

CD اصل مقاله در مجله

ENERGY AND MOMENTUM APPROACHES FOR ANALYSIS OF GRADUALLY-VARIED FLOW THROUGH COMPOUND CHANNELS

S. M. R. Alavi Moghaddam⁽¹⁾, S. M. Hosseini⁽²⁾

⁽¹⁾Lecturer, Civil Engineering Department, Islamic Azad University of Mashhad, Presently: Ph. D. Candidate, Hydraulic Engineering, Ferdowsi University of Mashhad, Mashhad, Iran
phone: +98 511 8763303; fax: +98 511 8763301; e-mail: alavimoghaddam@yahoo.com

⁽²⁾Associate Professor, Civil Engineering Department, Ferdowsi University of Mashhad, Mashhad, Iran

phone: +98 511 8763303; fax: +98 511 8763301; e-mail: shosseini@ferdowsi.um.ac.ir

ABSTRACT

Energy and momentum approaches can lead to different results in one dimensional analysis of flow through compound channels and therefore a choice between these two equations must be made to analyse the flow. This investigation is an effort to provide some insight into the validity of these two approaches for one dimensional analysis of steady gradually-varied flow through compound channels. To achieve this, at first the energy and momentum equations and a comprehensive form of steady gradually-varied flow governing equation (G.E.) are introduced. As the G.E. shows and it has been reported in the literature, the accuracy of the two approaches depend on two important factors. 1) correct evaluation of friction or energy slopes and 2) selection of a proper functional form for Froude number. It is a common practice to assume that energy and friction slopes are equal and can be estimated by typical resistance equations for corresponding steady uniform flow (conveyance estimation methods). This is a reasonable assumption and is justified because of the inexact empirical methods involved in evaluating the slopes. Then several computed water surface profiles corresponding to experimental data (M1, S1 and S2 types) are developed by combinations of different conveyance methods and Froude number definitions. Finally, experimental data collected in this study and those reported in the literature are used to compare different computed water surface profiles with laboratory measurements. The study indicates that the momentum principle is more consistent with corresponding steady uniform flow energy friction slope for water surface profile computation in compound channels at least for the profile types considered in this study. Interestingly, this result is independent of the conveyance method used to estimate the corresponding steady uniform flow energy friction slope.

Keywords: compound channel, conveyance, energy equation, Froude number, momentum equation, water surface profile

ENERGY AND MOMENTUM APPROACHES FOR ANALYSIS OF GRADUALLY-VARIED FLOW THROUGH COMPOUND CHANNELS

S. M. R. Alavi Moghaddam⁽¹⁾, S. M. Hosseini⁽²⁾

⁽¹⁾Lecturer, Civil Engineering Department, Islamic Azad University of Mashhad,
Presently: Ph. D. Candidate, Hydraulic Engineering, Ferdowsi University of Mashhad, Mashhad, Iran
phone: +98 511 8763303; fax: +98 511 8763301; e-mail: alavimoghaddam@yahoo.com

⁽²⁾Associate Professor, Civil Engineering Department, Ferdowsi University of Mashhad, Mashhad, Iran
phone: +98 511 8763303; fax: +98 511 8763301; e-mail: shosseini@ferdowsi.um.ac.ir

ABSTRACT

Energy and momentum approaches can lead to different results in one dimensional analysis of flow through compound channels and therefore a choice between these two equations must be made to analyse the flow. This investigation is an effort to provide some insight into the validity of these two approaches for one dimensional analysis of steady gradually-varied flow through compound channels. To achieve this, at first the energy and momentum equations and a comprehensive form of steady gradually-varied flow governing equation (G.E.) are introduced. As the G.E. shows and it has been reported in the literature, the accuracy of the two approaches depend on two important factors, 1) correct evaluation of friction or energy slopes and 2) selection of a proper functional form for Froude number. It is a common practice to assume that energy and friction slopes are equal and can be estimated by typical resistance equations for corresponding steady uniform flow (conveyance estimation methods). This is a reasonable assumption and is justified because of the inexact empirical methods involved in evaluating the slopes. Then several computed water surface profiles corresponding to experimental data (M1, S1 and S2 types) are developed by combinations of different conveyance methods and Froude number definitions. Finally, experimental data collected in this study and those reported in the literature are used to compare different computed water surface profiles with laboratory measurements. The study indicates that the momentum principle is more consistent with corresponding steady uniform flow energy/friction slope for water surface profile computation in compound channels at least for the profile types considered in this study. Interestingly, this result is independent of the conveyance method used to estimate the corresponding steady uniform flow energy/friction slope.

Keywords: compound channel, conveyance, energy equation, Froude number, momentum equation, water surface profile

1 INTRODUCTION

One dimensional analysis of flow through open channels is generally done by combining continuity equation with one of the energy or momentum equations. Selection of the energy or momentum equation depends on the problem under study and our interpretation of the phenomenon. In general, it can be said that in the analysis of local phenomena, when boundary shear stresses or forces involved in the problem are noticeable and unknown, but energy losses are negligible or known independently, the energy equation is a good start to analyse the flow. Analysis of flow over a short smooth step placed in the bottom of a channel is a good example of such analysis. After analysing the flow using energy equation (ignoring losses), and finding the depth of flow over the step, the momentum equation can be used to find the force on the step, if required. A different problem is the hydraulic jump in a horizontal channel. For the analysis of this phenomenon, the energy losses are noticeable and unknown while it is commonly assumed that the boundary shear forces and weight

component in the direction of flow can be ignored. Therefore, the momentum equation is a good start. After analysing the flow using the momentum equation, the energy equation can be used to find energy loss in the jump.

In gradually-varied flows, as longitudinal phenomena, both boundary shear stresses and energy losses are noticeable and unknown. Therefore, two different terms, energy (S_e) and friction (S_f) slopes find meaning and appear in the one dimensional analysis of flow and as stated by Field *et al.* [1] there continues to be considerable confusion in the literature about the use of energy or momentum equations in analyses of flow in one dimensional open channels. Almeida [2] provides a good insight into the subject by giving a more justified explanation of the terms starting from steady uniform flow. He states that the free-surface uniform and steady flow, is a unique situation in which $S_e = S_f = S_0$. In this case, using the concept of a one dimensional finite global control volume, the work developed by the gravity force is nullified or dissipated by the internal viscous process. However, within the frame of a water column model, with a pseudo cross-section uniform flow velocity, this work is balanced by the boundary shear or friction force in order that flow kinetic energy be constant [2]. He comments that in general $S_e \neq S_f$ and S_e can be greater or less than S_f depending on the type of the water surface profile [2]. The question is "What factors contribute to the difference between the two terms and how big the differences can be?". Many factors such as non-uniform velocity distribution and its variation with depth, curvature of the flow and even pressure distribution can contribute to the difference of the terms. As stated by Almeida, the problem of a more accurate prediction of S_e and S_f remains almost unsolved. Therefore, it is a common practice and reasonable approximation in engineering practice to estimate the slopes by typical resistance equations for corresponding steady uniform flow. In addition to the energy and friction slopes, other factors such as Froude number definition also affect the numerical results of energy and momentum equations in situations such as analysis of flow through compound channels.

Fig. 1 shows the general configuration of a compound channel. A compound channel consists of a main channel and one or two floodplains. Different flow velocities in the main channel and floodplains produce an interaction region between sub-sections and hence traditional methods such as Manning equation fail to estimate the conveyance of the channel. Therefore, one dimensional analysis of flow is based mainly on refined conveyance estimation methods. In the context of this paper, these methods are used to evaluate energy or friction slope depending on the equation used. Energy and momentum equations can lead to different results in this case and therefore a choice between these two equations must be made to analyse the flow. Field *et al.* [1] indicated the important differences between the energy and momentum equations for compound channels, but because of the lack of suitable experimental data, they failed to present the superiority of one to the other and suggested the necessity for more experimental and field measurements.

This paper is an effort to shed more light on the validity of these two approaches for one dimensional analysis of steady gradually-varied flow through compound channels. To achieve this, several computed water surface profiles corresponding to experimental data (M1, S1 and S2 types) are developed by combinations of different conveyance methods and Froude number definitions in energy and momentum equations. Then experimental data collected in this study and those reported in the literature are used to compare different computed water surface profiles with laboratory measurements to come to a conclusion about the choice between energy and momentum equation.

2 ONE DIMENSIONAL MOMENTUM AND ENERGY EQUATIONS

Eq. 1 presents the one dimensional momentum equation for steady flow through open channels under the assumption of hydrostatic pressure distribution [1].

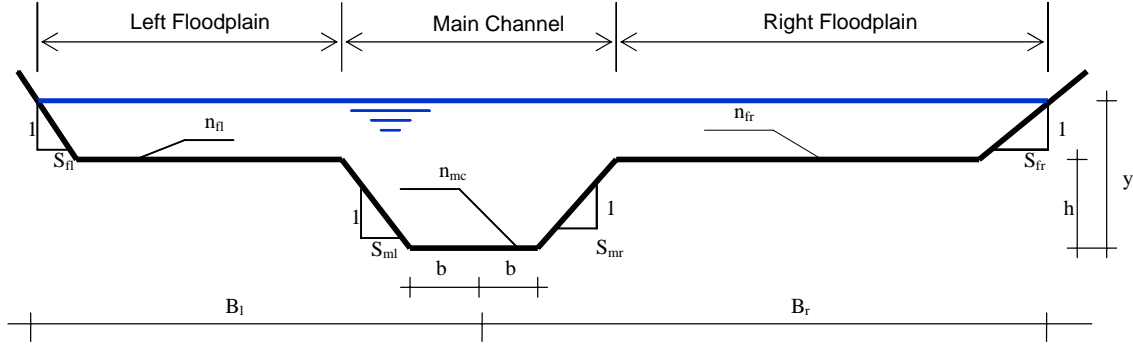


Figure 1. Compound channel cross section (geometry and terminology)

$$\frac{1}{A} \frac{dM}{dx} = S_o - S_f \quad (1)$$

where A is the cross sectional area, x is the direction along the channel and S_o is longitudinal bed slope of the channel. S_f and M are the friction slope and momentum function, respectively, which are defined as:

$$S_f = \frac{\tau_o}{\rho g R} \quad (2)$$

where τ_o is the bed shear stress, ρ is the density of water and R is the hydraulic radius of the cross section. And:

$$M = \beta \frac{Q^2}{gA} + \bar{y}A \quad (3)$$

where \bar{y} is the vertical distance between the water surface and the centre of area, g is the gravitational acceleration, Q is the discharge and β is the momentum correction factor, defined as:

$$\beta = \frac{\int_A v^2 dA}{V^2 A} \quad (4)$$

where v is the local streamwise velocity and V is the average flow velocity which satisfies the continuity equation.

Under the assumptions of no lateral discharge and prismatic channel, Eq. 1, results in Eq. 5 if the variation of β with depth is ignored and it will result in Eq. 6 if β varies with depth.

$$\frac{dy}{dx} = \frac{S_o - S_f}{1 - \left(\frac{\beta Q^2 T}{gA^3} \right)} \quad (5)$$

$$\frac{dy}{dx} = \frac{S_o - S_f}{1 - \left[\frac{Q^2 T}{gA^3} \left(\beta - \frac{A}{T} \frac{d\beta}{dy} \right) \right]} \quad (6)$$

where in these equations, T is the top width.

In a similar fashion and under the same assumptions, Eq. 7 presents the one dimensional energy equation.

$$\frac{dE}{dx} = S_o - S_e \quad (7)$$

where S_e and E are the energy slope and specific energy, respectively, which are defined as:

$$S_e = \frac{1}{g} \frac{du}{dx} + \frac{\tilde{q}}{Q\rho g dx} \quad (8)$$

where u is the internal energy per unit mass and \tilde{q} is the rate of heat dissipation [1]. And:

$$E = y + \frac{\alpha Q^2}{2gA^2} \quad (9)$$

where α is the energy correction factor which is defined as:

$$\alpha = \frac{\int_A v^3 dA}{V^3 A} \quad (10)$$

Under the assumptions of no lateral discharge and prismatic channel, Eq. 7 results in Eq. 11 if the variation of α with depth is ignored and it will result in Eq. 12 if α varies with depth.

$$\frac{dy}{dx} = \frac{S_o - S_e}{1 - \left(\frac{\alpha Q^2 T}{g A^3} \right)} \quad (11)$$

$$\frac{dy}{dx} = \frac{S_o - S_e}{1 - \left[\frac{Q^2 T}{g A^3} \left(\alpha - \frac{A}{2T} \frac{d\alpha}{dy} \right) \right]} \quad (12)$$

By looking at Eqs. 5, 6, 11 and 12, a more comprehensive form of governing equation for steady non-uniform flow through compound channels can be introduced as follows.

$$\frac{dy}{dx} = \psi(y) = \frac{S_o - S}{1 - F_i^2} \quad (13)$$

where S is substituted with S_e and S_f depending on the equation used, and F_i is Froude number of flow. In a comprehensive approach, the general functional form for Froude number can be defined as:

$$F_i = \left(\eta_i \frac{Q^2 T}{g A^3} \right)^{\frac{1}{2}} \quad (14)$$

where η_i can have different meaning and definitions as follows.

i=1: in this case $\eta_1 = 1$. This is equivalent to a uniform velocity distribution and $\alpha = \beta = 1$.

i=2: in this case $\eta_2 = \alpha$. It means that the energy approach is used and $\frac{d\alpha}{dy} = 0$.

i=3: in this case $\eta_3 = \alpha - \frac{A}{2T} \frac{d\alpha}{dy}$. This also means the use of energy equation and $\frac{d\alpha}{dy} \neq 0$.

i=4: in this case $\eta_4 = \beta$. This refers to the use of momentum approach and $\frac{d\beta}{dy} = 0$.

i=5: in this case $\eta_5 = \beta - \frac{A}{T} \frac{d\beta}{dy}$. This also refers to the momentum equation and $\frac{d\beta}{dy} \neq 0$.

There are other definitions in the literature proposed for Froude number in compound channels [3, 4 and 5]. They are not discussed here because they are not directly related to the subject of this paper.

3 PROCEDURE FOR SOLVING GRADUALLY-VARIED FLOW EQUATION

To solve the 1-D governing equation of gradually-varied flow (Eq. 13), it is customary to assume that the value of S (S_e or S_f) is predicted by:

$$S = \frac{Q^2}{K^2} \quad (15)$$

where K is the conveyance of a corresponding steady uniform flow with the same depth and discharge Q under non-uniform flow condition. The conveyance of regular cross sections can be calculated using the standard uniform flow equations such as Manning or Chezy equations. However, in a compound channels, due to its special characteristics, some improved methods are used. The followings are a brief description of the methods [6].

a) Single Channel Method (SCM): In this method, it is assumed that the whole cross section behaves as a single cross section and therefore the compound channel is considered as a regular cross section. In the case of different main channel and floodplain roughness, an equivalent roughness coefficient can be estimated using equations such as Horton equation [5].

b) Divided Channel Method (DCM): In this traditional method, the compound section is divided into a main channel and one or two floodplains. The conveyance of each sub-section is calculated separately by one of the standard resistance equations. The total conveyance is equal to the sum of the conveyances of sub-sections. In this research the vertical divided channel method is used.

c) Weighted Divided Channel Method (WDCM): This improved method has been developed by Lambert and Myers [7]. It uses a weighting factor to allow a transition between the velocity given by using a vertical division and the velocity predicted by a horizontal division. The weighting factor varies between zero and unity and is applied to both the main channel and the floodplain areas to give improved mean velocity estimate for these areas.

d) Coherence Method (COH): This method has been developed by Ackers [8]. "Coherence" is defined as the ratio of the basic conveyance calculated by the SCM, with the perimeter weighting of the friction factor, to that calculated by the DCM. Ackers introduces four regions of depth in the floodplain, which is distinguished by the coherence value and also suggests different discharge deficit (DISDEF) or discharge adjustment factors (DISADF) for improvement of discharge in each region.

e) Exchange Discharge Model (EDM): This method which was proposed by Bousmar and Zech [9], focuses on the interaction between the main channel and the floodplains and the exchange discharges and momentum transfers between them. Based on the EDM, the exchange discharge in non-uniform flow through compound channels depends on the turbulent momentum flux and the geometrical changes in cross sections. A non-linear computational procedure is required to calculate the conveyances of sub-sections.

In this research all these methods are used to investigate the effect of conveyance estimation methods on the results of the study. This is done because there is no general agreement on one method.

In addition to the energy and friction slopes, the Froude number also depends on the method selected for estimation of sub-section conveyance. The following equations are equations that can be used to calculate the terms involved in each Froude number definitions.

If $i=2$:

$$\eta_2 = \alpha = \frac{\sum_j k_j^3 a_j}{K^3 A} \quad (16)$$

where j is the sub-section number and a_j and k_j are the area and conveyance of sub-section, respectively.

If $i=4$:

$$\eta_4 = \beta = \frac{\sum_j k_j^2 a_j}{K^2 A} \quad (17)$$

If $i=3$, F_3 becomes:

$$F_3 = \left[\frac{Q^2 T}{g A^3} \left(\alpha - \frac{A}{2T} \frac{d\alpha}{dy} \right) \right]^{\frac{1}{2}} \quad (18)$$

This requires a working equation for F_3 that includes an evaluation of $\frac{d\alpha}{dy}$. Blalock and Sturm

[10] derived such an equation. For the case of homogeneous roughness for sub-sections, F_3 is calculated using the following equations.

$$F_3 = \left[\frac{Q^2}{2gK^3} \left(\frac{\sigma_2 \sigma_3}{K} - \sigma_1 \right) \right]^{\frac{1}{2}} \quad (19)$$

$$\sigma_1 = \sum_j \left[\left(\frac{k_j}{a_j} \right)^3 (3t_j - 2r_j \frac{dp_j}{dy}) \right] \quad (20)$$

$$\sigma_2 = \sum_j \left(\frac{k_j^3}{a_j^2} \right) \quad (21)$$

$$\sigma_3 = \sum_j \left[\left(\frac{k_j}{a_j} \right) (5t_j - 2r_j \frac{dp_j}{dy}) \right] \quad (22)$$

where in these equations, t_j , r_j and p_j are the top width, hydraulic radius and wetted perimeter of sub-section, respectively.

If $i=5$:

$$F_5 = \left[\frac{Q^2 T}{g A^3} \left(\beta - \frac{A}{T} \frac{d\beta}{dy} \right) \right]^{\frac{1}{2}} \quad (23)$$

Derivation of $\frac{d\beta}{dy}$ under the assumption of homogeneous roughness for sub-sections, results in

the following equations for calculating F_5 .

$$F_5 = \left[\frac{Q^2}{3gAK^2} \left(\frac{2\delta_2 \delta_3}{K} - 3\delta_1 \right) \right]^{\frac{1}{2}} \quad (24)$$

$$\delta_1 = \sum_j \left[\frac{4}{3} \left(\frac{k_j}{a_j} \right)^2 (2t_j - r_j \frac{dp_j}{dy}) \right] \quad (25)$$

$$\delta_2 = \sum_j \left(\frac{k_j^2}{a_j} \right) \quad (26)$$

$$\delta_3 = \sum_j \left[\left(\frac{k_j}{a_j} \right) (5t_j - 2r_j \frac{dp_j}{dy}) \right] \quad (27)$$

Eq. 13 can be solved numerically using the following scheme:

$$y_2 = y_1 + \frac{\Delta x}{2} [\psi(y_1) + \psi(\hat{y}_2)] \quad (28)$$

where y_1 is the control depth or depth calculated in the pervious step and Δx is the distance step. In an iterative procedure, $\psi(y_1)$ and $\psi(\hat{y}_2)$ are calculated corresponding to y_1 and trial

or improved value of \hat{y}_2 . y_2 is accepted when the difference between y_2 and \hat{y}_2 is less than a specified tolerance.

4 EXPERIMENTAL DATA

The data available in the literatures are more related to the experiments that have been conducted in uniform flow conditions. Unfortunately, experimental data on gradually-varied flow through compound channels are rare. Sturm and Sadiq [11] have conducted a series of experiments in a flume 17.1m long having a compound section with the hydraulic and geometric parameters (with reference to Fig. 1) as follows.

$$\begin{aligned} B_l = B_r = 1.0675 \text{ m}, & \quad b = 0.1335 \text{ m}, & \quad h = 0.152 \text{ m}, & \quad S_{ml} = S_{mr} = S_{fl} = S_{fr} = 0, \\ n_{fl} = n_{fr} = 0.0171, & \quad n_{mc} = 0.0176, & \quad S_0 = 0.005 \end{aligned}$$

They detected M1 and M2 water surface profiles. M1 profiles are used in this research.

Field *et al.* [1] used some experimental data on water surface profiles in compound channels that have been collected in UK-FCF. Unfortunately, the experimental noise was high and masked the details of observations. Other data on gradually-varied flow in compound channels have been collected by Bousmar and Zech [12], but the information provided was not found to be adequate enough to be used in this research.

Authors conducted some experiments in a concrete flume 10m long having a compound cross section. The flume was constructed in two steps. In the first step, the bed slope provided a steep slope condition. The following parameters refer to the hydraulic and geometric parameters (with reference to Fig. 1) in this case.

$$\begin{aligned} B_l = B_r = 0.378 \text{ m}, & \quad b = 0.074 \text{ m}, & \quad h = 0.151 \text{ m}, & \quad S_{ml} = S_{mr} = S_{fl} = S_{fr} = 0, \\ n_{fl} = n_{fr} = n_{mc} = 0.0104, & \quad S_0 = 0.0121 \end{aligned}$$

In the second step, the flume was reconstructed to be able to provide a mild slope condition. In this case, 0.0032 and 0.0725m were new values for S_0 and b , respectively. Other parameters were the same as in the first step.

In these experiments, the discharge was measured with an electromagnetic flow meter with 0.01 L/s precision and a V-notch weir (for measurement control). The water levels were recorded by a point gauge meter mounted above the flume with a precision of 0.5 mm. The overall precision in depth measurement is estimated to be 1 mm. The reproducibility of the experiments was tested and the average difference in depth between two experiments with similar inputs was found to be 0.5 mm and none greater than 1.3 mm. A set of experiments were conducted in the main channel to determine the Manning's n value reported above.

The water surface profiles developed in this research were S1, S2, M1 and M2 types. M1 and S1 profiles were developed using a gate control at the downstream and M2 and S2 profiles by a free overfall. The M2 profiles were found not to be suitable for one dimensional analysis. In this case, as reported by Sturm and Sadiq [11], also supported by our observations, a local drawdown region near the downstream end of the channel is developed and a noticeable unilaterally mass transfer from the floodplains to the main channel is observed where the flow has a fully two dimensional pattern. This phenomenon is intensified when the M2 profile approaches to the rapid vertical drawdown.

In the next section, the experiments that have been conducted by Sturm and Sadiq [11] are introduced using the notation Sturm(Q) and those conducted by the authors on the steep and mild slopes are referred to as S(Q) and M(Q), respectively. Q is the discharge in L/s.

5 DATA ANALYSIS

In one dimensional analysis of gradually-varied flows, normal and critical depth values play an important role in the behaviour of the governing differential equation and the

formation of the water surface profiles. Normal depth in compound channels is only a function of selected conveyance method, but critical depth values depend on both the conveyance method used and Froude number definition. In this research, both the specific energy and the momentum functions are used to determine critical depths. This makes the study comprehensive and clarifies the role of correct normal and critical depth computation in water surface classification in compound channels. In the analysis that follows in the case of energy equation, the Froude number definition corresponding to $i=3$ and in the case of momentum approach, the Froude number definition corresponding to $i=5$ are used in addition to $i=1$ definition. The results of the other definitions of Froude number ($i=2$ and $i=4$) are between the other results, correspondingly.

For the purpose of this study, the analysis of experimental data is divided into three different categories as follows.

5.1 FIRST CATEGORY

It was found for some experimental data that there is not any significant difference between the results obtained from energy and momentum equations. Different conveyance methods did not give significantly different results as well. This behaviour is observed in high relative depth values. Therefore, it can be postulated that M1 profiles far from the normal depth and S1 profiles far from the critical depth are not sensitive to the choice between energy and momentum equations. Fig. 2 shows the calculated results vs. the observed values for a M1 profile detected in M(24.46) test.

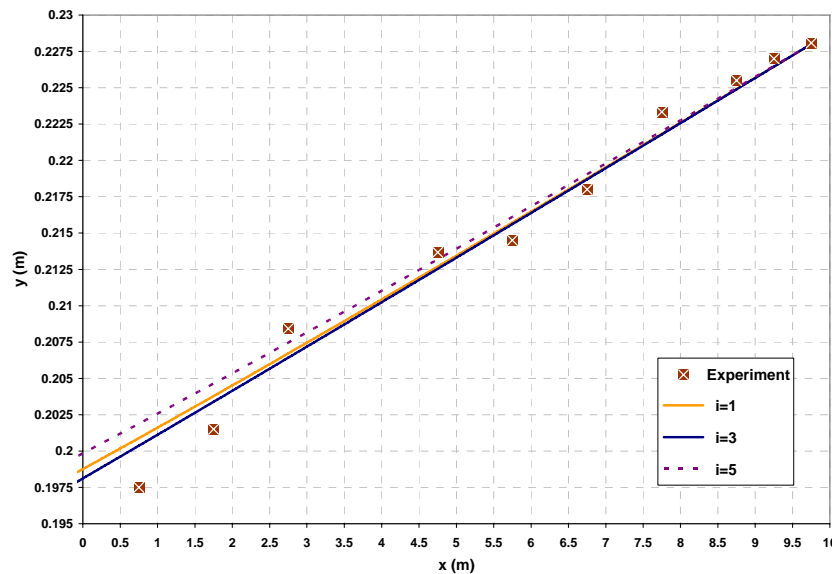


Figure 2. Observed vs. calculated M1 profiles for M(24.46) test

5.2 SECOND CATEGORY

For some experimental data, the differences between the results of the energy and momentum approaches have meaning but the differences compared to experimental noise are so small that a definitive conclusion cannot be made. This condition is observed in moderate values of relative depth while differences are increased near normal depth for M1 profiles and near critical depth for S1 profiles. Fig. 3 presents the observed values for one of the M1 profiles, detected by Sturm and Sadiq [11] (Sturm(113) test), vs. the calculated values. Although, the measured data show an overall trend towards the shape of M1 profiles, the noise in data is such that a definitive conclusion cannot be made. As reported in Table 1, the

COH method gives the best estimate of normal depth compared to other conveyance estimation methods. Therefore, COH method can be suggested as the best conveyance estimation method in this test.

Table 1. Observed and calculated normal depths for Sturm(113) test

Method	SCM	DCM	WDCM	COH	EDM	Measurement
y_0 (m)	0.2120	0.2105	0.2118	0.2122	0.2110	0.2122

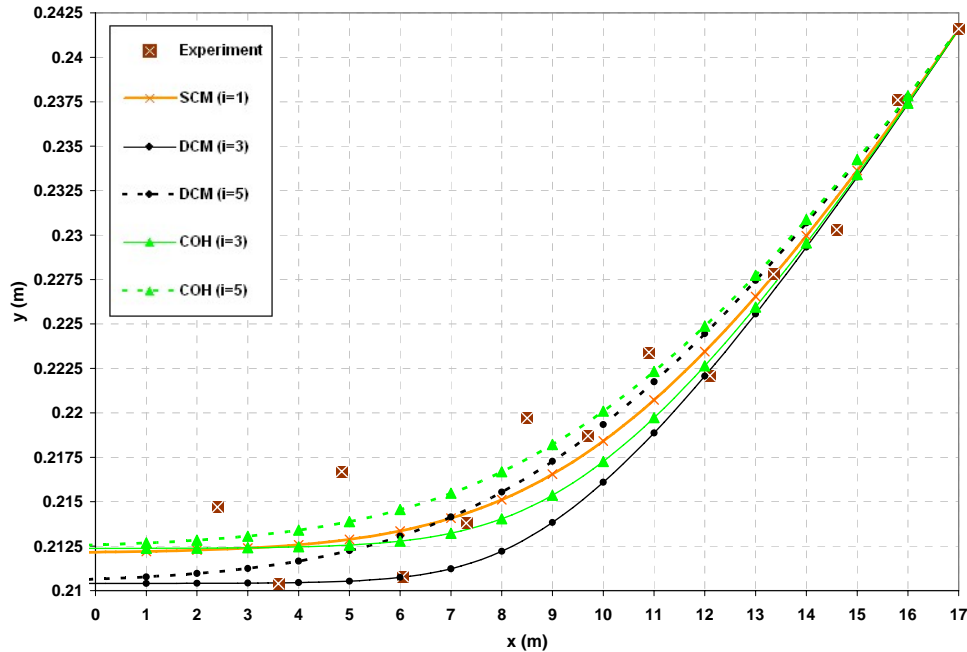


Figure 3. Observed vs. calculated M1 profiles for Sturm(113) test

5.3 THIRD CATEGORY

Analysis of some experimental data among those collected by Sturm and Sadiq [11] and those collected by the authors, not only shows a significant difference between the results of energy and momentum equations, but also gives a clear indication of superiority of one equation to the other. The followings describe these tests.

M(23.44) test: In this experiment, there are three critical depths. The value of the first critical depth is 13.86cm which occurs in the main channel. The normal depth and two other critical depths are found in Table 2. As shown in this table, except EDM method, other conveyance estimation methods identify M1 water surface profile type for momentum approach and S1 type for energy approach. EDM method identifies M1 type for both approaches.

Fig. 4 shows the observed vs. calculated water surface profiles. Experimental data also indicate the formation of M1 profile. Calculation based on the energy equation was stopped and discontinued near the related critical depth. As observed in the figure, water surface profiles calculated by momentum equation converge to normal depth and behave the same way as experimental observations. Therefore, in this experiment, the momentum approach performs better than energy approach for all conveyance estimation methods other than EDM.

Sturm(42.50) test: In this experiment, two separated water surface profiles, corresponding to two different water surface elevations at the downstream end of the flume, have been developed. The uniform flow depth was measured 17.39cm and the first critical depth was calculated 13.72cm in the main channel. The normal and other calculated critical depths are

reported in Table 3. The results are reported here only for one of the water surface profiles while the conclusions are valid for the other water surface profile as well.

Table 2. Calculated normal and critical depths for M(23.44) test

Method	SCM	DCM	WDCM	COH	EDM
y_0	0.1749	0.1699	0.1722	0.1720	0.1729
$y_c(i=1)$	-, 0.1685	-	-	-	-
$y_c(i=3)$	-	0.1518, 0.1742	0.1517, 0.1731	0.1517, 0.1742	-, 0.1721
$y_c(i=5)$	-	0.1521, 0.1692	0.1520, 0.1688	0.1521, 0.1692	-, 0.1678

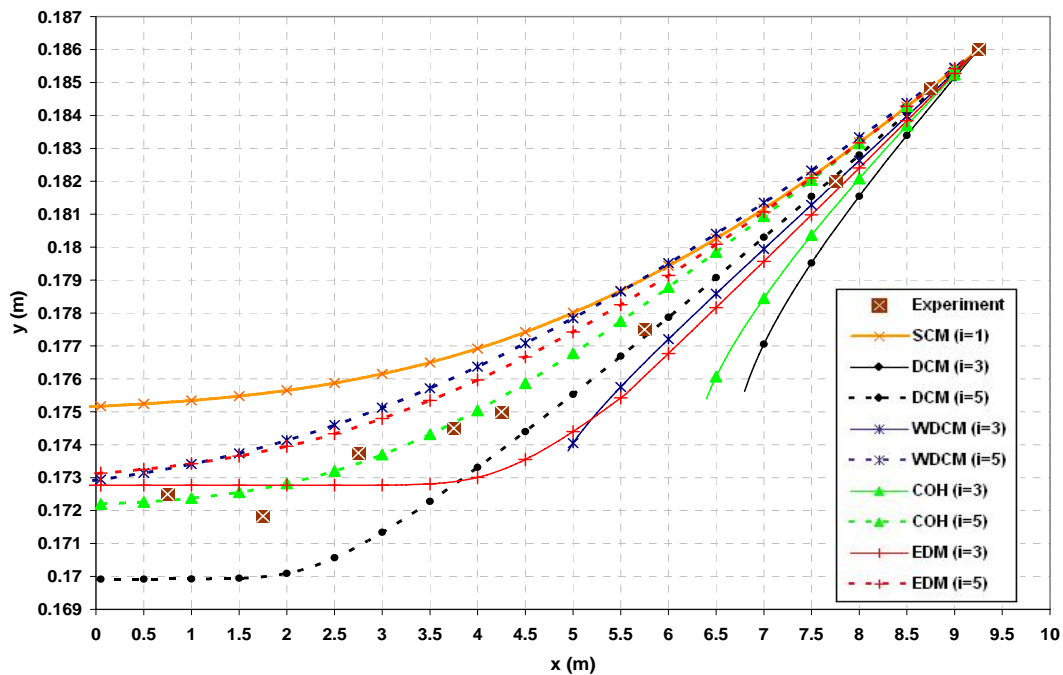


Figure 4. Observed vs. calculated M1 profiles for M(23.44) test

Comparison of the values given in Table 3 indicates that, independent of the conveyance estimation methods, the energy equation identifies a S1 profile type while the momentum equation identifies the type of profile as M1. Also, it can be seen that the COH method gives a more accurate estimation of normal depth than the other conveyance methods. Therefore, Fig. 5 presents only the results of SCM, DCM and COH methods vs. the observed values. Fig. 5 further supports the consistency of steady uniform flow conveyance methods with the momentum approach.

As mentioned before, in this study other set of experiments were conducted in a steep slope. The control gate at the downstream end of the flume was completely opened and a S2 profile was developed ending to a free overfall. Five experiments were conducted in this regard (S(51.61), S(61.34), S(72.59), S(80.70) and S(101.15)). Among them, the results of S(61.34) and S(101.15) tests are shown in Figs. 6 and 7, respectively. As shown in the figures, the dashed lines and solid lines refer to the momentum and energy equations, respectively. The results clearly show an overall agreement between experimental data and those resulted

from the use of momentum equation for this type of profile. The other experiments present similar results.

Table 3. Calculated normal and critical depths for Sturm(42.50) test

Method	SCM	DCM	WDCM	COH	EDM
y_0	0.1764	0.1695	0.1718	0.1729	0.1720
$y_c(i=1)$	0.1520 , 0.1673	–	–	–	–
$y_c(i=3)$	–	0.1522 , 0.1741	0.1522 , 0.1732	0.1522 , 0.1741	0.1521 , 0.1726
$y_c(i=5)$	–	0.1524 , 0.1692	0.1524 , 0.1691	0.1524 , 0.1692	0.1522 , 0.1688

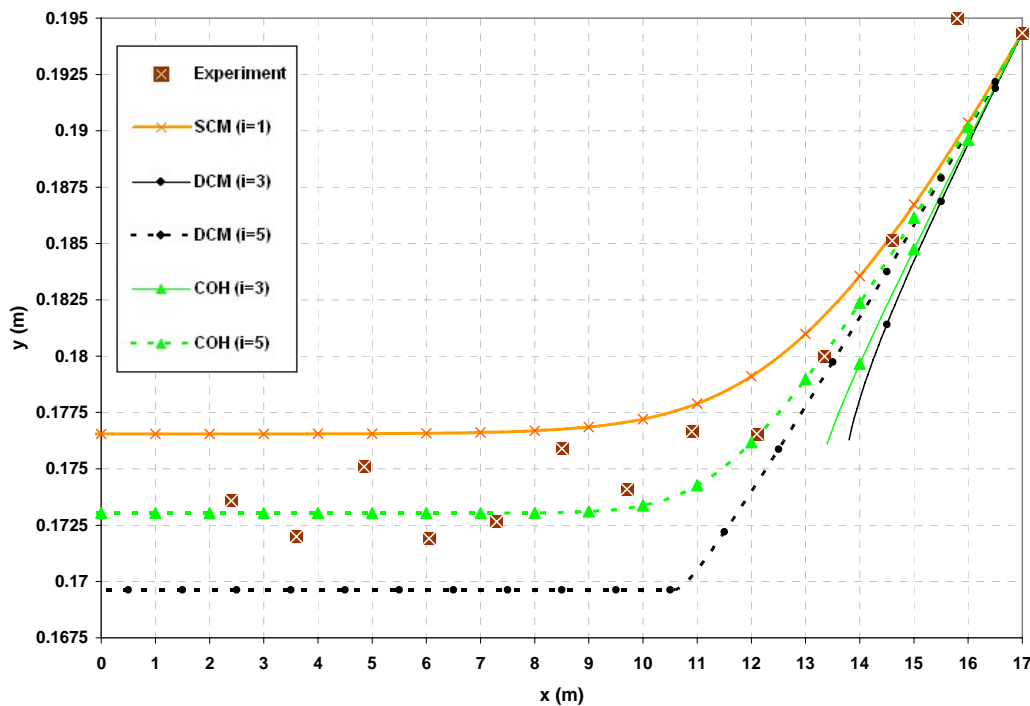


Figure 5. Observed and calculated M1 profiles for Sturm(42.50) test

6 CONCLUSIONS

In this paper, the consistency of the use of steady uniform flow conveyance estimation methods with one of the energy and momentum equations for analysis of steady one dimensional gradually-varied flow through compound channels was investigated. To achieve this, different conveyance estimation methods were combined with different Froude number definitions involved in momentum and energy governing equations in order to calculate water surface profiles corresponding to experimental data. The conclusion can be made that although in some conditions, the difference between the two approaches may not be significant, comparison of the observed and computed water surface profiles indicate the better performance of momentum equation than energy equation for the S1, S2, and M1 profiles investigated in this study. The role of conveyance estimation methods and Froude number definitions on identifying the correct type of profile and water surface profile computation in compound channel was also highlighted in this research.

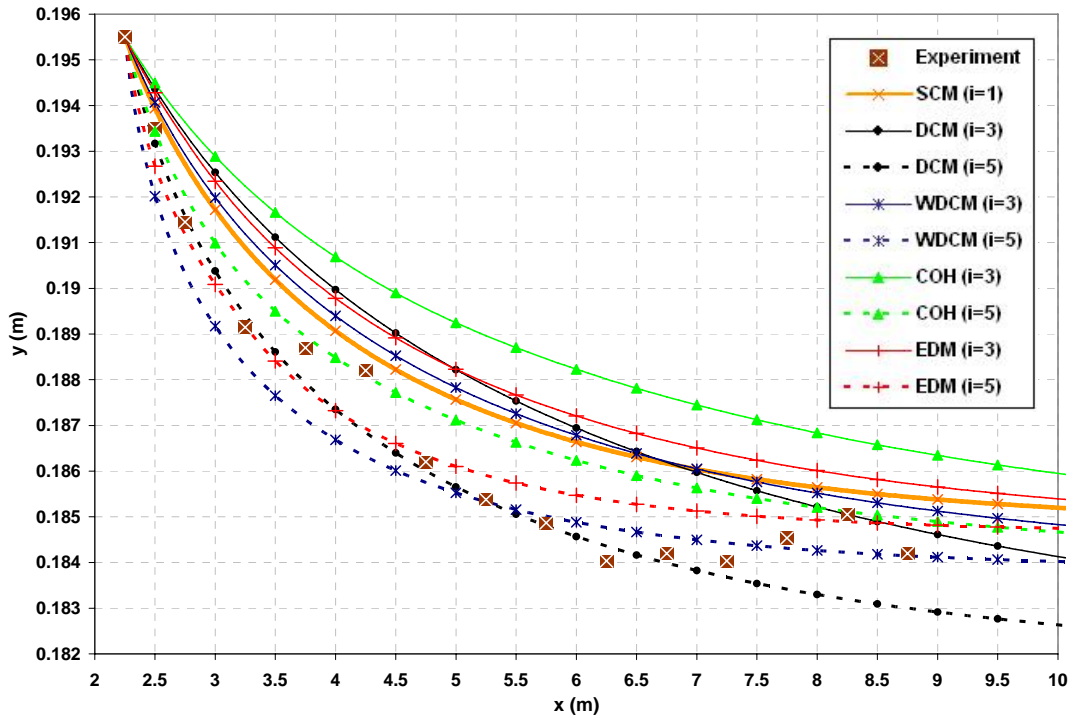


Figure 6. Observed and calculated S2 profiles for S(61.34) test

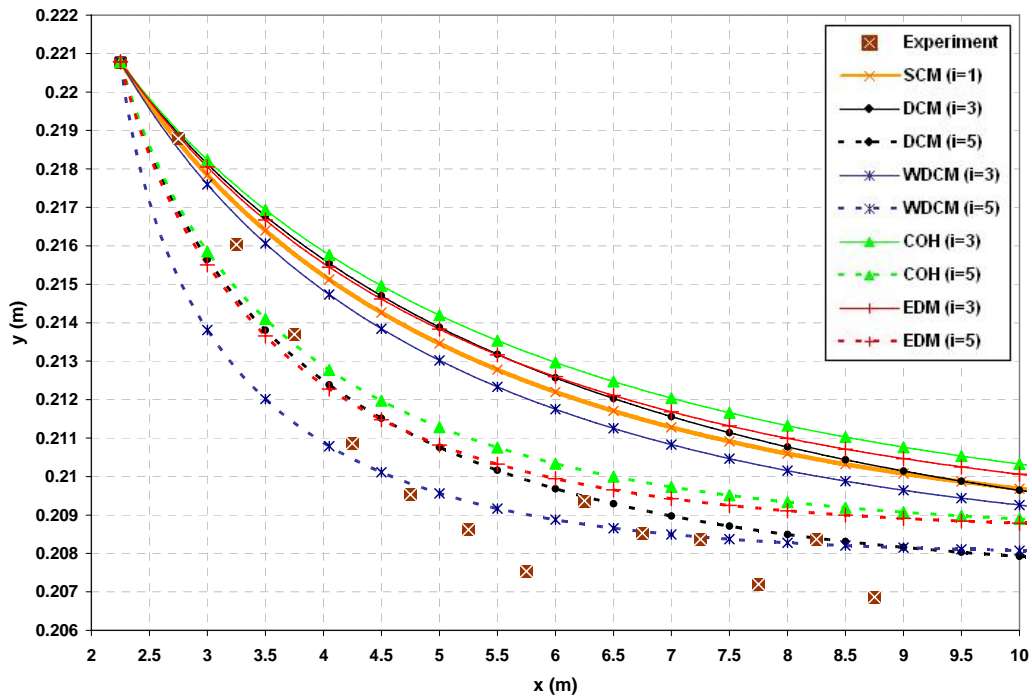


Figure 7. Observed and calculated S2 profiles for S(101.15) test

REFERENCES

- Field, W. G., Lambert, M. F., Williams, B. G. (1998), Energy and momentum in one dimensional open channel flow, *J. Hyd. Res.*, IAHR, 36(1), 29-42.

- 2- Hosseini, S. M., Bousmar, D., Zeck, Y., Franz, D, Almeida, A. B. (2000), Discussion on the article: Energy and momentum in one dimensional open channel flow, by Field, W. G., Lambert, M. F., Williams, B. G., , *J. Hyd. Res.*, IAHR, 38(3), 233-239.
- 3- Chaudhry, M. H., Bhallamudi, S. M. (1988), Computation of critical depth in symmetrical compound channels, *J. Hyd. Res.*, IAHR, 26(4), 377-395.
- 4- Subramanya, K. (2001), *Flow in open channels*. 2nd Ed., McGraw-Hill, New Delhi.
- 5- French, R. H. (1987). *Open-channel hydraulics*. 2nd Printing, McGraw-Hill, Singapore.
- 6- Hosseini, S. M. (2004), Equations for discharge calculation in compound channels having homogeneous roughness, *Iranian Journal of Science and Technology*, 28(B5), 537-546.
- 7- Lambert, M. F., Myers, W. R. C. (1998), Estimating the discharge capacity in straight compound channels, in *Proc. Instn. Civ. Engrs. Wat., Marit. and Energy*, 130(June), 84-94.
- 8- Ackers, P. (1992), Flow formulae for straight two-stage channels, *J. Hyd. Res.*, IAHR, 31(4), 509-531.
- 9- Bousmar, D., Zech, Y. (1999), Momentum transfer for practical flow computation in compound channels, *J. Hyd. Eng.*, ASCE, 125(7), 696-706.
- 10- Blalock, M. E., Sturm, T. W. (1980), Minimum specific energy in compound open channel, *J. Hyd. Div.*, ASCE, 107(HY6), 699-717.
- 11- Sturm, T. W., Sadiq, A. (1996), Water surface profiles in compound channels with multiple critical depths, *J. Hyd. Eng.* , ASCE, 122(12), 703-709.
- 12- Bousmar, D., Zech, Y. (2003), Adequacy of one dimensional flow modelling in compound channels near critical depth, in *Proc. 28th IAHR Cong.*, Graz, Austria.