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Procedia Engineering 154 (2016) 459 – 466

Procedia Engineering

www.elsevier.com/locate/procedia

12th International Conference on Hydroinformatics, HIC 2016

Determination of Apparent Shear Stress and Its Application in Compound Channels

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Abstract

The momentum exchange in the mixing zone of compound channel is a common phenomenon and has an important effect on discharge estimation. It can be quantified with apparent shear stress (ASS) at the interface of floodplain and main channel. The mechanisms of apparent shear stress are investigated. A strong relationship between apparent shear stress and difference of squared velocity at each compartment has been found. The variations of geometrical shape ratio and roughness ratio have been introduced. Improved formulas of calculation of apparent shear stress (ASS) have been proposed for symmetrical compound channels with regression analysis on the basis of a large amount of experimental data and the formulas have been validated with other data. The importance of roughness ratio in roughened compound channels is noted. Discharge estimation with ASS method gives a good agreement with experimental results. Compared with other methods the improved formulas present a high degree of accuracy. It is applicable to small scale and large scale compound channels.

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Keywords: momentum exchange; apparent shear stress; compound channel; discharge estimation; roughened floodplain

1. Introduction

River flow overtopping floodplain occurs during floods, the section of which appears compound. Such compound channel flow has received considerable attention over the past two decades [1]. The most important study is stage-discharge relationship. Traditional discharge estimation methods have been found they can't give satisfactory results. The single channel method (SCM) significantly underestimates discharge in compound channels and the divided channel method (DCM) which always adopts vertical segmentation lines overestimates discharge [2-3]. Researchers have made some modification to DCM methods, like inclined lines or horizontal lines [4-5]. However, none of these modification is satisfactory over a range of flow [6]. The errors are mainly due to ignorance of momentum exchange between main channel and floodplains. Momentum exchange will retard velocity in main channel and accelerate flow over floodplains. Some other methods have been put forward, such as, the Ackers method [7-8], the depth-averaged method [9-10], the apparent shear stress (ASS) method [5,11]. The three methods can give better results but the first two methods are complicated[12]. The ASS method is an improved method to DCM and revises velocity in each subsection by considering momentum exchange. Sellin [13] first observed vortices with significant momentum transfer generated in the turbulence shear mixing region and quantified the momentum transfer process. Zheleznyakov [14] confirmed the existence of this phenomenon in the field and regarded as "kinematic effects". After that, researchers began to take momentum exchange into discharge estimation. Myers [15] presented momentum transfer in asymmetrical channel and pointed out the conventional technique of dividing the channel section into hydraulically homogeneous subdivisions must be called in question. Ervine and Baird [11] evolved the discharge calculation method

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doi:10.1016/j.proeng.2016.07.538

considering ASS, but they didn't verify the method. Some other researchers have improved this method [2,5,16-17].So far, quantification of momentum exchange between subsections hasn't been resolved theoretically. Most studies are based on experimental data. Many empirical formulas are put forward to quantify momentum exchange which is named ASS. The ASS is a measure of the net effect of viscous shear, turbulence together with the action of vortices transferring momentum between channel and floodplains [15]. Most researchers concluded the ASS have a strong correlation with velocity difference between deeper faster main channel flow and slower shallower floodplains[6,11,18-20]. At the early stage, expressions of ASS are purely empirical and relationships between ASS and velocity difference aren't dimensionally correct. Christodoulou [18] proposed a dimensionally sound formula which related ASS with square of velocity difference. Huthoff et al. [12] proposed a new parameterization of ASS and associate ASS with difference of squared velocity at each compartment. At present, there isn't a good explanation that ASS should relate with square of velocity difference or difference of squared velocity. ASS equations are mostly for smooth boundary, and haven't taken into account the cases that floodplain is roughened or floodplain roughness is greater than main channel roughness, which is very common in natural rivers.

The paper first investigated mechanisms of momentum exchange and proposed a relation between ASS and velocity. And then based on a large amount of experimental data reported in previous papers, the authors expect to put forward a formula to calculate ASS for symmetrical compound channels. Discharge estimation with ASS method in accordance with authors' formula is compared with other ASS formulas and other discharge calculation methods.

2. Theoretical analysis

In order to study ASS in compound channel, the Reynolds equation in longitudinal stream-wise direction is used as a starting point. Considering fully developed steady uniform flow and adding the continuity equation to the Reynolds equation, we obtain

$$\rho\left(\frac{\partial uv}{\partial y}+\frac{\partial uw}{\partial z}\right)=\frac{\partial \tau_{yx}}{\partial y}+\frac{\partial \tau_{zx}}{\partial z}+\rho gS \tag{1}$$

where x, y, z are streamwise, transverse and vertical coordinates, shown in Fig.1. u, v, w are velocity components in x, y, z coordinate respectively; τ_{yx} and τ_{zx} are Reynolds stresses, ρ is mass density, S is bed slope, g is gravitational acceleration. Integrating Eq. (1) along water depth and considering w=0 at the bottom and surface. $H(y)$ and $h(y)$ indicate surface and bottom elevation at transverse coordinate y. Depth-averaged Reynolds equation can be obtained

$$\rho\frac{\partial}{\partial y}\int_{h(y)}^{H(y)} uvdz=\frac{\partial}{\partial y}\int_{h(y)}^{H(y)}\tau_{yx}dz-\tau_b+\rho g\left(H(y)-h(y)\right)S \tag{2}$$

where τ_b is bottom shear stress.

Supposing $\int_{h(y)}^{H(y)} uvdz=\left(H(y)-h(y)\right)\overline{uv}$, $\int_{h(y)}^{H(y)}\tau_{yx}dz=\left(H(y)-h(y)\right)\overline{\tau_{yx}}$ and then Eq. (1) can be written

$$\frac{\partial}{\partial y}\left(\left(H(y)-h(y)\right)\left(\rho\overline{uv}-\overline{\tau_{yx}}\right)\right)=\rho g\left(H(y)-h(y)\right)S-\tau_b \tag{3}$$

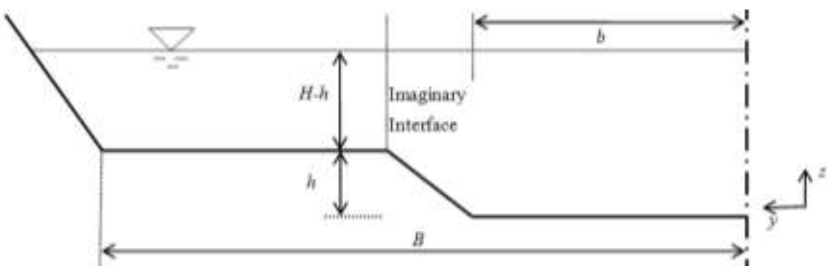

Fig.1 Sketch of a compound channel

Integrating Eq. (3) over transverse direction from center-line to imaginary interface yields

$$\left(H-h\right)\left(\rho\overline{uv}-\overline{\tau_{yx}}\right)=\rho gAS-\tau_b P \tag{4}$$

where, P and A are wetted perimeter and area of main channel respectively. According to balance of forces, ASS can be given

$$\tau_a = \left(\rho g A S - \tau_b P\right) / \left(H - h\right) \tag{5}$$

Substituting Eq. (5) into Eq. (4), we can obtain

$$\tau_a = \rho \overline{uv} - \overline{\tau_{yx}} \tag{6}$$

If velocity and turbulence characteristics in compound channels are measured, ASS can be calculated based on Eq. (6). However, in practical application it is time-consuming and inconvenient. Therefore, researchers generally relate ASS to large-scale motion, such as mean velocity. From Eq. (6) we can deduce that ASS has two components: one rising from secondary current, and the other from fluctuation velocity.

First secondary current is estimated. The distribution of v at the imaginary interface can be assumed in an approximate linear relation with water depth, which can be observed from experiments or simulations of some researchers [9, 21-22]. Although this distribution doesn't comply with zero velocity at the bed, Wormleaton [23] presented it was appropriate for secondary current analysis through comparison of three different profiles. The transverse velocity at the imaginary interface can be taken as

$$v_{(z)} = v_{\max}\left(\frac{2(z-h)}{H-h} - 1\right) \tag{7}$$

$v_{\max}$ is the maximum value of v at the interface.

Due to secondary current, the distribution of primary velocity u at the shear zone is hard to determine. The maximum velocity emerge under water surface at times if aspect ratio is small, which is called dip-phenomenon. To author's knowledge, there isn't a universal formula for it. According to Tominage and Nezu [21] and Wormleaton [23], the log-law distribution is appropriate for primary velocity at the imaginary interface. Rough channel bed has been considered herein. Velocity profile can be taken as

$$\frac{u}{u_*} = \frac{1}{k}\ln\left(\frac{z-h}{k_s}\right) \tag{8}$$

where u_* is local friction velocity, $u_* = (\tau_b / \rho)^{1/2}$; k is Karman constant equalling to 0.41, k_s is roughness height. The averaged secondary current effect at the interface can be writing as

$$\frac{1}{H-h}\int_h^H \left(-\rho uv\right) dz = \frac{1}{H-h}\int_{h+k_s}^H \left(\rho u_* \left(\frac{1}{k}\ln\left(\frac{(z-h)}{k_s}\right)\right) v_{\max}\left(\frac{2(z-h)}{H-h} - 1\right)\right) dz \approx \frac{\rho}{2k} u_* v_{\max} \tag{9}$$

Tominage and Nezu [21] thought that maximum magnitude of v was about 4% of the maximum primary velocity, that is, $v_{\max} = 0.04 u_{\max}$. $u_{\max}$ is of the same order of U_i, which is the averaged velocity at the imaginary interface. U_i is scaled on $U_c + U_f$. U_c is the mean velocity of main channel and U_f is the mean velocity of floodplain According to Prooijen et. al.[24] $u_* = \sqrt{c_f} U_i$, where c_f is frictional coefficient. Then Eq. (9) may be written

$$\overline{uv} \propto \frac{\rho}{50k}\sqrt{c_f}\,(U_c + U_f)^2 \tag{10}$$

And then Reynolds stress τ_{yx} is analyzed. Reynolds stress has two contributions: one due to bottom turbulence and the other due to transverse free shear (Prooijen et. al.([24]).The turbulent viscosity hypothesis is introduced to model Reynolds stress.

$$\tau_{yx} = \rho v_T \left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right) \tag{11}$$

where v_T is eddy viscosity and $\partial v / \partial x$ can be assumed to zero. Therefore, the depth-averaged Reynolds stress $\overline{\tau_{yx}}$ can be written as

$$\overline{\tau_{yx}} = \frac{1}{H-h}\int_h^H \left(-\rho \overline{u'v'}\right) dz = \rho \overline{v_T}\frac{\partial U}{\partial y} \tag{12}$$

Because Reynolds stress includes two components, the eddy viscosity can also be expressed into two parts: bottom turbulence $\overline{v_b}$ and transverse free shear $\overline{v_s}$. All the remains are to determine appropriate eddy viscosity $\overline{v_b}$ and $\overline{v_s}$. The eddy viscosity can be written as the product of a characteristic velocity u' and a characteristic length l' [25]. For the bottom turbulence part, the $u' \propto \sqrt{c_f} U$ and $l' \propto H - h$ can be adopted; for the transverse free shear, turbulent velocity fluctuations scale with transverse velocity difference [12]. Characteristic velocity can be written as $u' \propto U_c - U_f$ and characteristic length $l' \propto B$. It can be approximately assumed the derivative of U along direction y is proportional to $-\left(U_c - U_f\right)/B$. Therefore, Eq. (12) can be written as:

$$\overline{\tau_{yx}} = -\rho\alpha_1\sqrt{c_f}\left(U_c + U_f\right)(H-h)\left(U_c - U_f\right)/B - \rho\alpha_2\left(U_c - U_f\right)\left(U_c - U_f\right) \tag{13}$$

Substituting Eq. (13) and Eq. (10) into Eq. (6), we obtain:

$$\tau_a = \alpha_1\rho\left(U_c + U_f\right)\left(U_c - U_f\right)(H-h)/B + \rho\alpha_2\left(U_c - U_f\right)\left(U_c - U_f\right) + \alpha_3\frac{\rho}{2k}\sqrt{c_f}(U_c + U_f)(U_c + U_f) \tag{14}$$

α_1, α_2, α_3 are proportionality factor and influenced by channel geometry, water depth and roughness. For simplicity we put $(H-h)/B$ in the first term of Eq. (14) into α_1, and put $\sqrt{c_f}/2k$ in the third term of Eq. (14) into α_3. Eq. (14) can be simplified:

$$\tau_a = \alpha_1\rho\left(U_c + U_f\right)\left(U_c - U_f\right) + \alpha_2\rho\left(U_c - U_f\right)\left(U_c - U_f\right) + \alpha_3\rho(U_c + U_f)(U_c + U_f) \tag{15}$$

3. Regression analysis

Since 1980s, due to the importance of ASS in discharge estimation of compound channels, many researchers have attempted to quantify ASS. Empirical or semi-empirical formulas have been put forward, shown in Tab.1. Wormleaton et.al. [6] obtained an empirical equation based on their experimental data and others', and found that ASS increased with decrease of water depth or increase of floodplain roughness. However, their formula doesn't include the roughness. Prinos and Townsend [2] thought ASS depended on relative depth, relative width and relative roughness, and obtained a relationship based on a multiple linear regression. Wormleaton and Merrett [5] related ASS with velocity variation, water depth on the floodplain as well as the flood width. Christodoulou [18, 26] proposed a theoretical formula of ASS in terms of dimensional ground. Due to his less data, aspect ratio of channel wasn't analyzed. And his results indicated that ASS was decided by width ratio of compound section besides velocity difference. Huthoff et.al [12] put forward a new formulation to calculate vertical interface stress between adjacent flow compartments, which was related to actual velocity difference between the adjoining subzones. A dimensionless coefficient was estimated from various laboratory data, the range of which was from 0.01 to 0.05 with the best value is 0.02. Moteta and Martin-vide [17] proposed a dimensionally sound expression based on Christodoulou's and gave the variation of apparent friction coefficient with the geometrical and roughness ratios according to a mass of laboratory data.

Table 1 The existed formulas of apparent shear stress

Authors	Formula
Wormleaton et.al. [6]	$\tau_a = 13.84(\frac{H}{h})^{-3.123}(\frac{B-b}{b})^{-0.727}\Delta U^{0.882}$
Prinos and Townsend [2]	$\tau_a = 0.874(\frac{H-h}{H})^{-1.129}(\frac{B}{b})^{-0.514}\Delta U^{0.92}$
Wormleaton and Merrett [5]	$\tau_a = 3.325(H-h)^{-0.354}(B-b)^{0.519}\Delta U^{1.451}$
Christodoulou [18,26]	$\tau_a = 0.005\rho\frac{B}{b}\Delta U^2$
Huthoff et.al [12]	$\tau_a = \frac{1}{2}0.02^{+0.018}_{-0.012}\rho\left(U_c^{\ 2} - U_f^{\ 2}\right)$
Moteta and Martin-vide [17]	$\tau_a = \frac{1}{2}\rho\begin{bmatrix} 0.004\frac{B}{b_c}\left(\frac{h}{b_c}\right)^{(-1/3)}\left(\frac{H-h}{H}\right)^{(-1/3)} - \\ 0.018\left(\frac{H-h}{H}\right)^{(-1/3)}\left(\frac{n_f-n_c}{n_c}\right)^{0.2}\end{bmatrix}(\Delta U)^2$

From the above, we can deduce that formulas of ASS are transferred from purely data fitting to certain theoretical basis, such as dimension analysis sound. The main impact factors of ASS include geometry of cross-section, roughness and velocity relation between main channel and floodplains, which correspond to our previous analysis. The alphas in Eq. (15) can be decided by width ration B/b, width depth ratio h/b, relative depth D_r and roughness ratio n_f / n_c.However, how the relation of ASS and velocity is has been controversial.

The most appropriate way to determine the relations between ASS and velocity is based on Eq. (15). But every alpha in Eq. (15) has its own relation with B/b, h/b, D_r, n_f / n_c. It is very hard to estimate these relations between three alphas with their impact factors. So we need to rearrange Eq. (15). According to Eq. (15) and previous researchers' results we can see convention velocity U_c+U_f and velocity difference U_c-U_f both have an influence on ASS. Two kinds of equations can be simplified from Eq. (15).

$$\tau_a = K_1\rho\left(\frac{B}{b}\right)^{\alpha}(Dr)^{\beta}\left(\frac{h}{b}\right)^{\gamma}\left(\frac{n_f}{n_c}\right)^{\kappa}\left(U_c^2-U_f^2\right) \tag{16}$$

$$\tau_a = K_2\rho\left(\frac{B}{b}\right)^{\alpha}(Dr)^{\beta}\left(\frac{h}{b}\right)^{\gamma}\left(\frac{n_f}{n_c}\right)^{\kappa}\left(U_c-U_f\right)^2 \tag{17}$$

Christodoulou [18] and Wang et.al [27] have proposed ASS is proportional to B/b. Therefore, exponent α equals to 1.

In order to analyze Eqs. (16) and (17), experimental data (Tab.2) reported previously have been collected, especially the one that floodplains are roughened.

Table. 2 Main geometrical parameters for small scale flume experiments in symmetrical compound channels

Authors	$S\times1000$	B/b	h/b	D_r	n_f/n_c	flume	N
Prinos and Townsend[2]	0.300	3.90-5.35	0.67-1.00	0.089-0.329	1.00-2.00	small	40
Knight and Hamed[28]	0.966	4.00	1.00	0.100-0.600	1.11-3.49	small	39
Wormleaton et al.[6]	0.430	4.17	0.83	0.111-0.429	1.00-1.91	small	29

The multiple regression analysis is performed for Eq.(16) and Eq(17). When regressions use only D_r and n_f/n_c as variables, a correlation coefficient of 0.962 is obtained for Eq. (16), far larger than 0.848 for Eq. (17). Then, B/b and h/b are added for regression analysis, and correlation coefficient is 0.781 for Eq. (17), while the correlation coefficient can be reach 0.942 for Eq. (16). Thus, the authors deem that Eq. (16) presents a more essential relation between ASS with geometry, velocity and roughness. Eq. (16) can be expressed as

$$\tau_a = 0.00023\rho\frac{B}{b}\left(D_r\right)^{-1.128}\left(\frac{h}{b}\right)^{-0.396}\left(\frac{n_f}{n_c}\right)^{0.355}\left(U_c^2-U_f^2\right) \tag{18}$$

Then large scale experiments (Tab.3) are added into regression analysis. The SERC-FCF is a flume of 50m×10m and located at the Hydraulics Research Ltd at Wallingford. Details of SERC-FCF can be found from Knight and Sellin [29]. Considering B/b, D_r, h/b and n_f/n_c, the final regression equation is

$$\tau_a = 0.00025\rho\frac{B}{b}\left(D_r\right)^{-1.043}\left(\frac{h}{b}\right)^{-0.542}\left(\frac{n_f}{n_c}\right)^{0.363}\left(U_c^2-U_f^2\right) \tag{19}$$

Table. 3 Main geometrical parameters for large scale flume experiments in symmetrical compound channels

Authors	$S\times1000$	B/b	h/b	D_r	n_f/n_c	flume	N
Shiono and Knight[9]	1.027	2.20-6.67	0.20	0.094-0.475	1.00	large	19

The correlation coefficient is 0.941, slightly lower than only using small scale experimental data. To generalize the equation, there values are kept as β=-1, γ=-0.5, κ=1/3. And the correlation coefficient reduced to 0.928, and mean error is 19.17%, 1.31% increasing than the optimal index.

$$\tau_a = 0.00025\rho\frac{B}{b}\left(D_r\right)^{-1}\left(\frac{h}{b}\right)^{-0.5}\left(\frac{n_f}{n_c}\right)^{1/3}\left(U_c^2-U_f^2\right) \tag{20}$$

The calculated ASS using Eq. (20) compared with observed one are shown in Fig.2. They are found to be in a good agreement.

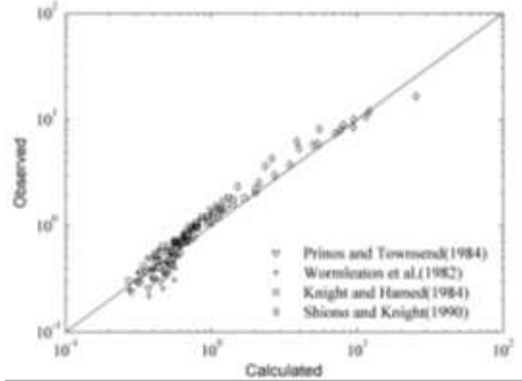

Fig.2 Calculated versus observed apparent shear stress

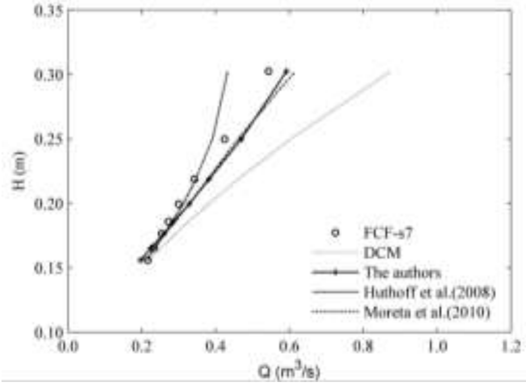

Fig.3 Comparison between the authors, Huthoff et al.(2008) and Moreta et al.(2010)'s methods

4. Application of ASS for discharge estimation

One of the main purposes of ASS is discharge calculation in compound channels. The ASS method have been extensively researched and compared to other methods. It is regarded as a promising method and can greatly improve accuracy [2,5,17]. The ASS method modifies traditional vertical divided method by φ index which is introduced by Radojkovic and Djordjevic [16]. φ_c is defined as the ratio of boundary shear force to streamwise weight component of the main channel, and φ_c can be expressed for floodplain.

$$\varphi_c = 1 - \frac{\tau_a P_a}{\rho g A_c S} \tag{21}$$

where, P_a is the total interface perimeter $P_a = 2(H-h)$ for compound channel with two floodplains. A_c is the cross-sectional area of main channel. S is the bed slope.

$$\varphi_f = 1 + \frac{\tau_a P_a}{\rho g A_c S} \tag{22}$$

where $P_a = (H-h)$ for compound channel no matter with one floodplain or two floodplains. And then the discharge of each subsection can be written as:

$$Q_c = Q_c{}'\varphi_c^{1/2} \tag{23}$$

$$Q_f = Q_f{}'\varphi_f^{1/2} \tag{24}$$

where $Q_f{}'$ $Q_c{}'$ are the respective main channel and floodplain discharges without interaction given by Manning's formula. The overall discharge for compound channels with two floodplains becomes

$$Q_t = Q_c + 2Q_f \tag{25}$$

and for symmetrical channels with one floodplain

$$Q_t = Q_c + Q_f \tag{26}$$

The ASS method is applied to FCF-s7. The FCF-s7 has a smooth main channel and two symmetrical roughened floodplains. The width and height of main channel are 0.75m and 0.15m respectively. The floodplain is 3.15m wide, roughened by rods [7]. Myers et al [30] exhibited that Manning's roughness coefficient for floodplains were strongly influenced by the surface-penetrating floodplain rods. The variation of floodplain roughness with relative depth can refer to Myers et al [30]. The Manning roughness is 0.01 for main channel.

ASS can be estimated using Eq. (20). Then according to the ASS method the total discharge in FCF-s7 can be calculated. The results obtained are compared with Moreta and Martin-Vide [17] and Huthoff et al.[12], shown in Fig.3. The author's results give a better agreement than Huthoff which have a greater deviation about 20% at large depths and exhibit almost the same precision as Moreta and Martin-Vide [17]. The mean errors are 7.6% and 6.7% and the maximum errors can reach to 11.5% and 12.7% for the author's and Moreta and Martin-Vide's respectively. Therefore, it's very hard to abandon any one. However, the authors haven't taken the FCF-s7 into regression analysis, so the validation of the author's formula has a stronger reasoning than Moreta and Martin-Vide's.

5. Discussion

In this study, we have found ASS has a strong relation with the difference of squared velocity over a large range of relative depth. Eq. (20) is obtained by regression analysis, and can be applicable to some certain cases, that is,

$0.1 \le D_r \le 0.6$, $2.0 \le B/b \le 6.0$, $0.2 \le h/b \le 1.0$, $1.0 \le n_f / n_c \le 3.5$

In our study exponents β, γ are -1, -1/2 respectively while in Moreta and Martin-Vide's they are -1/3 and -1/3 respectively. The difference is mainly due to different expression of ASS. Even so, both negative exponents illustrate that variation between ASS and D_r, h/b is consistent.

Comprehensiveness and accuracy of original data are the most crucial for regression analysis. However, there have been little experimental data for ASS in the range of $D_r \le 0.1$ which cause it's hard to find out the laws in this range. Therefore, when D_r is less than 0.1, a great error between calculated results with observed ones will arise.

The Manning's roughness has a significant effect on ASS, especially roughness of floodplain, which is seldom mentioned before. Eq. (20) improve accuracy when apply to the roughened floodplain compared with previous formulas. If the variation of roughness for floodplain doesn't take into account, errors when applying to Eq. (20) for FCF-s7 will be two times larger than the ones considering floodplain roughness variation.

At present, river engineers have realized that Manning's roughness varies with water depth, and at each subsection it is complicated. When compound channels are smooth in floodplains and main channel the roughness can be kept constant [5,30]. However, roughness of roughened floodplain will become hard to establish. Generally floodplain roughness increase with water depth [1, 7]. Reasonable values of Manning's roughness for floodplain and main channel can improve accuracy of Eq. (20). In the discharge estimation for FCF-s7, because Manning roughness coefficients at different relative depths have been known, the predicted discharge has a high degree of accuracy. However, the variation of Manning roughness coefficient with depth is hard to know in practice. Further experiments should be carried out to analyze general rule of variation of Manning's roughness with water depth.

6. Conclusions

1. A detailed analytical formulation of ASS is presented. Turbulence and secondary current are regarded as two contributions to ASS. Each effect on ASS has been illustrated and formulized. A strong relation between ASS and the difference of squared velocity ($U_c^2 - U_f^2$) calculated from Manning's equation in floodplain and main channel has been proved in accordance with regression analysis.

2. An improved formula (Eq. 20) has been put forward for symmetrical compound channels. The formula consider the relative depth Dr, B/b and h/b and Manning's roughness ratio and its range of application is:

$0.1 \le D_r \le 0.6$, $2.0 \le B/b \le 6.0$, $0.2 \le h/b \le 1.0$, $1.0 \le n_f / n_c \le 3.5$

3. The ratio of floodplain roughness to main channel roughness will influence the accuracy of calculation of ASS. Ignorance of Manning's roughness varying with water depth in roughened floodplains may cause a big discrepancy.

4. The Eqs. (20) have been verified by large-scale and small-scale experimental data. Comparison with other methods the ASS method and Eq. (20) have been found to a high accuracy in discharge estimation of compound channels.

Acknowledgements

This work is supported by National Science-Technology Support Plan Project of China (2013BAB12B04, 2013BAB12B03).

References

[1] S. Atabay, D.W. Knight, and G. Seckin. Effects of overbank flow on fluvial sediment transport rates. Water Management, Proceedings of the Institution of Civil Engineers 2005.
[2] P. Prinos, and R.D. Townsend. Comparison of methods for predicting discharge in compound open channels. Adv Water Resour 1984;7: 180-7.
[3] G. Seckin. A comparison of one-dimensional methods for estimating discharge capacity of straight compound channels. Can J Civil Eng 2004;31: 619-631.
[4] D.W. Knight. Flood plain and main channel flow interaction. J Hydraul Eng-Asce 1983;109: 1073.
[5] P.R. Wormleaton, and D.J. Merrett. An improved method of calculation for steady uniform flow in prismatic main channel/flood plain sections. J Hydraul Res 1990;28: 157-174.
[6] P.R. Wormleaton, J. Allen, and P. Hadjipanos. Discharge assessment in compound channel flow. Journal of the Hydraulics Division 1982;108: 975-994.
[7] P. Ackers. Flow formulae for straight two-stage channels. J Hydraul Res 1993;31: 509-531.
[8] P. Ackers. Stage-Discharge Functions for Two-Stage Channels: The Impact of New Research. Water and Environment Journal 1993;7: 52-59.
[9] K. Shiono, and D.W. Knight. Turbulent open-channel flows with variable depth across the channel. J Fluid Mech 1991;222: 617-646.
[10] X. Tang, and D.W. Knight. A general model of lateral depth-averaged velocity distributions for open channel flows. Adv Water Resour 2008;31: 846-857.
[11] D.A. Ervine, and J.I. Baird, Rating curves for rivers with overbank flwo. Ice Virtual Library, 1982, pp. 465-472.
[12] F. Huthoff, P.C. Roos, D.C.M. Augustijn, and S.J.M.H. Hulscher. Interacting divided channel method for compound channel flow. J Hydraul Eng-Asce 2008;134: 1158.
[13] R.H.J. SELLIN. A laboratory investigation into the interaction between the flow in the channel of a river and that over its flood plain. La Houille Blanche 1964: 793-802.
[14] G.V. Zheleznyakov, Relative deficit of mean velocity of instable river flow: Kinematic effect in river beds with floodplains, 1965.
[15] W. Myers. Momentum transfer in a compound channel. J Hydraul Res 1978;16: 139-150.
[16] M. Radojkovic, and S. Djordjevic, Computation of discharge distribution in compound channels, 1985, pp. 367-371.
[17] P.J.M. Moreta, and J.P. Martin-Vide. Apparent friction coefficient in straight compound channels. J Hydraul Res 2010;48: 169-177.
[18] G.C. Christodoulou. Apparent shear stress in smooth compound channels. Water Resour Manag 1992;6: 235-247.
[19] D. Bousmar, and Y. Zech. Momentum transfer for practical flow computation in compound channels. J Hydraul Eng-Asce 1999;125: 696.
[20] L.S. Hin, N. Bessaih, L.P. Ling, A.A.B. Ghani, and M.Y. Seng. Determination of apparent and composite friction factors for flooded equatorial natural rivers. International Journal of River Basin Management 2008;6: 3-12.
[21] A. Tominaga. Turbulent Structure in Compound Open-Channel Flows. J Hydraul Eng-Asce 1991;117: 21.
[22] G. Pezzinga. Velocity distribution in compound channel flows by numerical modeling. J Hydraul Eng-ASCE 1994;120: 1176.
[23] Wormleaton, P.R. Floodplain secondary circulation as a mechanism for flow and shear stress redistribution in straight compound channels, In Coherent Flow Structures in Open Channels [Eds Ashworth,Bennett, Best & cLelland], Chapter 28, J. Wiley, 1996;581–608.
[24] B.C. Van Prooijen, J.A. Battjes, and W.S.J. Uijttewaal. Momentum exchange in straight uniform compound channel flow. J Hydraul Eng-Asce 2005;131: 175.
[25] S.B. Pope, Turbulent flows, Cambridge Univ Pr, 2000.
[26] G.C. Christodolou, and W. Myers, Apparent friction factor on the flood plain-main channel interface of compound channel sections, 1999.
[27] H. Wang, K.J. Yang, S.Y. Cao, and X.N. Liu. Computation of momentum transfer coefficient and conveyance capacity in compound channels. Journal of Hydrodynamics, Ser. B 2007;19: 225-229.
[28] D.W. Knight, and M.E. Hamed. Boundary shear in symmetrical compound channels. J Hydraul Eng-Asce 1984;110: 1412-1429.
[29] D.W. Knight, and R. Sellin. The SERC flood channel facility. Water and Environment Journal 1987;1: 198-204.
[30] W. Myers, D.W. Knight, J.F. Lyness, J.B. Cassells, and F. Brown. Resistance coefficients for inbank and overbank flows. Proceedings of the Institution of Civil Engineers. Water, maritime and energy 1999;136: 105-115.