocity (m/s)
u	point velocity (m/s)
v	vertical velocity (m/s)
X	wetted perimeter corrector parameter (m)
x	longitudinal coordinate along the channel bed (m)
y	floodplain depth (m)
y_1	main channel bank-full depth (m)
y_r	relative compound channel depth (–)
z	coordinate normal to the channel bed, positive upwards (m)
α	Coriolis coefficient (–)
β	Boussinesq coefficient (–)
λ	shear force percentage for floodplain perimeter (–)
γ	specific weight of water (N/m^3)
ρ	density of water (kg/m^3)
$\sigma_1, \sigma_2, \sigma_3$	compound channel Froude number terms in energy equation (–)
τ_1, τ_2, τ_3	compound channel Froude number terms in momentum equation (–)
τ_a	apparent shear stress (Pa)
$\bar{z}$	distance from the free surface to the total-section centroid (m)
θ	angle of channel bed with the horizontal (–)

flows induces secondary flows and turbulent stresses at the virtual planes, which can be introduced in the governing equations by a momentum balance (Wormleaton et al., 1982). Wormleaton et al. (1982), Prinos and Townsend (1984) and Wormleaton and Merrett (1990) solved the momentum equation by introducing an apparent shear stress at the interfaces, and parameterized it in terms of velocity of the main channel and the floodplains. Dracos and Hardegger (1987) suggested the use of the ratio of hydraulic radius to total depth for the single-channel method, which involves several empirical parameters related to the geometry of the cross-sections. Ackers (1993a,b) proposed the coherence method, that introduces an empirical correction to the vertical (virtual) division method. Khatua et al. (2011) developed an equation to quantify the momentum transfer in terms of an appropriate interface length. Thus, despite it is well established that the momentum transfer between the main channel and the flood plains must be considered for an accurate determination of the discharge, this knowledge has so far been hardly transmitted to the basic hydraulic computations involving free surface flows. It is, however, unclear amongst various available methods, which discharge prediction method should be included in one-dimensional compound channel models. Further, it is also unclear, which is the best, whether the use of momentum or energy principle for the computations of flow in compound channels.

The prediction of the stage-discharge relationship in a compound channel directly influences other relevant gradually-varied flow computations. The discharge curve is needed to perform flow profile computations using gradually-varied energy or momentum models (Sturm and Sadiq, 1996; Sturm, 2001; Chaudhry, 2008). An aspect that particularly makes these computations in compound channels complicated relates to the nonuniform lateral velocity distribution within the cross-section induced by the large variation of hydraulic roughness. It results in velocity distribution coefficients much larger than unity that needs to be accounted for (Sturm and Sadiq, 1996; Sturm, 2001). The computations of these coefficients as well as the determination of the energy line slope are highly dependent on the discharge prediction method. Thus, the flow profile computations are dependent on the discharge predictor model. Critical depth is used to compute stage-discharge rating curves by using the energy or momentum principles (Petryk and Grant, 1978; Blalock and Sturm, 1981; Schoellhamer et al., 1985; Chaudhry and Bhallamudi, 1988; Yuen and Knight, 1990; Lee et al., 2002), and it is as well a boundary condition to initiate flow profile computations (Sturm and Sadiq, 1996; Field et al., 1998). The impact of the discharge predictor on the critical depth computations is also unclear. Field et al. (1998) compared energy and momentum equations of gradually-varied flows for the computation of flow profiles in compound channels. They concluded that more research was needed to evaluate both approximations, that give large differences. Errors in discharge prediction may result in large inaccuracies in computing energy and momentum fluxes, thereby provoking problems when solving the dynamic flow equations (Wormleaton and Hadjipanos, 1985). Further, the flow discharge measurement in open channels is usually done by weirs and flumes (Clemmens et al., 2001). If a long throated flume is installed into a compound channel to measure discharge, then

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