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ELATIONSHIP IN FLOW MEASUREMENT STRUCTURES OF SYMMETRICAL RECTANGULAR COMPOUND CROSS SECTIONS

Issam A. AL-KHATIB

Birzeit University,
West-Bank, Palestine
Tel: 02-2982972 or 02-2982973

العلاقة بين عمق المياه والتدفق في منشآت قياس التدفق ذات المقاطع المستطيلة المركبة

ملخـص فـي هذه الورقة تم تطوير نموذج رياضي لحساب العلاقة بين عمق المياه والتدفق في قناة لقياس التدفق ذات مقطع مركب، والتي هي عبارة عن مزيج من قناة المجـاز الضـيق الطويل وقنطرة الاحتجاز ذات القمة العريضة. نموذجان مختلفان تم استقصـائهما عملـيا وذلك لفحص صحة النموذج الرياضي لمدى واسع من التدفق. لعمـق المـياه المقـاس عند مقطع قياس العمق، تم احتساب التدفق المثالي والتدفق الحقيقـي بطريقتيـن مختلفتين. من النتائج التجريبية، تم الاستنتاج بأنه يمكن اعتماد طريقة حالة التدفق المثالي للتقدير الأولى للتدفق. تم الاستنتاج كذلك بأن حالة التدفق المثالي ينتج عنها أكبر الأخطاء في احتساب التدفق مقارنة بالطرق الأخرى. بينما في حالـة اسـتخدام القياس التجريبي للطاقة المفقودة نتج عنها أقل الأخطاء في احتساب التدفق.

ABSTRACT **In this paper, a mathematical method has been developed for computing the stage - discharge relation and energy losses in flow measurement flumes of rectangular compound cross sections, which is a combination of long -**

throated flumes and broad crested - weirs. Two different models have been experimentally investigated to check the validity of the mathematical method for a wide range of discharges. For a measured stage at the head measurement section, the ideal flow, and actual flow by two different methods have been computed. From the experimental results, it has been concluded that for preliminary estimation of discharge values, the method of ideal flow case can be used also. It has been found that the ideal flow case produces the highest errors in discharge computation compared to other methods. While in the case of using experimentally measured energy losses, the minimum errors are obtained in discharge computation.

Key Words: open channel flow, compound cross section, discharge, coefficient, flow measurement, flumes, stage-discharge

Introduction

Water is the essential perquisite for any form of life to exit, whether plant, insect or animal. The availability of water has determined the location of human settlements from prehistoric times, and technology relating to water such as dams and water channels, has been central to the development of civilization for thousands of years. The survival of cities in particular has depended on a reliable supply of clean water, Celik (1997).

To effectively accomplish surface water management for irrigation distribution, municipal supply, collection from watersheds, flood flow monitoring or other purposes, it is important that the flow be accurately measured, Al-Khatib (1996).

A hydraulic-flow measuring structure is generally designed to act as a "control" in the channel on which it is situated. This means that the flow conditions, the velocity and depth in the channel upstream of the structure are governed only by the geometry of the structure, the approach channel, and the physical properties of water.

At this control section, there is a unique head-discharge relationship and critical flow conditions occur. The term "critical flow" is used here in the more general case, meaning that for the given discharge the depth is such that the total head is minimum. An alternative definition which leads to the same mathematical results is that for a given total head the depth is such that the discharge is maximum.

Flow measuring structures in open channels of different cross sections have been studied by various authors (Bos 1989; Ackers et al., 1978; 1975; Bos and Reinink 1981; Boiten 1983; Replogle and Bos 1982; 1983; 1987; Bos et al. 1986; Kumar 1989; Gogus and Altinbilek 1990, 1993; Al-Khatib 1993; Baban 1995). In most of these studies theoretical analyses is followed by experimental investigations to obtain relations between hydraulic and geometric quantities.

In this study a flow measurement structure having a symmetrical rectangular compound cross-section has been theoretically and experimentally investigated.

Theoretical Considerations

Two approaches can be used to determine the stage-discharge relationship in flumes and weirs. One approach determines determine the empirical discharge coefficient, C_d, which is the ratio of actual to ideal flow.

$$C_d = \frac{Q}{Q_i} \qquad (1)$$

where Q is the actual flow and Q_i is the ideal flow.

The discharge coefficient, C_d, is the result of :

1. Friction on the channel wall and bottom between the gauging station and the control section.
2. The velocity profile in the approach channel and the control section, and
3. Changes in pressure distribution caused by streamline curvature.

This method has been explained in details by (Al-Khatib, 1993; Gogus and Al-Khatib, 1995; and Al-Khatib 1996).

The other approach is to compute the effects directly by the use of a mathematical theory, such as the one presented and applied in this study. Thus no empirical discharge coefficient is needed. In either case, the ideal flow is calculated as a base of reference or straight point.

Ideal Flow Case

For an ideal fluid at constant flow, there is only one value of critical depth, Y_c, for each value of energy head, H_c:

$$H_c = \mathrm{Y_c} + \frac{A_c}{2B_c} \tag{2}$$

where A_c is the wetted area at the control section and B_c is the water surface width at the control station. As illustrated in Fig. 1, for the gauging station.

$$H_1 = h_1 + \frac{Q_i^2}{2gA_1^2} \tag{3}$$

where H_1 is the total energy head at the gauging station; h_1 is the flow depth at the gauging station; $V_1 = Q_i / A_1$; A_1 = flow area at gauging station and g = acceleration due to gravity. For ideal fluid flow, there is no energy loss due to friction over the reach with acceleration flow, and thus $H_c = H_1$, or

$$Y_c + \frac{A_c}{2B_c} = h_1 + \frac{Q_i^2}{2gA_1^2} \tag{4}$$

Eq. (4) relates the upstream head h_1 to the ideal flow Q_i for given cross-sectional shapes of the approach channel and the control section.

The ideal flow Q_i for given cross-sectional shapes of the approach channel and the control section. The ideal flow, Q_i, can also be calculated by

$$Q_i = A_c\sqrt{2g(H_1 - Y_c)} \qquad (5)$$

in which, according to Eqs. (2) and (4)

$$Y_c = H_1 - \frac{A_c}{2B_c} \qquad (6)$$

combining Eqs. (5) and (6) gives

$$Q_i = \sqrt{gA_c^3 / B_c} \qquad (7)$$

Eq. (7) is general and valid for all arbitrarily shaped control sections. The combined use of Eqs. (3), (6) and (7) is easy if simple equations exist for A_c and B_c in terms of Y_c. For the present study, compound cross sections are investigated, so these equations read:

$$A_c = Y_c B_c \qquad (\text{for } Y_c \le Z) \qquad (8)$$

$$A_c = Y_c b + (Y_c - Z)B_c \qquad (\text{for } Y_c > Z) \qquad (9)$$

and

$$B_c = b \qquad (\text{for } Y_c \le Z) \qquad (10)$$

$$B_c = B_0 \qquad (\text{for } Y_c > Z) \qquad (11)$$

where b is the bottom width of the control section and B_0 is the bottom width of the upstream channel.

The approach channel may also have any shape, but for the purposes of the present study, rectangular compound cross section is used:

$$A_1 = \mathrm{B}\,h_1 \qquad \text{(for } h_1 \leq \mathrm{Z}) \qquad (12)$$

$$A_1 = \mathrm{BZ} + B_0\,(h_1 - \mathrm{Z}) \qquad \text{(for } h_1 > \mathrm{Z}) \qquad (13)$$

Thus for each combination of approach channel and control section shapes, Eqs. (3), (6) and (7) have unknowns Y_c and Q_i. If any one of these two is given, the other one can be solved by trial and error.

The procedure for this trial and error solution is rather straight forward and starts with determining the range of h_1 values for which the appropriate discharge Q_i needs to be computed. Next, an initial guess is made for Y_c in terms of h_1. The value of Y_c ranges from 0.67 H_1 to 0.80 H_1 for a rectangular to triangular control section respectively (Clemmens et al. 1987). Neglecting the velocity head $V_1^2/2g$, one can guess:

$$Y_c = 0.70\ h_1 \qquad (14)$$

in all first trials. It is not worthwhile to make better guess of Y_c for each computer run, since the trial and error method converges rapidly. Now, once Y_c has been guessed, values of A_c, B_c and Q_i can be computed by H_1 and Y_c (from computed Q_i value). If the new Y_c value equals to the input Y_c value then the computed Q_i is the flow rate for an ideal fluid matching the set h_1 value. After each trial, the new Y_c value replaces the previous Y_c. Using the new Y_c value, a new series of calculations is made until the values match.

This method does not require an estimate of the velocity coefficient, C_v, for converting from H_1 to h_1 since both H_1 and h_1 are used in the computation and the energy heads are balanced, where C_v is a coefficient that corrects for ignoring the velocity head at the head measurement section in the head discharge equation, (Gogus and Al-Khatib 1995). Also the method starts with h_1 rather than H_1, making it useful for the development of stage discharge relationships.

Energy Losses Due to Friction

Because no ideal fluids exist in the real world, we must account for the effects of friction. Evaluating the actual discharge through a flume requires an account for friction in the approach channel, converging transition, and throat as shown in Fig. 1. Friction in the diverging transition and tailwater does not affect the flume discharge, but it affects the tailwater limit for maintaining modular flow.

Several methods are available for estimating friction losses through the flume and are shown in Table 1. While the functions given are empirical, the boundary layer drag method has some distinct advantages. The Manning equation is useful for many applications in open channel flow. However, using a constant Manning for a wide range of flow conditions is unacceptable when recise calibration is necessary. Thus, this approach is not suitable for measuring flumes. Chezy's C_h and boundary layer drag coefficients take into account the absolute roughness height of the flume surface, the kinematic viscosity of the fluid, and Reynolds number of the flow. The Chezy equation (and similarly based Darcy-Weisbach equation) however, assumes that the flow is uniform, whereas the boundary layer theory would indicate a gradual change in the flow conditions. Thus the boundary layer method is preferred. Expanded upon their work and developed a flume model based on boundary layer development, which is presented in the following section with minor modifications.

The effects of friction could be replaced with a change in flow area represented by an artificial displacement thickness. However this method did not prove as reliable as the boundary layer drag method which is more appropriate because it is more consistent with the energy-based equations used to determine flow rate.

Table 1. Functions for Estimating Friction or Head Losses Through Flumes

Function	Equation for head loss	Terminology
Manning	$\Delta H = \frac{n^2 L V^2}{C_u^{\,2} R^{4/3}}$	ΔH = head loss due to friction L = length in direction of flow R = hydraulic radius C_u = units coefficient for the Manning n
Chezy	$\Delta H = \frac{L V^2}{C^2 R}$	C = Chezy C n = Manning n V = average flow velocity
Boundary Layer Drag	$\Delta H = \frac{C_f L V^2}{2gR}$	g = acceleration of gravity C_F = drag coefficient

Boundary Layer Theory

For the boundary layer analysis, it is assumed that the throat of the flume is one side of a thin and smooth flat plate held parallel to the fluid flow. The plate causes a drag on the fluid which results in energy or head losses. The boundary layer is assumed to be "tripped" by the break between the converging transition and the throat. Boundary layer theory indicates that the flow in the boundary layer is not constant but varies along the plate. The boundary layer starts out as laminar flow and then develops into turbulent flow as shown in Fig. 2. In reality, the transition from laminar to turbulent flow is gradual. For computing drag, however, the transition is assumed to occur at a distance L_x from the entrance to the throat.

The combined drag coefficient C_F can be found by adding the relative drag coefficients for the laminar and turbulent parts of the boundary layer. The turbulent part of the boundary layer acts as if the entire boundary layer is turbulent; thus the drag coefficient for the non-existent turbulent boundary layer over L_x, namely $C_{F,x}$ must be subtracted from the turbulent drag coefficient over L, $C_{F,L}$. The combined drag coefficient is then:

$$C_F = C_{F,L} - \frac{L_x}{L} C_{F,x} + \frac{L_x}{L} C_{f,x} \qquad (15)$$

where $C_{f,x}$ is the coefficient for the laminar boundary layer over L_x. The distance L_x can be developed from an empirical relationship for the Reynolds number of the laminar portion of the boundary layer:

$$R_{e_x} = 350000 + L / K_r \qquad (16)$$

where K_r is the absolute roughness height of the material. This Reynolds number is related to L_x by the definition:

$$R_{e_x} = V_c L_x / \nu \qquad (17)$$

where $V_c = Q / A_c$ is average velocity of flow, and ν is the kinematic viscosity of the fluid. Similarly, the Reynolds number over the entire length L is:

$$R_{e_L} = V_c L / \nu \qquad (18)$$

Values for the turbulent drag coefficients are found from the following relationship which was derived from:

$$C_{F,L} = 0.544 C_{F,L}^{0.5} / \left\{ \begin{matrix} 5.61 C_{F,L}^{0.5} - 0.638 \\ - \ln\left[\left(R_{e_L} C_{F,L} \right)^{-1} + \left(4.84 C_{FL}^{0.5} L / k \right)^{-1} \right] \end{matrix} \right\} \qquad (19)$$

Eq. (19) can be used to determine $C_{F,x}$ by replacing $C_{F,L}$, R_{e_L} and L with $C_{F,x}$, R_{e_x} and L_x. This equation must be solved by trial and error since $C_{F,L}$ (or $C_{F,x}$) appears several times.

The drag coefficient for laminar flow can be computed by the following equation suggested by:

$$C_{f,x} = 1.328 / R_{e_x}^{0.5} \qquad (20)$$

If $R_{e_L} < R_{e_x}$ then the entire boundary layer is laminar and $C_F = C_{f,L}$ which is found from Eq. 20 with R_{e_L} replacing R_{e_x}.

For a fully developed turbulent boundary layer, as would be expected in the approach, converging transition, diverging transition, and tail water channel; the drag coefficient can be taken as 0.00235 (Clemmens et al., 1987). The head loss for each part of the flume is found from the following equation (Table 1):

$$\Delta H_L = \frac{C_F L}{R} \frac{V^2}{2g} \qquad (21)$$

where L is the length of each part considered, and R is the hydraulic radius. The combined head loss of the approach channel, converging transition, and the throat is subtracted from the energy head at the gauging station to give the energy head in the critical section $H_c = H_1 - \Delta H_1$. Eq. 6 changes to:

$$Y_c = H_1 - A_c / 2B_c - \Delta H_1 \qquad (22)$$

where:

$$\Delta H_1 = \Delta H_a + \Delta H_{ct} + \Delta H_t \qquad (23)$$

where ΔH_a, ΔH_{ct} and ΔH_t correspond to the head losses in the approach channel, converging transition and throat, respectively.

Roughness of Construction Materials

An analysis of the effects of roughness height shows that a change of several orders of magnitude in the value of k_r produces less than 0.5-percent change in discharge (Clemmens et al. 1987). Thus, a change in use of materials from smooth glass to rough concrete will have a minor effect on the discharge rating. This minor effect, however, should not be used as an excuse for sloppy or poor construction. If surfaces in the control section have large undulations and irregularities, the resulting discharge can be considerably in error. Material roughness and construction tolerances should be considered as different sources of potential error.

Velocity Profiles

The equations for ideal flow developed previously assume that the velocity profile in the throat is uniform. It may not be uniform, however and so a velocity distribution coefficient, α, is introduced to account for non-uniform velocity profiles. The value of α is the ratio between the actual velocity head of the flow and the velocity head based on the average velocity of the flow, and it was always greater than one. In long prismatic channels with a fully developed flow profile, α approaches a value of roughly 1.04. In the present study α is taken as 1.045 which is the mean value of all the velocity distribution coefficients calculated for the various types of rectangular compound cross section models investigated by (Al-Khatib, 1993). For approach channel, the velocity profile is assumed to be fully developed. This mean value of α_1 = 1.045 is used without further adjustment since the error in energy head resulting from an error in α_1 or the velocity head is relatively small. For the control section, the velocity distributions for critical flow tend to be more uniform. Thus, some correction for α_c at the control section is warranted. The following equation has been developed to estimate α for fully developed flow in wide channels:

$$\alpha = 1 + 3\varepsilon^2 - 2\varepsilon^3 \qquad (24)$$

where $\varepsilon = (V_m / V) - 1$ with V_m = the maximum flow velocity. For fully developed flow, ε can be approximated by

$$\varepsilon = 1.77 C_{F,L}{}^{0.5} \qquad (25)$$

At the control section, the channel may not be sufficiently wide, and the flow profile may not be fully developed. Two additional factors are added to Eq. 24 to account for these deficiencies:

$$\alpha_c = 1 + [3\varepsilon^2 - 2\varepsilon^3][1.5(D/R) - 0.5][0.025(L/R) - 0.05] \qquad (26)$$

with $1 \le [1.5(D/R) - 0.5] \le 2$
and $0 \le [0.025(L/R) - 0.05] \le 1$

where D is the average depth or hydraulic depth and the other terms are as previously defined.
With the addition of velocity distribution coefficient, Eq. 7 becomes

$$Q = \sqrt{gA_c^3 / \alpha_c B_c} \qquad (27)$$

and Eq. 3 becomes

$$H_1 = h_1 + \alpha_1 \frac{Q^2}{2gA_1^2} \qquad (28)$$

where α_1 = 1.045 and α_c is found from Eq. 26. The equations for the hydraulic ratios of the different sections are

$$R_1 = A_1 / (B + 2h_1) \qquad (\text{for } h_1 \le Z)$$

$$R = A_1 / \lfloor B + 2(h_1 + B_{F_1}) \rfloor \qquad (\text{for } h_1 > Z)$$

$$R_b = A_b / (b + 2Y_b) \qquad (\text{for } Y_b \le Z)$$

$$R_b = A_b / \lfloor b + 2(Y_b + B_{F_c}) \rfloor \qquad (\text{for } Y_c > Z) \qquad (29)$$

$$R_c = A_c / (b + 2Y_c) \qquad (\text{for } Y_c \le Z)$$

$$R_c = A_c / \lfloor b + 2(Y_c + B_{F_c}) \rfloor \qquad (\text{for } Y_c > Z)$$

where the subscript b refers to the entrance of the flume throat (that is, entrance has same cross sectional shape as throat but greater depth. The equations for the hydraulic depths are

$$D_1 = A_1 / B \quad \text{(for } h_1 \le Z\text{)}$$

$$D_1 = A_1 / B_0 \quad \text{(for } h_1 > Z\text{)}$$

$$D_c = A_c / b \quad \text{(for } Y_c \le Z\text{)} \qquad (30)$$

$$D_c = A_c / B_0 \quad \text{(for } Y_c > Z\text{)}$$

Experimental Apparatus and Procedure

All experiments series were conducted a glass-walled horizontal flume 9.0 m long, 0.67 m wide and 0.75 m deep in the Hydromechanics Laboratory of the Middle East Technical University.

Two models of rectangular compound channels were manufactured from Plexiglas at the workshop of the laboratory and placed at a bout mid-length of the laboratory flume. Fig. 1 shows the plan view, longitudinal profile and cross section of the models with symbols designating important dimensions of model elements. In Table 2 all the model dimensions with model types are presented.

Table 2. Dimensions of Models BZ1 and BZ2

Model Type	B_0 (cm)	b (cm)	B (cm)	B_f (cm)	Z (cm)	L_{ent} (cm)	L_{app} (cm)	L_{ct} (cm)	L_{thr} (cm)	θ (degree)	β **(degree)**
BZ1	67	30	45	11	5	22	160	15	75	153.43	153.43
BZ2	67	30	45	11	10	22	160	15	75	153.43	153.43

Sharp rectangular crested weir was equipped at the inlet box of the flume for discharge measurements. A point gauge was used for stage measurements at the head measurement section.

For a selected model type, a range of discharges, which could be obtained from the constant-head storage tank of the laboratory, were examined. The depth of the flow above the crest level at the approach channel was measured when the tailwater gate of the flume was fully open (free flow measurements).

Presentation and Discussion of Results

Al-Khatib (1993) has conducted many experiments in two different flow measurement flumes with rectangular compound cross sections to investigate the methods described for ideal and actual flow computation. In the following sections results of the experiments are summarised.

Ideal Flow Computation

According to the procedure described in the ideal flow case, two models have been investigated: BZ1 and BZ2. The measured flow depth at the head measurement section h_1 and the measured flow discharge Q_m in addition to the ideal flow discharges Q_i are shown in Tables 3 and 4 for models BZ1 and BZ2 respectively. From comparison of Q_m versus Q_i and related error $(e_r)_{Q_i}$ given in these tables one can say that by performing ideal fluid case, maximum error of 49.24% is made in calculation of the discharge flow. The percentage error mentioned in these tables, $(e_r)_{Q_i}$, is calculated as $100(Q_i - Q_m)/Q_m$. As it is seen from the tables the maximum errors correspond to the flow cases where the flow depths are just above or less than the step height, Z. Since the flow depths are quite small, the frictional resistance plays an important role in the formation of the flow. Hence, the neglect of the frictional losses into the calculations with depths greater than the step height, Z the errors made in the calculation of discharge become smaller as the flow depth increases. The average errors made in the calculation of discharge for h_1 > Z with the assumption of no frictional losses are about 30.62% and 16.30% for models BZ1 and BZ2 respectively. From this result it can be concluded that for preliminary estimation of the discharge Q values, the method of ideal flow case can be used.

Table 3. Ideal and Actual Flow Computation Results for Model BZ1

h_1 (m)	Q_m (m^3/s)	Q_i (m^3/s)	$(e_r)_{Q_i}$ (%)	Q_{calc1} (m^3/s)	$(e_r)_{Q_{calc1}}$ (%)	Q_{calc2} (m^3/s)	$(e_r)_{Q_{calc2}}$ (%)
0.074	0.0095	0.0140	47.37	0.0133	40.14	0.0107	19.99
0.085	0.0132	0.0197	49.24	0.0189	43.00	0.0152	15.07
0.100	0.0214	0.0287	34.11	0.0276	29.19	0.0250	17.04
0.120	0.0314	0.0426	35.67	0.0413	31.49	0.0387	23.20
0.137	0.0428	0.0559	30.61	0.0545	27.31	0.0503	17.43
0.160	0.0623	0.0760	21.99	0.0745	19.62	0.0718	15.29
0.180	0.0805	0.0953	18.39	0.0938	16.52	0.0913	13.36
0.200	0.0964	0.1161	20.44	0.1148	19.11	0.1056	9.51
0.213	0.1107	0.1304	17.80	0.1293	16.82	16.82	7.48

Table 4. Ideal and Actual Flow Computation Results for Model BZ2

h_1 (m)	Q_m (m^3/s)	Q_i (m^3/s)	$(e_r)_{Q_i}$ (%)	Q_{calc1} (m^3/s)	$(e_r)_{Q_{calc1}}$ (%)	Q_{calc2} (m^3/s)	$(e_r)_{Q_{calc2}}$ (%)
0.077	0.0095	0.0123	29.47	0.0116	22.54	0.0107	12.99
0.097	0.0132	0.0174	31.82	0.0166	25.42	0.0152	15.07
0.125	0.0214	0.0249	16.36	0.0243	13.77	0.0250	17.04
0.147	0.0314	0.0388	23.57	0.0377	20.11	0.0387	23.20
0.163	0.0428	0.0503	17.52	0.0491	14.71	0.0503	17.43
0.190	0.0623	0.0723	16.05	0.0709	13.75	0.0718	15.29
0.213	0.0805	0.0933	15.90	0.0918	14.02	0.0913	15.36
0.229	0.0964	0.1090	13.07	0.1075	11.56	0.1056	9.51
0.243	0.1107	0.1236	11.65	0.1221	10.31	0.1190	7.48

Actual Flow Computation

Actual flow rates are computed by the same procedure that was used for ideal flow rates except Eqs. 22, 27, and 28 replace Eqs. 6, 7, and 3 respectively. Values of ΔH_L are obtained from Eqs. 13 to 19, and the value of α_c is found from Eq. 26. The ideal flow rate is computed first and is used as the initial guess for the actual flow rate. Next, the friction losses and velocity distribution coefficients are computed for the estimated discharge. Then, the actual flow rate (Eq. 27) and the critical depth (Eq. 22) are computed. The trial and error process is repeated (as for ideal flow rate) until Y_c converges. The resulting flow rate is checked against the flow rate for the previous values of ΔH_L and α_c (the first time through, it will be compared with the ideal Q_i). If the flow rate has not converged, ΔH_L and α_c are computed with the new Q and process is repeated until the flow rate converges.

Another way of computing actual discharge is also used in the present study. The procedure is the same as the previously mentioned one except the way of computing ΔH_1. Here ΔH_1 is determined as the difference of H_1 and H_c as follows:

$$H_1 = h_1 + \alpha_1 \frac{Q^2}{2gA^2} \tag{31}$$

$$H_c = Y_c + \alpha_c \frac{Q^2}{2gA_c^2} \tag{32}$$

$$\Delta H_1 = H_1 - H_c \tag{33}$$

where α_1 = 1.045 as mentioned previously. α_c values are taken as the same values computed in the first procedure of actual flow computation.

Tables 5 and 6 present the total energy losses as well as those of the approach channel, converging transition and throat, and energy correction coefficient for control section calculated from the related equations given for models BZ1 and BZ2, respectively. For both models, maximum energy losses occur, when the components of the models are concerned, in the throat due to the higher flow velocities than those in the other sections of the models α_c values approaches to unity as the flow rate increases. From Tables 5 and 6 a comparison of these calculated energy losses can be made with those measured from the experiments. As it is seen the measured energy losses are much greater than the calculated ones. Because the measured losses include not only frictional losses but also local losses as well as covering the effect of the geometry of the model. Since the equations are mostly derived from the theory of boundary layer considering flat plates, they do not take into account the geometry of the cross section. Here, the presence of a compound cross section for flow depths higher than step height makes the problem more complicated.

Tables 3 and 4 present the Q values calculated from ideal case. The described method used calculated energy losses Q_{calc1}, and finally the same method with measured energy losses, Q_{calc2}. From the errors corresponding to the calculated discharges given in these tables one can say that the ideal case produces the highest errors compared to the other methods. In the case of using experimentally measured energy losses, the minimum errors are obtained, and in general, these errors get smaller as the flow rate increases. The reasons of still having these errors are the errors made in the measurements and some other assumptions in the derivations of equations referred to in the methods. Rating curves for model BZ1 obtained from Table 3 are plotted in Fig. 3 as h_1 versus Q. From this figure it is seen that all of the methods overestimate flow rate for a given h_1 value. The same thing can be concluded if the rating curves shown in Table 4 are plotted. Among all the methods the one which used the measured energy losses gives the better estimation.

Table 5. Results of Friction Losses Computation Through Model BZ1

h_1 (m)	Q_m (m^3/s)	ΔH_a (m)	ΔH_{ct} (m)	ΔH_t (m)	ΔH_1 (m) Eq. 23	ΔH_1 (m) Eq. 33	α_c
0.027	0.0015	0.0002	0.0001	0.0005	0.0008	0.0049	1.074
0.044	0.0032	0.0002	0.0001	0.0009	0.0012	0.0078	1.0508
0.074	0.0095	0.0002	0.0001	0.0007	0.0010	0.0051	1.0162
0.085	0.0132	0.0003	0.0001	0.0008	0.0012	0.0065	1.029
0.100	0.0214	0.0004	0.0001	0.0009	0.0014	0.0002	1.0101
0.120	0.0314	0.0005	0.0001	0.0011	0.0017	0.0004	1.0078
0.137	0.0428	0.0005	0.0001	0.0012	0.0018	0.0006	1.0065
0.160	0.0623	0.0006	0.0001	0.0013	0.0020	0.0009	1.0054
0.180	0.0805	0.0007	0.0002	0.0013	0.0022	0.0012	1.0046
0.200	0.0964	0.0007	0.0002	0.0014	0.0023	0.0014	1.0041
0.213	0.1107	0.0008	0.0002	0.0015	0.0025	0.0016	1.0038

Table 6 Results of Friction Losses Computation Through Model BZ2

h_1 (m)	Q_m (m^3/s)	ΔH_a (m)	ΔH_{ct} (m)	ΔH_t (m)	ΔH_1 (m) Eq. 23	ΔH_1 (m) Eq. 33	α_c
0.027	0.0015	0.0002	0.0001	0.0005	0.0008	0.0049	1.0740
0.044	0.0032	0.0002	0.0001	0.0009	0.0012	0.0078	1.0508
0.077	0.0095	0.0002	0.0001	0.0014	0.0017	0.0051	1.0360
0.097	0.0132	0.0002	0.0001	0.0017	0.0020	0.0065	1.0323
0.125	0.0214	0.0002	0.0001	0.0009	0.0012	0.0011	1.0126
0.147	0.0314	0.0003	0.0001	0.0011	0.0015	0.0004	1.0094
0.163	0.0428	0.0004	0.0001	0.0012	0.0017	0.0005	1.0080
0.190	0.0623	0.0004	0.0001	0.0013	0.0018	0.0011	1.0063
0.213	0.0805	0.0005	0.0001	0.0014	0.0020	0.0024	1.0053
0.229	0.0964	0.0006	0.0001	0.0014	0.0021	0.0034	1.0048
0.243	0.1107	0.0006	0.0002	0.0015	0.0023	0.0041	1.0044

Conclusions

In this study, three different methods for computing the stage-discharge relation have been presented and applied to two different models of flow measurement flumes with rectangular compound cross section. A series of laboratory experiments was conducted to estimate the discharge in these two models for a wide range of discharges.

From the above, the following conclusions can be drawn:

1. In the different methods, the maximum errors in discharge computation correspond to the flow cases where the flow depths are less than or just above the step height Z. These errors get smaller as the flow rate increase.

2. For preliminary estimation of Q values, the method of ideal flow case can be used.

3. Ideal flow case produces the highest errors in discharge computation compared to other methods. While in the case of using experimentally measured energy losses, the minimum errors are obtained.

4. The flow rates to be obtained from the rating curves of the structures for the ideal and real flow cases are always overestimated.

5. Maximum energy losses through the structure occur in the throat due to higher flow velocities than those of other sections.

6. The measured energy losses (Eq. 33) are much greater than the calculated ones (Eq. 23).

Notation

The following symbols are used in this paper:

A = cross sectional area of flow

A_C = cross sectional area of flow at critical depth measurement section

B = bottom width of the approach channel

b = bottom width of the control section

B_C = top width of the flow at the control section

B_0 = bottom width of the upstream channel

C = Chezy C

C_d = characteristic discharge coefficient
C_F = drag coefficient
C_u = units coefficient for the Manning n
D = hydraulic depth
g = acceleration due to gravity
H = total energy head
h = gauged head
k_r = absolute roughness height
L = length in direction of flow
L_{ap} = length of approach channel
L_{ct} = length of converging transition
L_{dt} = length of the diverging transition
L_{ent} = length of entrance channel
L_{thr} = length of throat in the direction of flow
n = Manning n
Q = volume rate of flow
Q_{calc1} = estimated rate of flow by utilizing Eq. 23
Q_{calc2} = estimated rate of flow by utilizing Eq. 33
Q_i = ideal rate of flow
Q_m = measured rate of flow
R = hydraulic radius
R_e = Reynolds number
V = average velocity
Y = water depth
Y_c = critical depth of water within the throat
Z = step height
α = energy correction coefficient
ΔH = head loss due to friction
AH_a = head loss in the approach channel
ΔH_b = head loss in the conversion transition

ΔH_t = head loss in the throat

Subscripts

1 refers to head measurement section; and

c indicates critical flow conditions

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LIST OF THE FIGURE LEGENDS

FIG. 1. Definition Sketch of the Flume used in the Theoretical Analysis and Experiments.

FIG. 2. Transition from Laminar to Turbulent Boundary Layer

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FIG. 3. Stage - Discharge Relationship for Model BZ1

بسم ا الرحمن الرحيم

الاخ د. عاطف عدوان المحترم

عميدا\ البحث العلمي

الجامعة الاسلامية –غزة

السلام عليكم ورحمة ا وبركاته

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<u>ا وضوع: تعديل البحث</u>

تسلمت رسالتكم الخاصة بالتعديلات المطلوبة لبحثي

"Stage - Discharge Relationship in Flow Measurement Structures of Symmetrical Rectangular Compound Cross Sections "

وقد قمت بالتعديلات المطلوبة، ونشكركم على اهتمامكم. وأما بالنسبة لإرسال نسخة مطبوعة على ورق فانه يصعب جدا إرسالها بالبريد بسبب الظروف الراهنة، حيث يصعب وصولها إليكم. لذلك نرجو التكرم بقبولها بدون ورق حيث أرسلها بوساطة البريد الإلكتروني، وأما بالنسبة للأشكال فلم يتغير منها شيء وهي موجودة لديكم. أرجو التكرم بإخباري عن وصولها لديكم بالسرعة الممكنة.

ولكم التحية والمودة.

والسلام عليكم ورحمة ا وبركاته

د. عصام الخطيب

معهد الصحة العامة والمجتمعية

Al- Kahatib

جامعة بيرزيت
Tel: 02-2982972 or 02-2982973
Fax: 02-2982980