A PRACTICAL METHOD FOR PREDICTING THE DISCHARGE IN ALLUVIAL AND RIGID BOUNDARY TWO STAGE CHANNELS

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ABSTRACT:

Equilibrium laboratory straight bank full flow channels were established. These channels were then left to develop freely under over bank flow conditions until they adjusted to a new regime condition. From the analysis of the data a new method for predicting the total flow in compound channels is proposed. This method considers a compound channel between two extreme points. The first is the channel at the threshold of inundation (at relative depth = 0) and the second is the channel is inundated to a maximum level (the relative depth approaches unity). At these two extremes the total flow can be calculated by the single channel method and between them this method assumes that the total flow is partially calculated by the single channel method and partially by the traditional divided channel method. The portions of flow calculated by the single and the divided channel methods rely on two adjustment factors, AF1 and AF2 respectively. These adjustment factors are function of two dimensionless parameters, the relative depth and the channel coherence and hence this method is termed the Dimensionless Total Flow Adjustment Method (DTFAM). This method was tested using mobile boundary data and rigid boundary data from different sources then compared with Ackers [1] Coherence method (COHM) and the Lambert and Myers [2] weighted divided channel method (WDCM). The result shows that this method is simpler and predicts more satisfactory total discharge values than the COHM and WDCM do. This method can be applied to symmetric or asymmetric channels with homogeneous or non-homogeneous roughness.

1 INTRODUCTION

Predicting conveyance and roughness of alluvial channels during overbank flow is a major problem to engineers involved in the design and management of irrigation channels, rivers and drainage systems. This is because of the interaction effect between fast flow of the main channel and the slow flow of the floodplains, which results in transfer of momentum from the main channel to the floodplains. Most conventional methods of discharge calculations, such as Chow [3], attempt to account for the large variation in velocity across the channel section by dividing it into sub-sections, each of which is considered as hydraulically homogenous. The discharge in each sub-section is then calculated using one of the well-known formulae such as Chezy, Manning or Colebrook-White. However, such traditional method fails to take this interaction effect into account, which results in poor estimation of discharge.

Taking this interaction into consideration different one-dimensional (1D), two-dimensional (2D) and three-dimensional (3D) models have been developed. Examples of 1D empirical models based on apparent shear stresses acting on a particular interface are those developed by Wormleaton, Allen & Hadjipanos [4], Knight & Demetriou [5] and Wormleaton & Merrett [6]. 2D models based on depth averaged parameters have been developed to give lateral distribution of both velocity and boundary shear stress. See for example, Keller & Rodi [7] and Shiono & Knight [8,9]. Examples of 3D turbulence models are those developed by Krishnapan & Lui [10] and Tominaga & Nezu [11]. 2D and 3D models are more complicated and hence they are more frequently used as research tools than for design purposes. 1D models are less accurate, but due to their simplicity practical engineers favour them; such models are those produced by Ackers [12,1] and Lambert and Myers [2]. These two models adopt different concepts in which the interaction effect is implicitly expressed as explained hereafter.

The intensity of the interaction effect between the main channel and the floodplain flows has been related to the relative depth, H*, [H*=(H-h)/H] by all researchers dealing with compound channels. A typical compound channel and symbols used are shown in Figure 1.

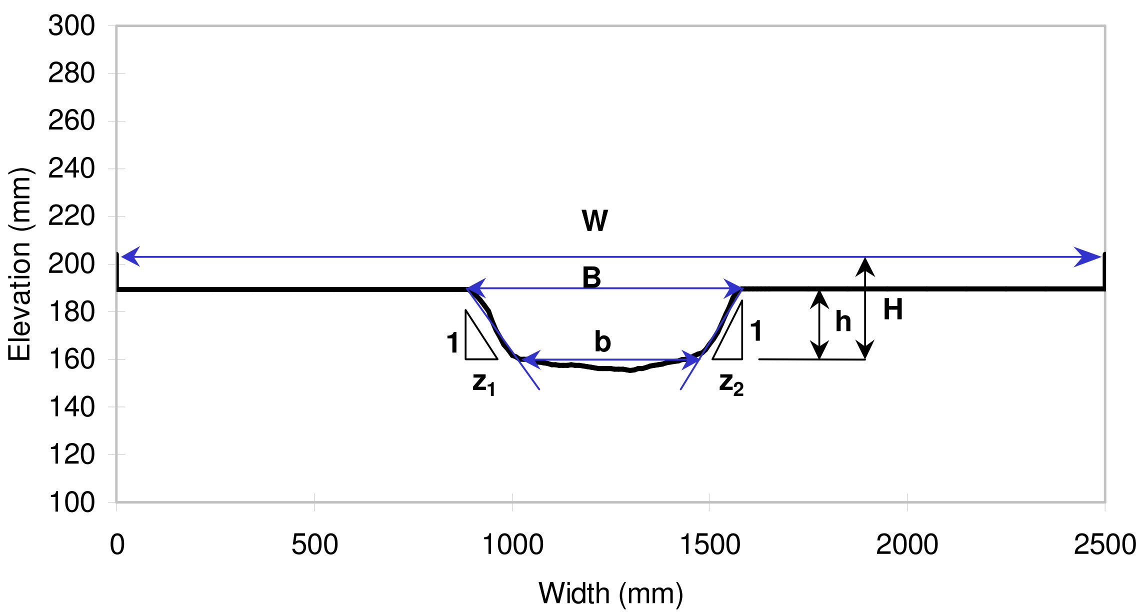

Figure 1: The applied average hydraulic parameters in an overbank cross-section.

Ackers [12,1] merged all the parameters that have influence on the interaction effect in one dimensionless parameter termed the channel Coherence (Coh), and came up with a practical 1D model known as the Coherence method. The coherence of a compound channel is defined as ratio of the nominal conveyance calculated by treating a channel as a single unit to that calculated by summing the conveyances of the separate flow zones. When Manning equation is used it is expressed as,

$$Coh = \frac{\dfrac{\sum_{i=1}^{i=N} A_i^{5/3}}{\sum_{i=1}^{i=N}\left[n_i p_i^{2/3}\right]}}{\sum_{i=1}^{i=N}\left[\dfrac{A_i^{5/3}}{n_i p_i^{2/3}}\right]} \qquad (1)$$

where p_i, A_i and n_i are wetted perimeter, area and the Manning's roughness coefficient of i=1 to N flow zones respectively. Based on the Coherence concept, Ackers [12,1] was the first who linked the intensity of the interaction effect to different regions of flow. The existence of different regions of flow also confirmed by Haidera and Valentine [13]. In this method, first the nominal total conveyance of a channel is computed using the traditional divided channel method with a vertical interface, which is excluded from the wetted perimeter calculation. The nominal total conveyance is then adjusted for the interaction effect using different empirical adjustment factors in each region of flow. Finally, a procedure has to be followed in order to define the applicable region of flow and hence selecting the appropriate total adjusted flow.

Another 1D model of practical use is that developed by Lambert & Myers [2]. Lambert and Myers [2] Weighted Divided channel Method (WDCM) assumes there is an interface appropriate to account for the momentum transfer and this interface lies somewhere between the horizontal and vertical interfaces. Instead of determining the location of this interface explicitly, they suggested a weighting factor to allow a transition between the velocities determined by assuming a horizontal interface and a vertical interface. Though, they stated that this factor varies between 0 and 1, they gave a single weighting factor value of 0.5 for smooth channels and 0.2 for rough channels.

It has been known that the intensity of the interaction effect varies with the relative depth and hence any correction factor used to account for this variation must be a function or a series of constants to be introduced at different relative depths (or range of relative depths). Thus, due to the long procedure associated with the empirical nature of the Ackers [12,1] Coherence method (COHM), and the use of an empirical single weighting factor by Lambert and Myers [2] Weighted Divided channel Method (WDCM), these methods do not meet all flow conditions. From the above discussion it can be understood that there is a need for a simple formula close to the form of the WDCM but which has variable adjustment factors making use of the relative depth and the Ackers Coherence concept.

2 OBJECTIVES AND PROCEDURE

The main objective of this study was to produce a simple and practical method for predicting the total discharge in rigid and loose boundary compound channels. Rigid boundary data are available in literature while loose boundary compound channels data are scarce. Therefore, free-form overbank flow tests had to establish. The programme included 26 overbank flow tests divided into two series, A & B, with slopes around 0.0017m/m and 0.00214m/m respectively. The first series, A, was divided into two sub-series, the first included 6 bankfull flow tests with discharges range from 2 to 6ls^{-1} followed by 6 overbank flow tests with discharge of 15ls^{-1}. The next sub-series included 7 bankfull flow tests with discharges range from 2 to 6ls^{-1} followed by 7 overbank flow tests with discharges around 25ls^{-1}. The same was applied to series B but with slope around 0.00214m/m.

For each test, a bankfull flow channel was first developed until the rate of widening became less than 2% per hour, which suggest an equilibrium state. The discharge was then increased to the required overbank discharge and run until the widening rate also became 2% per hour. For all experiments uniform flow was established by adjusting the tilting gate such that the difference between the water surface slope and the bed slope was less than 3%. The initial sections (screeded sections) of the bankfull flow channels were predicted using the White, Bettess & Paris theory [14] (WBP method). They were trapezoidal with side slope z =1 (1 vertical: z horizontal). In all tests sediment was bed load only and recirculated in the main channel while the floodplains were kept below the threshold of motion. These experiments were carried out in flume 22m long, 2.5m wide and 0.6m deep filled with uniform sand of 1mm median size.

For every experiment, traversal velocity profiles and cross-sectional profiles were measured at three sections three meters apart. By dividing these cross-sectional profiles into small trapezoidal strips the wetted perimeter, cross-sectional area, depth and side slope were calculated, and then their average values were adopted. From the velocity profiles the total discharge in the channel was obtained and compared with the flow meter reading. For details see Haidera and Valentine [15, 13]. As an example, the adopted average hydraulic parameters in a final overbank section are shown in Figure 1. For the side slope an average value of z_1 and z_2 was adopted.

3 METHOD DEVELOPMENT

In a compound channel it is known that the interaction between the main channel and the floodplain flows is a maximum at lower relative depths then it decreases with the increase in the relative depth until it become negligible at higher relative depths. When the relative depth of a compound channel approaches unity the channel coherence approaches unity (Ackers [12,1]) and hence the divided channel method with vertical division and the single channel method calculations are approximately equal. Thus, consider a bankfull flow channel where its banks are inundated gradually until reaches a maximum level. Assume also that according to the channel coherence at each relative depth the total discharge in the compound channel is partly calculated by the single channel method and partly by the divided channel method with vertical division according to the equation,

$$Q = AF_1 Q_{SC} + AF_2 Q_{DC\text{-}v} \qquad (2)$$

where Q is the total adjusted flow, AF_1 and AF_2 are adjustment factors must be function of (H*, Coh). To determine these adjustment factors two extreme boundary conditions were considered; at which the channel can be treated as a single unit. These are, the compound channel is at the threshold of inundation (at relative depth = 0, i.e. bankfull channel) and the channel is inundated to a maximum level (the relative depth approaches unity).

At the first boundary condition, i.e. when H*=0, the flow can be calculated by the single channel method only if $AF_2 = \varphi(H^*) = 0$ and $AF_1 = \varphi(H^*, Coh) = 1$ or if $AF_1 = \varphi(H^*) = 0$ and $AF_2 = \varphi(H^*, Coh) = Q_{SC}/Q_{Dc\text{-}v}$. The first assumption does not satisfy Eq.2, because at H*=0 the Coh≠1. The second assumption satisfies Eq.2 only if $AF_2 = (Coh - H^*) = Q_{SC}/Q_{Dc\text{-}v.}$ Based on this Eq.2 can be rewritten as,

$$Q = H^* Q_{SC} + (Coh - H^*) Q_{DC\text{-}v} \qquad (3)$$

Thus, at the first boundary condition, $H^*=0$ and $Coh-H^* = Q_{SC}/Q_{Dc\text{-}v}$ as $Coh = Q_{SC}/Q_{Dc\text{-}v}$ and hence $Q = Q_{SC}$. At the second boundary condition, $H^* \approx Coh \approx 1.0$, $Coh-H^* = 0$ and hence $Q=Q_{SC.}$ As AF_1 and AF_2 are dimensionless factors, this method will be termed the Dimensionless Total Flow Adjustment Method (DTFAM).

Between the two boundary conditions, i.e. when $0<H^*<1$ it was hypothesised that the total adjusted flow is contributed by both the single channel method and the divided channel method with ratios equal to their adjustment factors AF_1 and AF_2. It was found (Ackers [12], Haidera and Valentine [13]) that when the relative depth increases the channel coherence increases too. Consequently, it is expected that the portion of discharge contributed by the single channel method will increase with the relative depth. In other words, at lower relative depths the divided channel method contributes most of the discharge while at higher relative depths the single channel calculation dominates as the channel approaches the single unit behaviour. To test this hypothesis the DTFAM was applied to the present loose boundary data (Figure 2). Figure 2 shows the total adjusted discharge, the measured discharge and the contributed discharges by the divided channel method with a vertical division and by the single channel method. It can be seen in Figure 2 that at low relative depths most of the total discharge is dominated by the DC-v calculation but when the relative depth approaches 0.5 the contributed discharges by the DC-v and the SC methods are approximately equal. This is because when the relative depth approaches 0.5 the channel coherence also approaches unity. Above relative depth of 0.5 most of the discharge is contributed by the SC as the channel approaches single channel behaviour; this is why Ackers (1992, 1993) suggested that the channel should be treated as a single unit. In fact, above relative depths of 0.5, though the SC contributes most of the discharge (Figure 2), it is not correct to treat the compound channel completely as a single unit. This is evident in Figure 3 which shows that at higher relative depths (≥ 0.6) the SC and the DC-v total discharge calculations are very close but not equal.

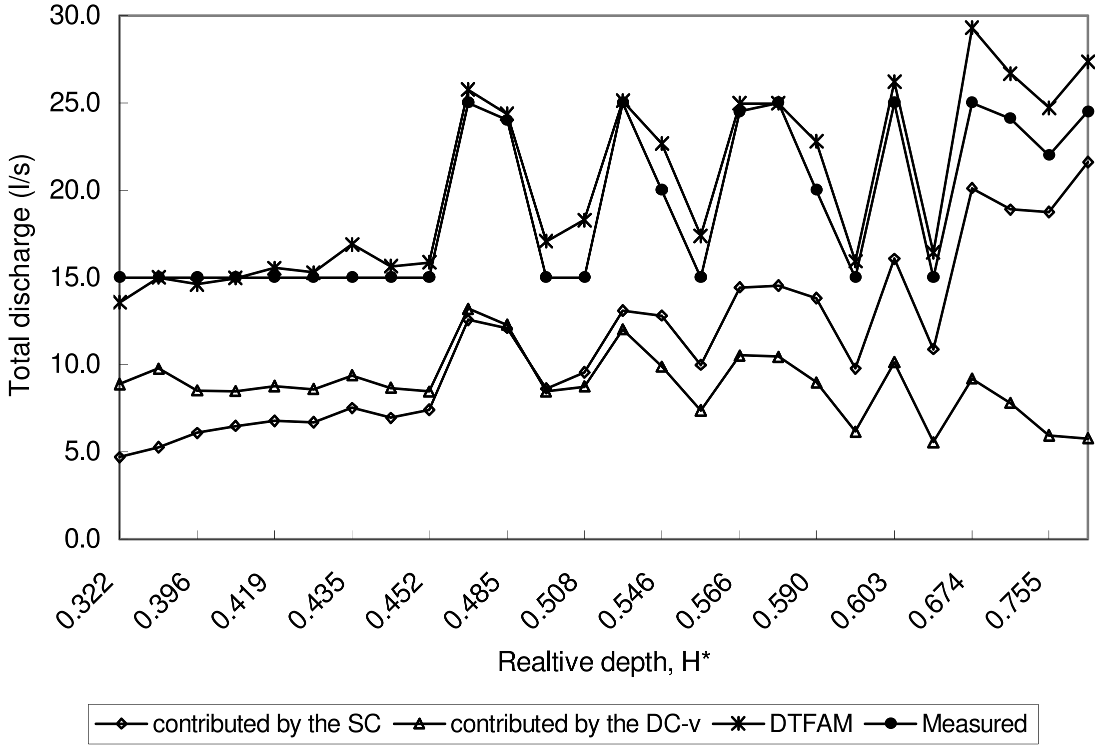

Figure 2: The contributed discharge by the divided and the single channel methods to the total discharge using present data.

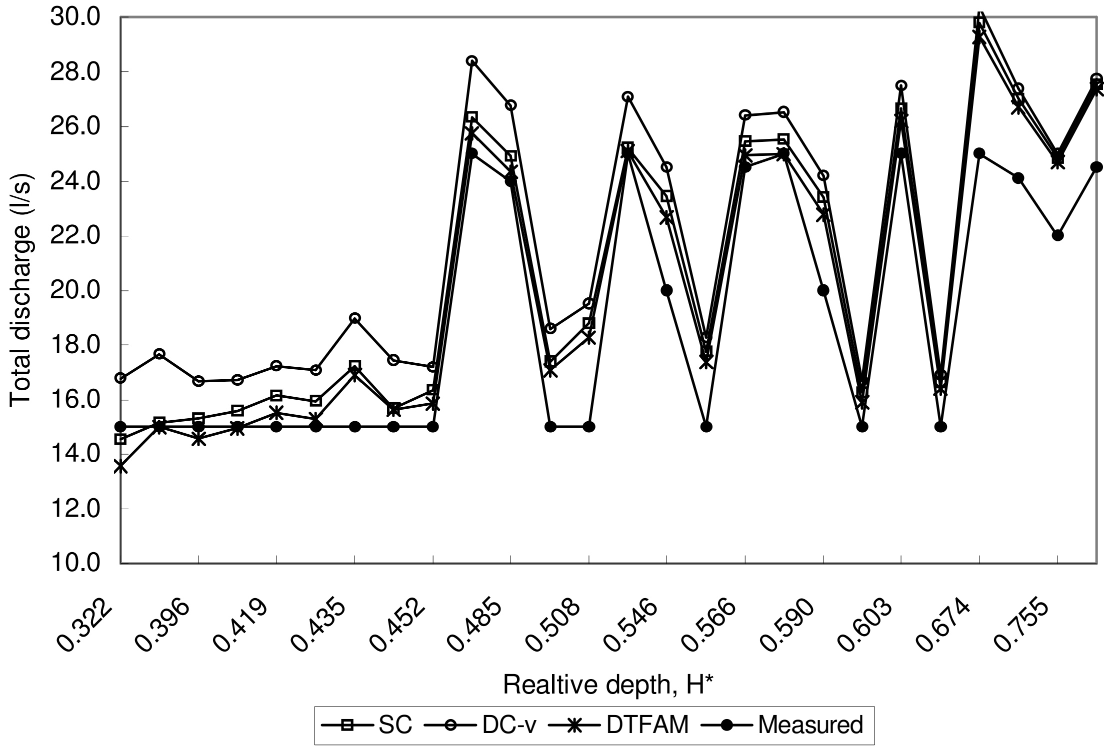

Figure 3: Comparison between the DTFAM, the divided and single channel methods total discharge prediction using present data.

This is because at higher relative depths the interaction effect between the main channel and the floodplain is not completely negligible. Figure 3 also shows that the predicted total discharges by the new method (DTFAM) are very close to the measured values compared with the SC and the DC-v methods.

3 COMPARISON WITH ACKERS AND LAMBERT-MYERS METHODS

3.1 Using mobile boundary data

Figure 4 shows a comparison between the, the DTFAM, the COHM and the WDCM predictions using the present loose boundary data. For loose boundary compound channels Figure 4 shows that the DTFAM predicts better total flows than the Lambert-Myers WDCM and the Ackers COHM methods. The COHM though it overpredicts the total discharge it comes next while the WDCM overpredicts the total discharges especially above relative depth of 0.5 (see Figure 4 and Table 2). Table 2 shows a comparison between these methods in terms of the Mean Absolute Error (MAE), the Maximum Error (Max.E) and Minimum Error (Min.E). As can be seen in this table, for the loose boundary data the MAE is 7.64% for the DTFAM, 11.13% for the COHM and 14.8 for the WDCM.

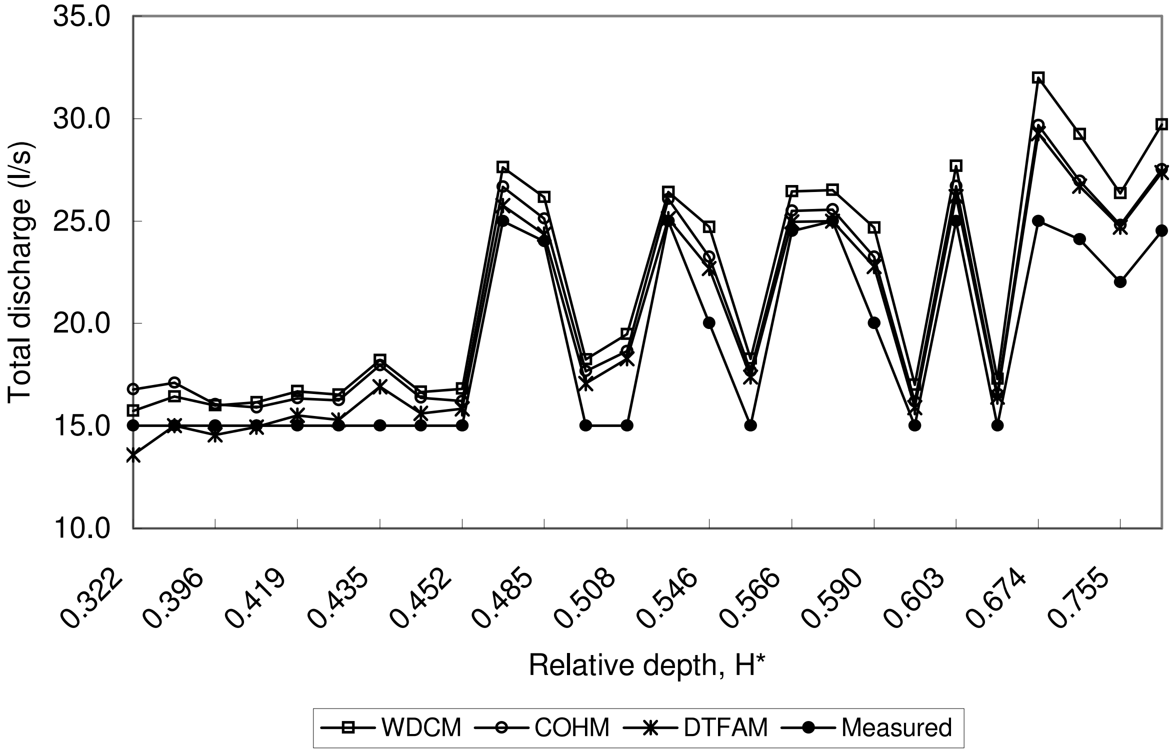

Figure 4: Comparison between the DTFAM, the COHM and WDCM total discharge prediction using present data.

3.2 Using mobile and rigid boundary data

Figure 5 shows a comparison between all these methods, but in terms of the discharge discrepancy ratio using the present alluvial overbank flow tests and 58 rigid boundary tests chosen from the sources shown in Table 1. As shown in Figure 5, the best predicted total discharge is obtained by the DTFAM, where most of the data is located within SD=1 then the COHM and finally the WDCM. For the rigid boundary tests the best predicted total discharge was obtained by the DTFAM where the MAE is 5.13%, while the WDCM and the COHM come next and have approximately the same accuracy (see Table 2, Row 1). If the total data are considered the DTFAM also predicts more satisfactory values than the COHM and the WDCM methods (see Table 2, last row).

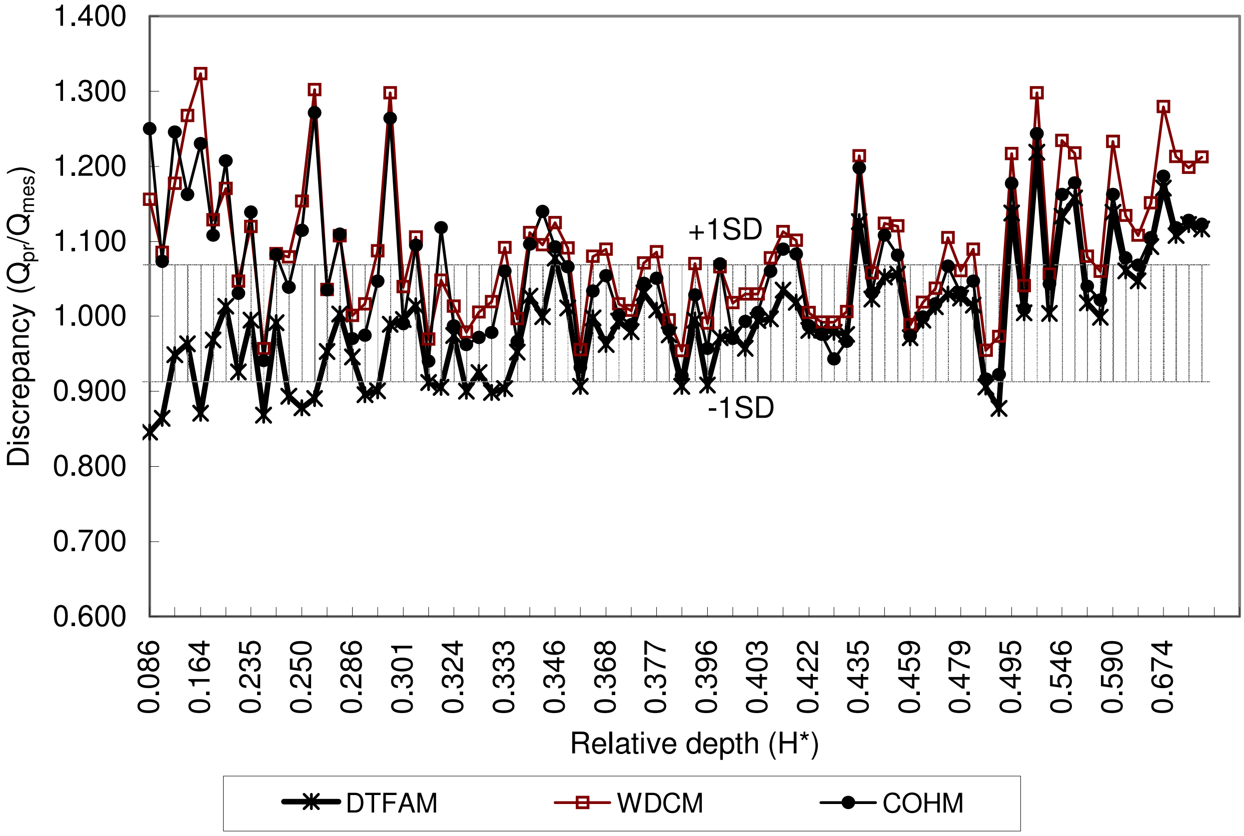

Figure 5: Comparison between the DTFAM, COHM and WDCM total discharge prediction using loose and rigid boundary compound channels.

4 CONCLUSIONS

In this study a new method for predicting the total discharge was developed. This method is based on Ackers channel coherence concept and relies only on two dimensionless adjustments factors vary with the relative depth. These adjustment factors are only functions of relative depth and channel coherence, which makes the method very simple to apply. In addition it uses the well-known traditional divided channel method with vertical division and the single channel method. This method has improved features than the other 1D methods, which are summarised as,

1. Simple and dimensionless which may make it of general use by practice engineers.
2. Can be applied to loose and rigid boundary channels with homogenous or nonhomogeneous roughness (refer to Table 2).
3. Can be applied to symmetric and asymmetric channels.
4. It predicts better discharge values compared with the Coherence and the Weighted Divided Channel methods.

Because this method does not predict the components of discharge in the compound channel it is recommended to use the WDCM method to calculate the discharge in the main channel, in cases where the sediment transport needs to be quantified.

Data source	Channel type	NO.	Channel characteristics							
			$Q(ls^{-1})$	$S*10^{-3}$	(H-h)/H	n_{fp}/n_{mc}	W/B	B/h	b/h	z
Prinos et al. [16]	Rigid symmetric	2	30.2,32.2	1.0	0.164	1.0-1.273	2.701	5.98	4.98	0.5
Knight and Demetrriou [5]	symmetric	13	7.3-29.4	0.966	0.131-0.506	1.0	2.0-4.0	2.0	2.0	0.0
Wormleaton et al. [4]	symmetric	17	15.0-48.0	0.430	0.250-0.429	1.308-1.963	4.175	2.417	2.417	0.0
Nousopoulos and Hadjipanos [17]	symmetric	16	9.0-45.0	1.5	0.187-0.479	1.0	4.0-6.667	2.0	2.0	0.0
Myers [18]	asymmetric	10	6.3-18.2	0.265	0.086-0.394	1.0	3.803	2.49	2.49	0.0
Present data	Loose symmetric	26	15.0-25.0	1.6-2.19	0.32-0.784	0.917-1.0	2.66-5.682	17.983-99.328	9.741-59.597	3.145-19.866
	Total	84								

Table 1: The experimental data, characteristics and sources, which used in the comparison

Channel boundary	Error Type	DTFAM	COHM	WDCM
Rigid 58 tests	**MAE(%)**	5.13	6.91	7.35
	Max.E(%)	-15.40	27.13	32.31
	Min.E(%)	-0.17	-0.08	0.09
Loose 26 tests	**MAE(%)**	7.64	11.13	14.80
	Max.E(%)	21.86	24.36	29.78
	Min.E(%)	-0.03	2.17	4.85
Total 84 tests	**MAE(%)**	**5.91**	**8.22**	**9.66**
	Max.E(%)	**21.86**	**27.13**	**32.31**
	Min.E(%)	**-0.03**	**-0.08**	**0.09**

Table 2: Mean Absolute Error (MAE), Maximum Error (Max.E) and Minimum Error (Min. E) for different methods in predicting total discharge in compound channel with loose and rigid boundaries (Table 1).

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