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New dynamic data-driven model for predicting the apparent shear force and discharge of compound channels

Xiaonan Tang*, Prateek Singh, Yutong Guan

Xi'an Jiaotong-Liverpool University, Suzhou, China
e-mail: Xiao.Tang@xjtlu.edu.cn

Abstract

In this paper, based on the concept of apparent shear, a new dynamic model for apparent shear force is obtained using a genetic algorithm program, a well-documented machine-learning software, which can examine the existing relationship among the variables and explore the influencing factors. It was found that a unified relationship exists between apparent shear force and the variables of ratios of area, height, width, and roughness. The obtained formula of interfacial apparent shear force can predict the flow discharge of compound channels, either zonal or total discharge. This study shows that the predicted flow using the new model agrees well with the data from the literature. This newly derived model for apparent shear force has a single expression for both smooth and roughened compound channels, which provides a simple and easy-use formula for engineers to apply for wide applications.

Keywords: Urban compound channel; Apparent shear force; Compound channel flow; Rough flood plain; Genetic programming

1. INTRODUCTION

In nature, compound channels (two-stage channels) widely exist. The compound channel has characteristics that the main channel delivers the flow in moderated flow conditions while the floodplain carries out the extra flow in very high flow conditions, so this type of channel has been applied in urban river design for flood mitigation eco-environment purposes (see Fig. 1). It is well known that the traditional single or divided channel method either underestimates or overestimates the discharge. The main reason is that those traditional methods do not consider the impact of momentum exchange at the interface between the main channel and floodplain flow, where apparent shear force exists due to the difference in velocity between the two subsections. Many researchers have recently developed various methods to consider the effect of momentum exchange at the interface, e.g., by the modified wetter parameter, the modified area of subsection, apparent shear stress based on the velocity difference or difference in velocity square, and apparent shear force (Prinos and Townsend 1984; Wormleaton and Merrett 1990; Christodoulou 1992; Huthoff et al. 2008; Moreta and Martin- Vide 2010; Khatua et al. 2012; Mohanty and Khatua 2014; Chen et al. 2016; Devi et al. 2016; Singh et al. 2019; Tang 2017a, b, 2018a, b, 2019a, b; Singh and Tang 2020). The apparent shear-based method has a sound rational basis and shows promising results for a certain range of data. However, this method is mainly based on an empirical function of apparent shear, which also has a different form for different types of compound channels, e.g., homogeneous and heterogeneous compound channels.

In this study, a new unified method to calculate flow in compound channels is proposed in which percentage shear force ($\%SF_f$) carried by floodplains are modeled depending on geometric and hydraulic parameters for predicting zonal and overall discharge. Previously, Knight and Demetriou (1983), Knight and Hamed (1984), Khatua and Patra (2007), Khatua et al. (2012), and Mohanty et al. (2014) showed distinctive $\%SF_f$ models using the non-linear function of geometrical parameters for different types of compound channels. However, the derived mathematical model obtained using a genetic algorithm (GA) can generally be used for homogeneous, heterogeneous symmetrical, and asymmetrical compound channels. The current approach is easier and capable of evaluating the intensity of momentum transfer across interfaces near the zero shear line using percentage shear force, percentage area, and depth ratio of the compound channels for predicting discharge by modified interacting length method with reasonable accuracy.

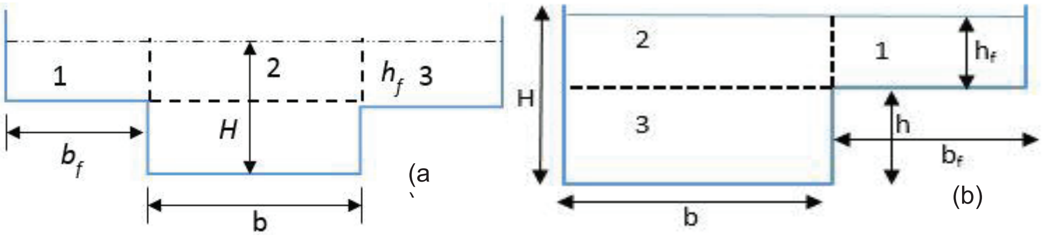

Figure 1. Cross-sectional details for (a) symmetric and (b) asymmetric compound open-channel flows.

2. METHODS

2.1 Genetic Algorithm and Discharge Estimation Method

GEP is a new technique explored in water resources by numerous researchers, which shows its capability and vigor. The GEP is a full-fledged genotype/phenotype system, which has surpassed the old genetic programming systems (Ferreira 2001, Guven and Aytek 2009). Koza (1992) introduced a new evolutionary algorithm based on the population of potential subsets of results structured using simulation. Following well-known biological evolution, metaphor-based genetic programming works on the principle of mutation and crossover. This means random change and sharing in solution from the last best output are obtained through simulations. An evolutionary algorithm is a complex methodology to produce the best fitting. The solution steps include the initial population sets of best results obtained from fitness functions that decide the population's quality. These initial populations are linear chromosomes, expressed through user-defined properties like head size, number of chromosomes, and complexity of the chromosomes. The size and complexity define the population, i.e., results' size, complexity, and order.

The net force on the main channel is affected by the flow of the floodplain, which should be compensated by enlarging the wetted perimeter of the main channel and reducing the wetted perimeter of the floodplain. The assumptions consider that the sum of the boundary shear forces acting on the channel boundary plus the shear force on the assumed interface must be equal to the weight component of the fluid, which is no different from the force balance concept used in all these models. The unique concept of the particular model was to relate the interfacial length for inclusion on the main channel from floodplain wetted perimeter as an interaction length to compensate for the inadequacy in the divided channel method.

By considering the force balance of each part of the channel per unit length (i.e., main channel and floodplain), it follows:

$$P_c\tau_c + X_c\tau_c = \rho g A_c S_o \qquad [1]$$

$$P_f\tau_f + X_f\tau_f = \rho g A_f S_o \qquad [2]$$

where, S_o is the slope of channel, P is the wetted perimeter, τ is the averaged boundary shear stress, ρ is the density of the fluid, g is the acceleration due to gravity, A is the area, and X is the interacting length at the interface and is calculated by:

$$X_c = P_c[\frac{100}{100-\%SF_f}\frac{A_m}{A} - 1] \qquad [3]$$

$$X_f = P_f[\frac{100}{100-\%SF_f}\left(\frac{A_m}{A} - 1\right) - 1] \qquad [4]$$

where $\%SF_f$ is the percentage of boundary shear force on the floodplain. Note that subscripts c & f are used for the main channel and floodplain, respectively. Empirically, Khatua et al. (2012) and Mohanty and Patra (2014) suggested $\%SF_f$ as a function of geometrical parameters of the channel for symmetric smooth (Eq. 5) and rough (Eq. 6) channels, respectively. Furthermore, Devi et al. (2016) proposed a similar Eq. (7) for the asymmetric compound channel.

$$\%SF_f = 4.1045(\%A_f)^{0.6917} \qquad [5]$$

$$\%SF_f = 3.3245(\%A_f)^{0.717}[1 + 1.02\sqrt{\beta}\log_{10} n_r] \qquad [6]$$

$$\%SF_f = 3.576(\%A_f)^{0.717} \quad [7]$$

where $\%A_f$ is the percentage of the floodplain area, n_r is the ratio of Manning coefficients between the main channel and floodplain (=n_f/n_c). Thus the zonal discharge can be obtained by:

$$Q_c = \frac{\sqrt{S_o}}{n_c} {A_c}^{5/3} (P_c + X_c)^{-2/3} \quad [8]$$

$$Q_f = \frac{\sqrt{S_o}}{n_f} {A_f}^{5/3} (P_f - X_f)^{-2/3} \quad [9]$$

In Eqs. (8) and (9), Manning's equation is used where Q is the discharge. It should be noted that $\%SF_f$in Eqs. (5-7) was empirically derived for the set of experiments where the largest width ratio of experimental tests range was used was 6.67. Note that it has not yet had any proposed model for $\%SF_f$ for rough asymmetric channels, which could be open for discussion in the future.

3. OVERVIEW OF DATASETS IN STUDY

To model $\%SF_f$, a wide range of datasets has been compiled and used here, given in Table 1. These datasets include small-scale experimental data and have large-scale heterogeneous and homogeneous symmetrical and asymmetrical data. Data from Flood Channel Facility (FCF) is also undertaken, archived by the first author (refer to www.flowdata.bham.ac.uk). Forty-two datasets are used here, 21 are smooth, and the others are rough compound channels. Three out of the first twenty-one have homogenous, smooth asymmetrical channels, while three from the 21 rough have heterogeneous asymmetric geometry (floodplain has differential roughness compared to the main channel). Table 1 summarizes all the relevant parameter ranges for each dataset in this study.

Table 1. Summarized range of experimental datasets for calibration of $\%SF_f$. Note that the nomenclature given for each data group is kept consistent throughout the study.

Nomenclature	B/b	h_f/B	Dr	$\%A_f$	$\%SF_f$	n_r
Smooth symmetric compound channel						
Knight and Hamed (1984)						
DWK2	2	0.000-0.486	0.000-0.493	0.000-33.01	0.000-48.65	1.00
DWK3	3	0.050-0.321	0.131-0.491	20.81-49.53	35.07-60.29	1.00
DWK4	4.01	0.030-0.242	0.108-0.493	24.55-59.75	42.97-6689	1.00
www.flowdata.bham.ac.uk						
Bham_S	3.05	0.006-0.075	0.069-0.477	12.36-49.38	23.00-59.67	1.00
FCF01	6.67	0.002-0.020	0.057-0.400	21.87-65.74	32.48-75.94	1.00
FCF02	4.2	0.002-0.044	0.042-0.479	10.15-56.34	22.70-65.00	1.00
FCF03	2.2	0.005-0.091	0.051-0.500	4.40-32.36	10.87-41.92	1.00
FCF08	4	0.003-0.050	0.050-0.500	13.09-58.47	25.75-70.01	1.00
FCF10	4.4	0.002-0.039	0.051-0.464	11.25-54.39	17.65-63.59	1.00
Patra et al. (2012)						
Patra	15.75	0.032-0.059	0.277-0.410	66.74-73.94	81.23-84.98	1.00
Khatua et al. (2011)						
Khatua	3.67	0.096-0.373	0.150-0.406	28.59-52.00	42.10-61.10	1.00
Mohanty et al. (2014)						
Mohanty	11.97	0.004-0.025	0.110-0.435	48.75-78.19	56.62-82.25	1.00
Prinos and Townsend (1984)						
PT1	3.05	0.019-0.094	0.089-0.329	20.83-48.07	42.20-58.36	1.00
PT2	2.87	0.019-0.094	0.089-0.329	15.87-40.21	35.98-50.97	1.00
Wormleaton et al. (1982)						
WH	4.17	0.025-0.116	0.111-0.368	26.06-53.89	39.91-60.89	1.00
Noutsopoulos and Hadjipanos (1983)						
NHA1	6.67	0.035-0.128	0.187-0.459	51.45-72.25	67.42-79.51	1.00
NHA2	5.53	0.075-0.165	0.286-0.468	61.82-72.62	73.85-79.22	1.00
NHA4	4	0.083-0.230	0.248-0.479	58.44-73.08	66.66-75.80	1.00

Nomenclature	B/b	h_f/B	Dr	$\%A_f$	$\%SF_f$	n_r
Smooth asymmetric compound channels						
www.flowdata.bham.ac.uk						
Bham_A	2.02	0.007-0.139	0.056-0.529	5.38-35.12	11.02-42.97	1.00
FCF06	2.7	0.004-0.075	0.052-0.503	6.65-40.41	11.06-53.90	1.00
Knight and Hamed (1984)						
DWK15	2.51	0.059-0.575	0.123-0.590	15.68-47.07	27.52-48.85	1.00
Rough symmetric compound channels						
Patra et al. (2012)						
Patra_R	15.75	0.000-0.058	0.000-0.408	0.00-73.83	0.00-83.02	1.12
Wormleaton et al. (1982)						
WH-B3	4.17	0.051-0.149	0.205-0.429	39.44-57.62	57.01-64.10	1.27
WH-C3	4.17	0.033-0.149	0.143-0.429	31.19-57.62	51.59-65.22	1.55
Wh-D3	4.17	0.033-0.149	0.143-0.429	31.19-57.62	54.77-66.86	1.91
Prinos and Townsend (1984)						
PTB1	3.50	0.019-0.094	0.089-0.329	20.83-48.07	43.13-59.22	1.27
PTC1	2.87	0.019-0.094	0.089-0.329	20.83-48.07	45.55-60.94	1.64
PTD1	3.50	0.019-0.094	0.089-0.329	20.83-48.07	47.97-63.08	2.00
PTB2	2.87	0.019-0.094	0.089-0.329	15.87-40.21	37.82-51.68	1.27
PTC2	3.50	0.019-0.094	0.089-0.329	15.87-40.21	40.37-53.48	1.64
PTD2	2.87	0.019-0.094	0.089-0.329	15.87-40.21	42.07-55.63	2.00
Knight & Demetriou (1983)						
DWKR41	4.01	0.056-0.412	0.123-0.508	27.07-60.48	41.94-69.04	1.11-1.16
DWKR51	4.01	0.045-0.405	0.101-0.504	23.30-60.28	54.01-71.94	1.34-1.22
DWKR61	4.01	0.050-0.479	0.111-0.545	25.13-62.17	45.78-77.52	1.63-1.38
DWKR71	4.01	0.051-0.546	0.113-0.578	25.41-63.52	46.83-83.93	2.40-1.69
DWKR81	4.01	0.051-0.599	0.113-0.600	25.45-64.39	51.87-85.84	3.74-2.04
DWKR91	4.01	0.064-0.407	0.138-0.505	29.33-60.34	56.85-86.49	4.77-2.51
DWKR131	2.00	0.092-0.684	0.122-0.506	29.33-60.34	56.85-86.49	5.20-2.34
DWKR141	3.00	0.070-0.521	0.122-0.510	19.65-50.50	52.64-82.61	5.86-2.75
Rough Asymmetric compound channels						
Knight & Demetriou (1983)						
DWKR110	4.01	0.056-0.421	0.123-0.513	15.63-43.60	40.74-70.86	5.22-2.49
DWKR111	3.00	0.078-0.524	0.134-0.512	11.86-33.84	40.21-66.20	4.83-2.45
DWKR121	2.00	0.132-1.044	0.117-0.511	5.51-20.34	34.78-55.56	5.39-2.33

4. RESULTS AND DISCUSSIONS

Based on the forty-two data in Table 1, we proposed the following new sets of formulas using the GEP analysis:

$$\%SF_f = 3.3320 \times \%{A_f}^{0.7645} - 14.6809 \times Dr^{0.9402} + k \qquad [10]$$

$$k = \log n_r \times \left(9.2743 + 11216.4057 \times Dr^2 \times (1 + \%A_f)^{-1.437}\right) \qquad [11]$$

In modeling, Eq (10) is for the smooth and rough compound channels, while the model of k is given in Eq. (11). The value of the k model is based on the roughness ratio such that it takes the value zero for smooth channels. The overall model Eq. (10) has unified in such a way that one model is sufficient to predict $\%SF_f$ for any kind of compound channels. Note that n_r is n_f/n_c, Dr is $(H-h)/H$, where h is the bankfull depth and the log used is the natural logarithm. The $\%SF_f$ is defined as the shear force percentage of floodplain per weight of fluid ($\rho g R_f S_o$) and $\%A_f$ is the area of floodplain per total area of the channel.

To demonstrate the predictability and efficiency of the model given in Eqs. (10), and (11), proposed in this paper, Fig. 2 is shown. For each experimental set of smooth and rough compound channels, the error percentage of the predicted $\%SF_f$ is calculated by Eq. (12). Fig 2 (a) and (b) depict the scatter plot of the predicted versus experimental $\%SF_f$ for smooth and rough compound channels, respectively. For the entire datasets combined for the smooth compound channels, the R^2 value is 0.98, and for the rough compound channels, the R^2 value is 0.87. On the other hand, Fig. 2 (c) shows the number of modeled data sets having percentage error within the range of less than 3%, 10%, and 20%. The upper cap for this analysis is kept as data having a percentage error of more than 20%. Only 1% and 1.6% of the predicted $\%SF_f$ data are found above this categorical value of more than 20% for smooth and rough compound channels, respectively. The new model's overall performance ranges under 3% error with 57% and 44% of modeled data and 10% with 87% and 84% for smooth and rough channels, respectively.

$$\%Error_i = \frac{|Predicted_i - Experimental_i|}{Experimental_i} \times 100\% \qquad [12]$$

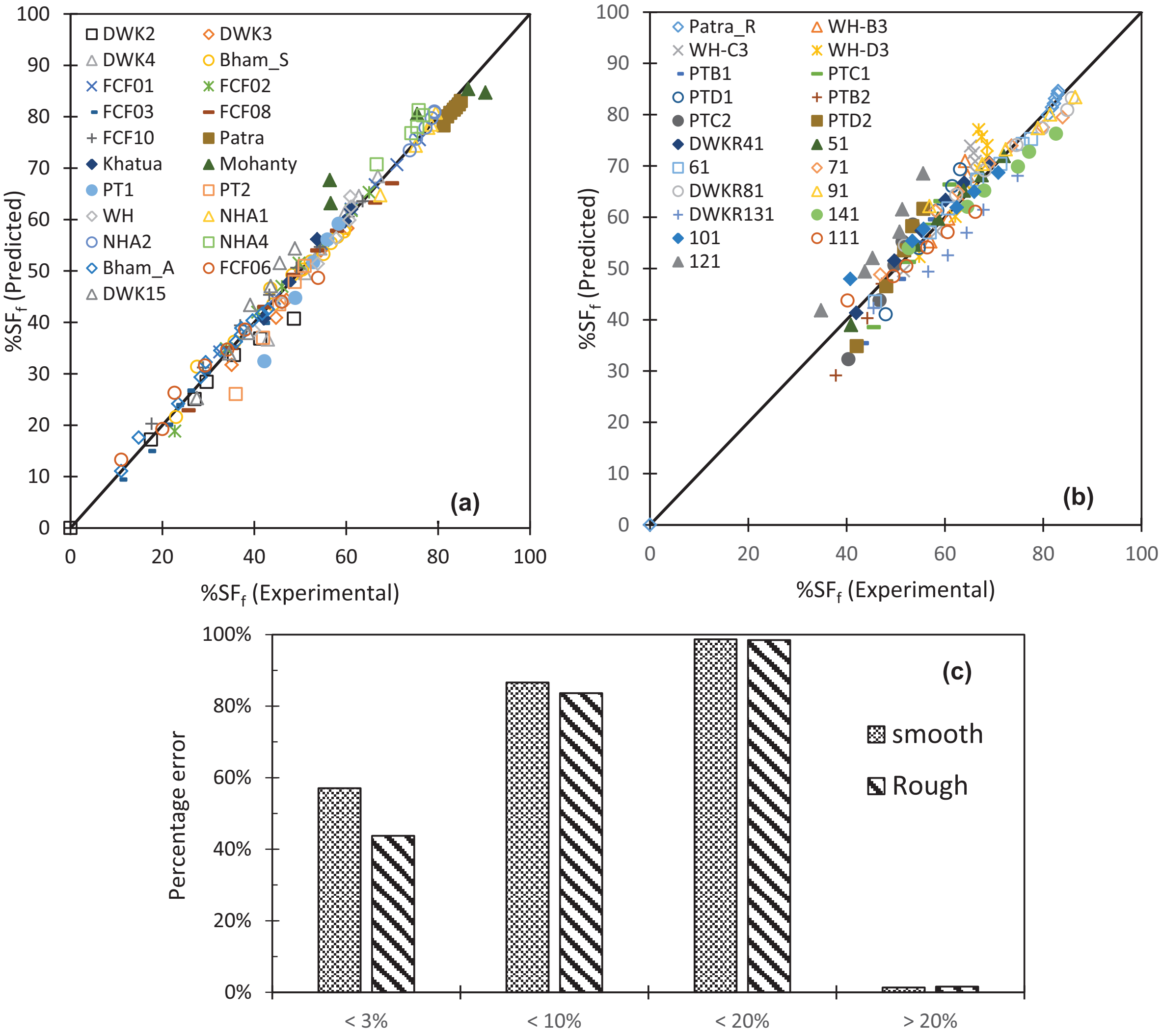

Figure 2. Comparison of experimental and estimated $\%SF_f$ for compound channels with (a) smooth and (b) rough symmetric and asymmetric configurations. (c) Percentage error cap of the estimated $\%SF_f$ in four categorical sets out of 149 and 128 smooth and rough test datasets.

A practical property of the proposed new model is to yield zonal and overall discharge using linear scale analytical solution given through Eqs. 3-4, Eqs. 8-9 and Eqs. 10-11. To estimate the discharge, the divided channel method can be applied by including the interacting length to the main channel wetted perimeter and excluding the wetted perimeter of the floodplain (see Eqs. 8-9). The sign convention in the equation explains the momentum transfer concept from the main channel to the floodplain. Also, the concept of zero shears at the suitable interface without momentum transfer is conjecture that the interacting length is zero.

Four independent datasets corroborate the overall discharge for experimental data using the proposed model, which are given in Table 2. Figure 3 shows the predicted discharge's percentage error (Eq. 12) using DCM (VD) with vertical division and the proposed model (new model). The performance of the proposed model is less than 5% for all the ranges of depth in smooth and rough compound channels, except for the rough asymmetric data of Joo and Seng (2008). However, DCM (VD) performed unsatisfactorily with 23.6% for the same data, and the proposed model still had the range in the 10% bracket for different depth ratios.

Table 2. Validation experimental set for the corroboration of the discharge estimation

Nomenclature	B/b	h_f/B	Dr	Q (m^3/s)	n_r
Smooth symmetric compound channel					
Yang et al. (2007)	3.75	0.13	0.03-0.41	0.143-0.447	1.00
Rough symmetric compound channel					
Hu et al. (2010)	3.33	0.20	0.00-0.54	0.009-0.038	1.18
Smooth asymmetric compound channel					
Joo & Seng (2008)	5.00	1.00	0.00-0.26	0.004-0.006	1.00
Rough asymmetric compound channel					
Joo & Seng (2008)	5.00	1.00	0.00-0.34	0.003-0.006	1.90

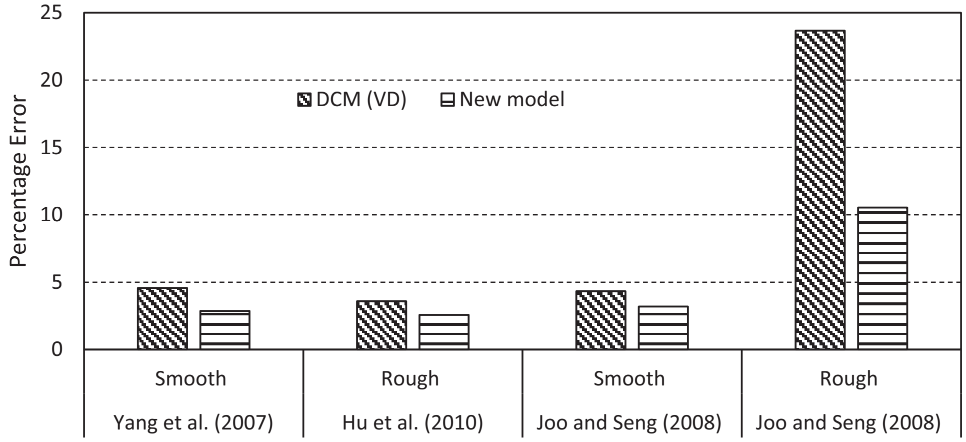

Figure 3. Average percentage error of the overall discharge for smooth, rough symmetric, and asymmetric compound channels

5. CONCLUSIONS

A new unified model of $\%SF_f$ is proposed using a genetic algorithm for the smooth and rough asymmetric and symmetric compound channels using dynamic datasets. The unified model has a tuning term defined as k, which can generally be used for any compound channels irrespective of roughness configuration. The value of k is reduced to zero when n_r takes the value of one for smooth channels or otherwise adjust the overall $\%SF_f$ value through an associative property of addition. The following model is further tested to corroborate discharge estimation using the inclusive, interactive length concept in DCM methodology. The analytical method for estimating flow discharge performs better than the DCM method for symmetrical and asymmetrical channels. Further corroboration of the present model can be tested for the real-time datasets to check the overall performance of the inclusive, interactive length concept incorporating the proposed unified $\%SF_f$ model based on genetic algorithm.

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