Experimental Study of Smooth Asymmetric Compound Channels Flow: An Investigation of the Interaction of Flow Using Scaling Argument for Prediction of Overall Discharge

P Singh¹, X Tang*, Y Guan³

Department of Civil Engineering, Xi’an Jiaotong-Liverpool University, Suzhou, 215123, China
Email: Xiao.Tang@xjtlu.edu.cn

Abstract. A simple model for the apparent shear stress on the vertical interface between the floodplain and main channel in asymmetric smooth compound channels is proposed using experimental data obtained in this study. The turbulent structure, including Reynolds shear stress in asymmetric compound channel flows, is investigated for three different flow depths. The lateral distribution of the apparent shear stress obtained shows that the total apparent shear stress has a negative peak near the junction edge in the main channel. Furthermore, the intensity of the advection terms and the Reynolds shear stress near the interface are investigated as the function of the bankfull height and floodplain width. The momentum transport due to Reynolds stress and secondary current between main channel and floodplain is finally modeled as depth ratio using scaling argument. The validation of the current model on three datasets shows an accurate prediction of overall discharge for the asymmetric smooth compound channels.

Keywords: Overall discharge, asymmetric compound channel, Momentum transfer, turbulent shear, secondary current

1. Introduction

The decrease in velocity in the different sections of compound channels, intensifies as the depth somewhat reaches just above the bankfull height [1-3]. Thereafter, the decrease in channel velocity would directly relate to the retarding effect of apparent shear force. For the modelling purpose, a good approximation of the apparent shear stress on the interface is needed to accurately predict the discharge over the flooded areas. Accuracy of the predicted apparent shear ($\tau_a$) at the interface of the compound section occurring on the interfacial vertical, horizontal or diagonal plane helps to improve 1D methods, which are lucid to apply and can be corrected to predict overall discharge and zonal discharge [4-9]. Apparent shear can be defined as a measure of the combining effect of viscous shear, turbulence with the action of vortices induced between main-channel and floodplain(s) [3, 10]. Two components of large-scale motions, namely the fluctuation velocity ($\overline{\tau_{yx}}$) and secondary current ($\rho \overline{u'v'}$) where $\rho$ is the fluid density and $\overline{u'v'}$ is the time average product of streamwise and lateral velocity, are key characteristics to measure momentum exchange in any compound channel [11-15]. However, in practice, measuring $\tau_a$ is time consuming and cumbersome because small scale (in time and size) vortices are difficult to capture. Therefore, researchers generally relate $\tau_a$ to large-scale motions, such as mean velocity. The overall $\tau_a$ is often approximated as a function of the difference between main channel ($U_c$) and floodplain ($U_f$) velocity [16-19].
The aforementioned approach is identified in the linear scaling argument by describing the lateral momentum transfer between adjacent flow sections [20]. This lateral momentum transfer is usually introduced as the interfacial stress \( \tau_{int} \) between the corresponding sections. Our contention lies on the same hypothetical assumption where in the streamwise direction, the largest eddy scale is observed as the typical difference in average velocity due to no-slip condition at the channel bed. This paper aims to investigate the characteristics of spanwise shear stress due to the advection induced secondary currents, Reynolds shear stress, and then the apparent shear stress, which represents the magnitude of the spanwise momentum transport. Finally, a scaling argument model for interfacial shear stress is proposed to estimate the overall discharge of an asymmetric compound channel.

2. Experimental Methodology

The experiments were carried out in a 0.75m wide and 20m long glassed-wall flume at the hydraulics laboratory of Xi’an Jiaotong Liverpool University (XJTLU), China (figure 1). Three compound channel cross sections were tested in the rectangular flume with the bed slope of \( S_0 =0.003 \) in all the scenarios. The three test asymmetrical channels has the bankfull height of 4 and 8 cm with the floodplain width of 20 and 40cm, respectively (figure 1b). In total, three depth ratios for each configuration are tested and designated as low depth \( (D_r=0.1) \), intermediate depth \( (D_r=0.3) \) and high depth \( (D_r=0.5) \). In the experiments, the main channel Manning’s roughness \( n \) is found to be 0.01. The floodplain material is polyvinyl chloride (PVC), used to construct three different cases of the experiments (table 1). In table 1, \( Q \) is the total flow discharge of channel; \( U_{mc} \) and \( U_p \) are the main channel and floodplain velocity respectively; Reynolds number \( Re = U_{mc}R/\theta \), where \( R \) is the hydraulic radius and \( \theta \) is kinematic viscosity; and Froude number \( Fr = U_{ave}/\sqrt{g(H-h)} \), where \( g \) is the acceleration due to gravity.

The flow depths were measured using point gauges, while discharges were measured by an electromagnetic flowmeter installed in front of the channel at the upstream end. The 3D velocities were measured using side and down looking Acoustic Doppler velocimeter (ADV) at the cross section located at the 10m downstream from the entrance. For all the tests, uniform flow condition remains with the averaging flow depth being discrepancies of ±4 mm between 5 and 18 m sections. The x-, y- and z-axes refer to streamwise, transverse and vertical (normal to the bed) directions, respectively. The corresponding instantaneous velocities, time averaged velocities and velocity fluctuations are denoted as \((u,v,w)\), \((U,V,W)\) and \((u',v',w')\), respectively. The measuring points in a cross-section were taken at an interval of 5 mm vertically and at the interval of 20 to 50 mm laterally. Also, measurements were obtained by averaging time series at 50Hz over 60-120 mins. The accuracy of the ADV was ±1 to 3% of the measured mean velocities and ±7 to 10% for the Reynolds stresses. The ADV raw data were processed with the software WinADV using the [21] filtering method based on de-spiking concept.

**Table 1.** Summary of the flow conditions of all test cases where test names signify first three numbers as floodplain width and last digit as bankfull height.

| Tests | Dr (=1-h/H) | Q, (l/s) | \( U_{ave} \) (m/s) | \( U_{mc} \) (m/s) | \( U_p \) (m/s) | Re \( \times 10^4 \) | Fr | \(-u_x u_y / U_{ave}^2\) |
|-------|-------------|---------|---------------------|-----------------|----------------|-----------------|----|---------------------|
| R0204 | 0.1         | 16.83   | 0.3876              | 0.4116          | 0.978          | 4.90            | 0.5605 | 0.1083 |
|       | 0.3         | 21.14   | 0.4315              | 0.4564          | 0.1390         | 7.16            | 0.5755 | 0.0464 |
|       | 0.5         | 35.23   | 0.5161              | 0.5208          | 0.2509         | 12.4            | 0.5821 | 0.0118 |
| R0208 | 0.1         | 40.27   | 0.3294              | 0.3054          | 0.1735         | 13.2            | 0.5402 | 0.0145 |
|       | 0.3         | 40.43   | 0.4296              | 0.4864          | 0.1707         | 14.4            | 0.4683 | 0.0121 |
|       | 0.5         | 40.50   | 0.5076              | 0.5537          | 0.1334         | 13.8            | 0.2637 | 0.0120 |
| R0404 | 0.1         | 16.81   | 0.3296              | 0.5173          | 0.2003         | 2.77            | 0.4999 | 0.1795 |
|       | 0.3         | 21.14   | 0.4034              | 0.5892          | 0.2645         | 5.82            | 0.5179 | 0.1133 |
|       | 0.5         | 25.32   | 0.4669              | 0.6571          | 0.4368         | 9.36            | 0.5306 | 0.0101 |
3. Cross-sectional Variation of Flow Variables

3.1. The Lateral Distribution of the Depth-Averaged Streamwise Velocity

Figure 2 shows the depth-averaged streamwise velocity for nine test cases in Table 1. To obtain the depth-averaged values for hydrodynamic parameters, these cross-sectional measurements are averaged over depth and time, which is usually called double average. For normalization, the double-averaged value of the interfacial velocity \( U_{x,\text{int}} \) is used in practice, as shown in [22]. On the contrary, other parameters like friction velocity \( (U_f) \) or the velocity scale defined as the difference of main-channel \( (U_{mc}) \) and floodplain \( (U_{fp}) \) divided by the characteristic length at the interface [23-25]. In our study, the foremost priority should be given to the significant effect of the channel geometry and the flow depth on the interfacial region velocity, so the depth-averaged interface velocity plays a key role in understanding the behavior of flow. Furthermore, the flow type in a compound channel is classified as shallow flow when \( D_f < 0.3 \), and intermediate flow when \( 0.3 < D_f < 0.5 \) [26-27]. The characteristics of the shallow flow are established as the monotonic and large gradient of velocity flow at the interface, as shown in Figure 2. A significant difference can be observed over the interfacial region for \( D_f \leq 0.3 \) against \( D_f > 0.3 \) where the lateral variation of velocity is small. The 2D macro-vortices over the horizontal plane near the interface \( (y/B_f = 1) \) are induced due to the sudden change of geometry from main-channel to floodplain. The floodplain width in R0404 is twice that of R0204, and the velocity distribution in the two different geometries is strongly dependent on the momentum exchange over the interface. Moreover, the lateral variation of \( U_{x,d} \) over the interfacial region in the case of a wider floodplain (R0404) is smaller than the cases like R0204 and R0208, indicating the strong effect of width ratio on the momentum transfer of flow between main-channel and floodplain.
Figure 2. Distribution of normalized depth-averaged velocity over the cross section for (a) R0204; (b) R0208; (c) R0404. The standard errors estimated for all three cases are 1%, 3% and 1%, respectively.

3.2. Depth-Averaged Reynolds Stress

Figure 3 shows the lateral distribution of the normalized Reynolds stress ($-u_x'u_y'/U_{x,int}^2$) for different flow depths under shallow flow ($D_r < 0.3$) and intermediate flow ($0.3 < D_r < 0.5$) regime for three configurations. The Reynolds shear stress is generally related to the gradient of the streamwise mean velocity. Figure 3 clearly shows that the maximum value of the Reynolds shear stress occurs at the interface where $y/B_f = 1$. Shiono and Knight [28] also experimentally observed that the highest value of Reynolds shear is generally seen near the free surface in the interfacial shear zone. In all our tests, the most notable fluctuation of Reynolds shear stress is in the shallow flow region, with the maximum at $D_r = 0.1$. On the contrary, the lateral variation of $-u_x'u_y'$ for the flow condition of $D_r = 0.5$ is found to be very small over the interface. Even for the channel having a higher bankfull height (R0208), there is a visible change in the lateral gradient of velocity over the two sections (figure 3b). The peak at the interface (i.e., $y/B_f = 1$) is significant for the case of $D_r < 0.3$, although it is not valid for the case of $D_r = 0.5$ where a higher flow exists in the floodplain. Moreover, the effect is not as noteworthy compared to other cases like figure 3 (a, c). Table 1 also shows the normalized peak values of $-u_x'u_y'/U_{x,int}^2$ at the interface ($y/B_f = 1$) for all nine tests.

The peak value for $-u_x'u_y'/U_{x,int}^2$ is found to shoot at $y/B_f = 1$ for shallow depths, as also pointed by [24]. Interestingly, the peak of Reynolds stress is somewhat smaller in the case of R0208, which points to the reduced turbulent kinetic energy. Indicatively, the water depth in the main channel for this case is comparatively high, so the mixing length does not grow proportionally to the shear layer generation over the interface. In other words, in these conditions, the wall induced turbulence overpowers the shear layer based turbulence. Furthermore, turbulence in deeper bankfull height is no more dominant by the bottom turbulence, especially in the main channel section. Usually on contrary, for shallow depth conditions, the lateral velocity gradients are undermined over bottom turbulence experienced over the interface; however, it is otherwise in R0208.
Figure 3. Lateral distribution of the dimensionless transverse Reynolds stress for (a) R0204; (b) R0208; and (c) R0404. The standard error for this parameter was about 7-10% in overall cases with a maximum of 9.8% in R0208.

4. Flow Interaction and Effects of Transverse Currents on Main Channel and Floodplain

For the fully developed flow in the section with steady uniform flow, the momentum equation can be deduced to [8]:

\[(H - h) \left( \rho \bar{w} \bar{v} - \tau_{y/x} \right) = \rho g A \tau_d - \tau_b P \]  

(1)

where \(A\) and \(P\) are the area and wetted perimeter of the main-channel, respectively. By rearranging Eq. (1), the apparent shear stress \(\tau_a = \rho \bar{w} \bar{v} - \tau_{y/x}\) becomes \(\tau_a = \left(\frac{\rho g A \tau_d - \tau_b P}{H - h}\right)\).

In figure 4 (a-c), the magnitude of spanwise momentum transport is depicted through apparent shear stress in the transverse direction of the cross section. The experimental data in figure 4 show the apparent shear stress attains a negative peak near the interface of the main channel and floodplain, irrespective of the higher depth ratio \((D_r=0.5)\). [23, 29-30] indicated that the apparent shear stress became extremely large as the depth ratio decreases, which is depicted in all the experimental results illustrated in figure 4. They have also identified that the Reynolds stress term is expected to be dominant compared to the advection term. Therefore, it is essential to estimate the magnitude of momentum transport due to Reynolds stress and secondary currents between the main channel and the floodplain in asymmetric compound channel flow, as a function of floodplain width and depth ratio.

4.1. Interface Stresses on Linear Scale Argument

Van Prooijen et al. [12] and Bousmar and Zech [31] have derived interfacial stresses for compound channels, demonstrating the lateral momentum transfer in shallow mixing layers using scaling arguments. In general, the apparent shear stress \(\tau_a = \rho \bar{w} \bar{v} - \tau_{y/x}\) has two components: advection due to secondary currents, and shear stress due to the Reynolds stress. By assuming the largest eddy scale as a typical difference of streamwise velocities, i.e. the order of the mean flow in each compartment of compound channel, the interfacial velocity is estimated as an average of the main channel \((U_c)\) and floodplain \((U_f)\) velocity [18]. The \(a\) can be expressed as \(\tau_a = \frac{1}{2} \varphi \rho \left(U_c^2 - U_f^2\right)\).

The dimensionless interface coefficient \(\varphi\) is estimated from the experiments done in this study in the transverse direction for all the cases (see table 2).

Table 2. Dimensionless coefficient \(\varphi\) for parameters h/b_f and Dr for asymmetrical compound channels.

| Depth ratio (Dr) | Test case | R0204 | R0208 | R0404 |
|-----------------|-----------|-------|-------|-------|
|                 | h/b_f = 0.2 | h/b_f = 0.4 | h/b_f = 0.1 |
| 0.1             | 0.0331     | 0.0654 | 0.0305 |
| 0.3             | 0.0251     | 0.0127 | 0.0204 |
| 0.5             | 0.0150     | 0.005  | 0.0160 |
Figure 4. Spanwise distribution of apparent shear stress $\tau_a$ for (a) R0204, (b) R0208 and (c) R0404.

Figure 5. Correlation of the vertical interface coefficient $\varphi$ of apparent shear friction to the depth ratio $D_r$ for the range of $0.1 \leq h/b_f \leq 0.4$ in our experiments.

Figure 5 shows the vertical interface coefficient $\varphi$ of apparent shear friction against depth ratio $D_r$ for three $h/b_f$ data. The data points suggest a power function to estimate interfacial stress at the vertical junction with the coefficient of determination as $R^2 = 0.99$. Based on the above argument, a very simple function as $\varphi = 0.0018 D_r^{-1.581}$ is found to hold true for the data range of $0.1 \leq h/b_f \leq 0.4$ with smooth asymmetric compound channels.

5. Validation of the Current Model for Discharge Calculations

The classical divided channel method (DCM) and vertical divisional line DCM (QDCMV) are commonly used for discharge estimation, which is based on the Manning’s Eq. (2). Much commercial software like HEC based modules, CES (Wallingford), and others use the DCM in their algorithms. In spite of simplicity, the DCM overshoots the overall discharge estimation because it does not take momentum transfer into account [32-33].
\[
Q = \frac{1}{n} AR^2 S_o \frac{1}{2} \quad \text{or} \quad Q = \left[ \sum_{i=1}^{n} \left( \frac{1}{n_i} A_i R_i^2 \right) \right] S_o \frac{1}{2}
\]

where \( n \) is the Manning’s coefficient, \( R \) is the hydraulic radius, i.e. the ratio of the wetted area \( (A) \) to perimeter \( (P) \), and \( i \) denotes the subsection as main channel \( c \) or floodplain \( f \).

To overcome the problem of overestimation in DCM-based methods, the effect of apparent shear stress at the vertical interface between the subsections of an asymmetric channel is included in the model as a weighting factor. Thus, a coefficient \( \omega_i \) is included in the QDCM (V) methods as:

\[
\omega_m = 1 - \frac{x \sigma P_a}{\rho g h m^2} \quad \text{and} \quad \omega_f = 1 + \frac{A_m}{A_f} (1 - \varphi_m)
\]

\[
Q_m = Q_m^0 \omega_m^{0.5} \quad \text{and} \quad Q_f = Q_f^0 \omega_f^{0.5}
\]

where the weightage of the boundary shear force to the fluid flow for each section is defined as \( \omega_m \), \( \omega_f \); \( P_a = 2(H - h) \) is the perimeter on which effective apparent shear force acts. The actual main channel and floodplain discharges are defined as \( Q_m \), \( Q_f \), while \( Q_m^0 \), \( Q_f^0 \) are the discharges estimated through classical QDCM (V) without considering the effect of momentum transfer at the interface.

**Table 3.** Experimental and river datasets used in the analysis.

| Data | \( Q_t \) (m³/s) | h/Bf | b/B | b/bf | h/Bf | L/B | \( D_r = (H-h)/H \) |
|------|-----------------|------|----|------|------|-----|-----------------|
| [34] | 0.0140-0.0373   | 0.12 | 0.4942 | 0.9772 | 0.5058 | 22.35 | 0.1843-0.5434 |
| [35] | 0.2235-0.99292  | 0.06 | 0.3846 | 0.6667 | 0.5769 | 15.39 | 0.0522-0.5031 |
| [36] | 0.0035-0.0058   | 0.25 | 0.2000 | 0.2500 | 0.8000 | 20.00 | 0.1844-0.2607 |

**Figure 6.** Prediction of total discharge \( Q_t \) using DCM and QDCM (V) with Eq. 4, which is the present modeled equation for the coefficient of apparent shear friction on the vertical interface \( \varphi \).

Twenty-eight homogenously smooth data of asymmetric experimental channels are considered in the validation of the present model (see table 3). The range of data varies from 0.0522 \( \leq Q_t \leq 0.5434 \) in m³/s, 0.00103 \( \leq S_o \leq 0.0103 \), 0.0013 \( \leq D_r \leq 0.8182 \).

The error percentage between predicted and experimental total discharge for each flow depth is calculated as \%\( Q_t = \frac{|Q_{exp,i} - Q_{exp,i}|}{Q_{exp,i}} \times 100\% \), where \%\( Q_t \) is the relative error percentage of the predicted and observed discharge at \( h_i \) flow depth, respectively. Figure 6 shows the percentage of errors of the predicted discharge for all the datasets.

**6. Conclusions**

The experimental results for the spanwise apparent shear stress obtained in the asymmetric compound channel are used here to propose a new model for predicting the overall discharge, which is based on the lateral momentum transfer parameter using the scaling argument. The model is easy to use and has only one parameter defined as the coefficient \( \varphi \) of apparent shear friction on the vertical interface. This dimensionless coefficient \( \varphi \) is found to have a power function with the depth ratio for the
geometrical range of $0.1 \leq h/b_f \leq 0.4$ for the asymmetric smooth compound channels. The application of the new model gives a good agreement for the datasets in comparison to the DCM that overestimates the results in every case. However, the results obtained in our model are well within the reasonable percentage error with a maximum of 6.1% in our test datasets. The overall conclusion shows that the present experimentally calibrated model for interfacial stress has potential and can be extended to the rough asymmetric compound channels.

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