ResearchGate

See discussions, stats, and author profiles for this publication at: https://www.researchgate.net/publication/278560452

FLOW-MEASUREMENT FLUMES OF RECTANGULAR COMPOUND CROSS-SECTION

Article *in* Journal of Irrigation and Drainage Engineering · March 1995

CITATION
1

READS
16

2 authors:

M. Gogus
Middle East Technical University

18 PUBLICATIONS 27 CITATIONS

SEE PROFILE

I. A. Al-Khatib
Birzeit University

73 PUBLICATIONS 204 CITATIONS

SEE PROFILE

Available from: I. A. Al-Khatib
Retrieved on: 06 October 2016

FLOW-MEASUREMENT FLUMES OF RECTANGULAR COMPOUND CROSS SECTION

By Mustafa Göğüş[1] and Issam Al-Khatib[2]

ABSTRACT: A series of laboratory experiments were carried out in a flow-measurement flume of a rectangular compound cross section to investigate the effect of the throat width and step height on the values of discharge coefficient, approach-velocity coefficient, and modular limit. For this reason, nine different models made of Plexiglas were tested in a horizontal laboratory flume for a large range of discharges. In each test, the head, h_1, over the crest elevation at depth-measurement section and head, h_2, over the crest elevation in the tailwater channel were measured. The calculated discharge coefficients, modular limits, and approach-velocity coefficients were related to relevant parameters. The consistency between aforementioned quantities and those given in the literature are found to be quite good. Modular limit values as high as 95% are obtained.

INTRODUCTION

Field measurements of flow in open channels can be accomplished by a wide variety of structures, which, broadly speaking, can be classified into three groups: orifices, weirs, and flumes. The popularity of long-throated flumes is somewhat limited since ready-to-use rating tables are not available. On the other hand long-throated flumes can be tailored to fit almost any field condition. The flexibility of the long-throated flume is an undeniable advantage, especially since discharge equations have been derived for flumes whose throat cross section may be parabolic, truncated triangular, circular, trapezoidal, or U-shaped.

Studies of flow-measuring structures in open channels, such as broad-crested weirs and long-throated flumes of different cross sections, have been reported by various investigators (Bos 1977, 1978; Bos and Reinink 1981; Bos et al. 1984; Clemmens et al. 1984; Bos et al. 1986). In all these studies, theoretical analyses were followed by experimental investigations to obtain relations between hydraulic and geometric quantities.

The main difference between the long-throated flumes of rectangular and rectangular compound cross sections is that the latter one has a main channel at the bottom of the flume that is narrower than the width of the cross section of former one (Fig. 1). Therefore, sediment carried by the flow passes through the main channel of the compound cross section. Since the flow is accelerated in the main channel due to the contraction applied to the original upstream-channel width, all of the incoming sediment passes through the flow-measurement structure of rectangular-compound cross section. Therefore, no sediment deposition occurs on the flume. Hence, one can get reliable rating curves from these kinds of structures, which are free of sediment deposition for any flow discharge.

In the present study, a flow-measurement structure having a symmetrical rectangular-compound cross section proposed by Göğüş and Altınbilek (1990, 1994), which is a combination of a long-throated flume and a broad-crested weir, was experimentally studied. Laboratory tests were conducted on different models of the structure with varying step heights and throat widths. The effect of these variables on the discharge coefficient, C_d, approach-velocity coefficient, C_v, and the modular limit were investigated.

Derivation of Head-Discharge Equation

Long-throated flumes have nearly parallel flow in the approach channel where the flow depth is measured. Thus, the pressure distribution is assumed hydrostatic, and existing theory based on critical flow is used. Fig. 1 shows plan view, longitudinal profile, head measurement, and control sections of the flow-measurement structure. One can write the energy equation between the head measurement and control sections, assuming that energy losses are neglected, velocity distributions are uniform, and streamlines are all straight and parallel to each other as

$$H_1 = y_c + \frac{V_c^2}{2g} \quad \text{or} \quad Q = A_c\sqrt{2g(H_1 - y_c)} \qquad (1, 2)$$

where H_1 = the total energy head of the flow at the head measurement section; y_c = the critical

---

[1] Prof., Civ. Engrg. Dept., Middle East Tech. Univ., Ankara, Turkey.

[2] Asst. Prof., Civ. Engrg. Dept., Near East Univ., Lefkoşa, North Cyprus.

Note. Discussion open until September 1, 1995. To extend the closing date one month, a written request must be filed with the ASCE Manager of Journals. The manuscript for this paper was submitted for review and possible publication on May 26, 1993. This paper is part of the *Journal of Irrigation and Drainage Engineering*, Vol. 121, No. 2, March/April, 1995. ©ASCE, ISSN 0733-9437/95/0002-0135-0142/$2.00 + $.25 per page. Paper No. 6251.

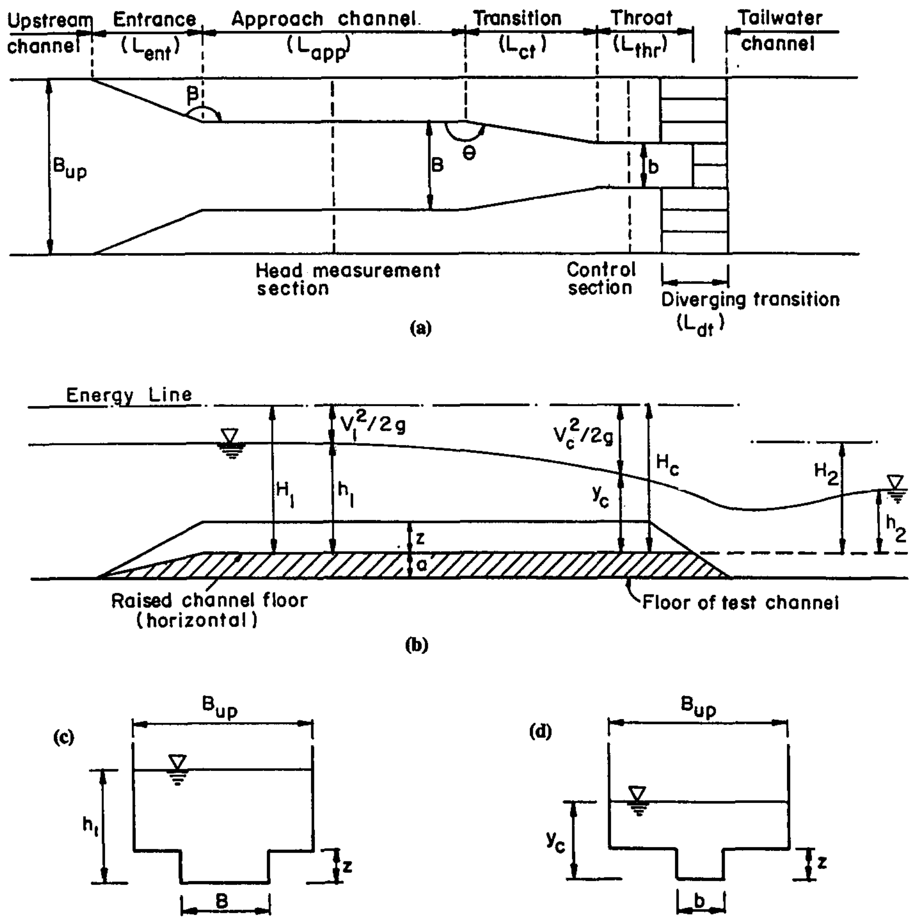

FIG. 1. Definition Sketch of Flume Used in Theoretical Analysis and Experiments: (a) Plan View; (b) Longitudinal View; (c) Head Measurement Section; (d) Control Section

depth; V_c = average critical velocity; g = acceleration due to gravity; Q = flow rate ($= A_c V_c$); and A_c = flow area at the control section.

If the flow is critical in the flume throat, from the equation of critical flow one can write

$$V_c^2/2g = A_c/2B_c \tag{3}$$

where B_c = top width of the flow at the control section ($B_c = b$ when $y_c \le z$ and $B_c = B_{up}$ when $y_c > z$).

Referring to (2) and (3), head-discharge equations can be derived for long-throated flumes with a prismatic control (throat) section of arbitrary shape. In this paper, only the head-discharge equation of flumes of symmetrical rectangular compound cross section will be presented for three cases as described next.

Case 1. $h_1 \le z$ and $y_c < z$

This is the situation where flow occurs only through the bottom part of the compound cross section. Since the cross section of the flume at the control section is rectangular, for $A_c = b.y_c$, (3) can be written as

$$\frac{V_c^2}{2g} = \frac{y_c}{2} \quad \text{Thus, yielding} \quad Q = \frac{2}{3} b \left(\frac{2}{3} g\right)^{1/2} H_1^{3/2} \tag{4, 5}$$

Case 2. $h_1 > z$ and $y_c \le z$

In this case, the flow depth at the depth-measurement section, h_1, is greater than z, but the critical-flow depth at the control section may be either less than or equal to z. For both situations, (5) is utilized in the calculation of discharge.

Case 3. $h_1 > z$ and $y_c > z$

In this case, flow occurs through the compound cross section over the total length of the flume. The area of the flow at the control section is

$$A_c = bz + (y_c - z)B_{\mathrm{up}} \tag{6}$$

A series of substitutions into (2) yields

$$Q = \left(\frac{g}{B_{\mathrm{up}}}\right)^{1/2} \left[bz + B_{\mathrm{up}}\left(\frac{2}{3}H_1 - \frac{bz}{3B_{\mathrm{up}}} - \frac{2z}{3}\right)\right]^{3/2} \tag{7}$$

Eqs. (5) and (7) are based on idealized assumptions such as uniform velocity distribution at the head-measurement and control sections. In reality, these assumptions are accounted for by introducing a discharge coefficient C_d. Hence, (5) and (7) are expressed as

$$Q = \frac{2}{3}C_d b\left(\frac{2}{3}g\right)^{1/2} H_1^{3/2} \quad \text{and} \quad Q = C_d\left(\frac{g}{B_{\mathrm{up}}}\right)^{1/2} \left[bz + B_{\mathrm{up}}\left(\frac{2}{3}H_1 - \frac{bz}{3B_{\mathrm{up}}} - \frac{2z}{3}\right)\right]^{3/2} \tag{8, 9}$$

In a field installation it is not possible to measure the energy head H_1 directly, and it is, therefore, more common to relate the discharge to the upstream water level over the crest h_1. The neglect of the velocity head at the head-measurement section, $V_1^2/2g$, however, has to be corrected by the factor C_v, "approach-velocity coefficient." Eqs. (8) and (9) then become

$$Q = C_d C_v \frac{2}{3} b\left(\frac{2}{3}g\right)^{1/2} h_1^{3/2} \quad \text{and} \quad Q = C_d C_v\left(\frac{g}{B_{\mathrm{up}}}\right)^{1/2} \left[bz + B_{\mathrm{up}}\left(\frac{2}{3}h_1 - \frac{bz}{3B_{\mathrm{up}}} - \frac{2z}{3}\right)\right]^{3/2} \tag{10, 11}$$

Modular Limit

The difference between the upper sill-referenced energy head H_1 and the downstream sill-referenced energy head H_2 is the available head loss over the structure. The ratio H_2/H_1 is known as the submergence ratio of the structure. For low values of the submergence ratio H_2/H_1, the tailwater level and H_2 do not influence the relationship between h and Q, and the flow through the channel is called "modular" or "free." For high values of H_2/H_1, the flow in the throat cannot become critical; hence, the upstream head is influenced by the tailwater level, and the flow is called "nonmodular" or "submerged." The value of submergence ratio at which the transition from modular flow to nonmodular flow occurs is referred as "modular limit." This limit is typically set as the value of the submergence ratio at which the real discharge deviates from the discharge calculated [(8) and (9)] by 1%. A procedure given by Bos and Reinink (1981) is used for calculation of the modular limit values attributed in this paper.

Experimental Apparatus

All series of experiments were conducted in a glass-walled horizontal flume 11.0 m long, 0.287 m wide, and 0.70 m deep, in the Hydromechanics Laboratory of the Middle East Technical University.

The model shown in Fig. 1 was manufactured from Plexiglas and placed to the midsection of the main-channel system. The original floor level was raised by $a = 4$ cm and kept horizontal up to the end of the throat length. Then, the diverging transition was formed towards the tailwater channel. By doing this, an elevation difference of $a = 4$ cm was obtained between the floor of test channel and the invert of flume to avoid submerged flow downstream of the throat.

The dimensions of the various models used in the experiments are given in Table 1. The constant diverging transition slope (one vertical to three horizontal) is attained over the total width of the tailwater channel by keeping the length of the side walls of the throat at required values.

The symbols used in the description of model types, b_i and z_i ($i = 1, 2, 3$), correspond to the width and height of the throat, respectively. The volumetric flow rate was measured with a rectangular sharp-crested weir mounted in the inlet box of the flume. Two point gauges were

TABLE 1. Model Dimensions

Model number (1)	Types of models (2)	b (cm) (3)	B (cm) (4)	z (cm) (5)	B_{up} (cm) (6)	β (degrees) (7)	θ (degrees) (8)	L_{ent} (cm) (9)	L_{ap} (cm) (10)	L_{ct} (cm) (11)	L_{thr} (cm) (12)	L_{dt} (cm) (13)
1	b_1z_1	6	10	2	28.7	166	173	37.4	60	16	18	16.5
2	b_1z_2	6	10	6	28.7	166	173	37.4	60	16	30	28.5
3	b_1z_3	6	10	10	28.7	166	173	37.4	60	16	42	40.5
4	b_2z_1	11	15	2	28.7	166	173	27.4	60	16	18	16.5
5	b_2z_2	11	15	6	28.7	166	173	27.4	60	16	30	28.5
6	b_2z_3	11	15	10	28.7	166	173	27.4	60	16	42	40.5
7	b_3z_1	16	20	2	28.7	166	173	17.4	60	16	18	16.5
8	b_3z_2	16	20	6	28.7	166	173	17.4	60	16	30	28.5
9	b_3z_3	16	20	10	28.7	166	173	17.4	60	16	42	40.5

used along the centerline of the model for head measurements. The bottom elevation of throat was used as reference.

Experimental Procedure

For a selected model type, a range of discharge, which could be obtained from the constant-head storage tank of the laboratory, was examined. Depth of the flow above the crest level at approach channel was measured when the tailwater gate of the flume was fully open (free flow measurements). For the same discharge, the point gauge was set to the value of $h_{1(101)}$ (Bos and Reinink 1981), which is the flow depth corresponding to a 1% increase in free discharge and obtained from the rating curve of the model. The tailgate of the flume was then raised gradually until water surface at the measurement section touched the point gauge. At that moment, depth of the flow in the tailwater channel above the crest elevation was measured and the corresponding H_2 and H_2/H_1 ratio as modular limit was calculated.

PRESENTATION AND ANALYSIS OF RESULTS

All of the measured and calculated quantities from the experiments conducted in the course of the present study were given by Al-Khatib (1989). In the following sections, results of the experiments are summarized.

Discharge Coefficient C_d

The discharge coefficient C_d is a coefficient that corrects for a number of idealized assumptions, as stated in the section entitled *Derivation of the Head-Discharge Equation.* Variation of C_d for various types of flumes were analyzed by Bos (1977), and it was expressed as a function of the dimensionless-approach head-to-throat length ratio H_1/L_{thr} in the range of 0.1 and 1.0. If H_1/L_{thr} is smaller than 0.1, friction with the channel bottom results in unsteady flow. On the other hand, when H_1/L_{thr} becomes greater than 1.0, the streamlines become increasingly curved, and the assumption of hydrostatic pressure distribution of the control section made in the derivation of discharge equation cannot be accepted. Here it should be kept in mind that values just stated have been given for long-throated critical depth flumes.

In order to see the effect of throat width, b, on the values of discharge coefficient, C_d, for constant step height, z, C_d versus H_1/L_{thr} values were plotted for each experiment conducted. From the preanalysis of the available data, it was concluded that there was no effect of throat width greater than b_2 (11 cm) on C_d values for the range of H_1/L_{thr} between 0.3 and 1.3 utilized in the present study. For models of $b \geq b_2$, the C_d values almost coincide with each other with an increasing trend as H_1/L_{thr} values increase. However, the model types of b_1z_1, b_1z_2, and b_1z_3 produce much smaller C_d values than those of other models for same H_1/L_{thr}. Therefore, one can emphasize that the bottom width of the compound channel, b, should not be selected less than b_1 = 11 cm. In fact, this dimension of b is quite small even for flow-measurement structures to be used at the laboratories. The figures plotted as C_d versus H_1/L_{thr} for varying step heights revealed that C_d values increase as the step height, z, increases for a given H_1/L_{thr}.

From the best-fitting curves of C_d versus H_1/L_{thr} for model types tested, excluding the values of models b_1z_1, b_1z_2, and b_1z_3 due to the reasons explained, C_d values corresponding to fixed H_1/L_{thr} values were determined and tabulated in Table 2. The arithmetic mean values of C_d are given in the last column of Table 2 as a function of H_1/L_{thr}. The resultant mean C_d values versus H_1/L_{thr} are plotted in Fig. 2, which is valid for

TABLE 2. Mean Value of Characteristic Discharge Coefficient C_d

H_1/L_{thr} (1)	Types of Models						Mean C_d (8)
	b_2z_1 (2)	b_2z_2 (3)	b_2z_3 (4)	b_3z_1 (5)	b_3z_2 (6)	b_3z_3 (7)	
0.30	—	0.891	0.979	0.930	0.934	—	0.934
0.40	0.968	0.933	0.975	0.968	0.969	0.962	0.963
0.45	0.978	0.958	0.967	0.969	0.968	0.976	0.969
0.50	0.982	0.956	1.003	0.976	0.967	0.995	0.980
0.55	0.976	0.974	1.024	0.958	0.984	1.017	0.989
0.60	0.988	0.999	1.042	0.968	1.004	1.036	1.006
0.70	1.004	1.031	—	0.981	1.040	—	1.014
0.80	1.007	1.025	—	0.998	—	—	1.010
0.90	1.018	—	—	1.009	—	—	1.014
1.00	1.003	—	—	—	—	—	1.003

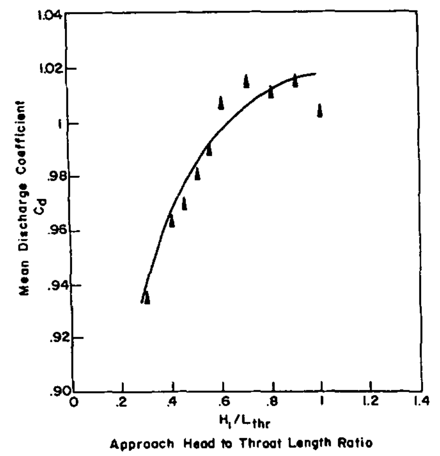

FIG. 2. Variation of Mean Discharge Coefficient, C_d, with Approach Head to Throat Length Ratio, H_1/L_{thr}

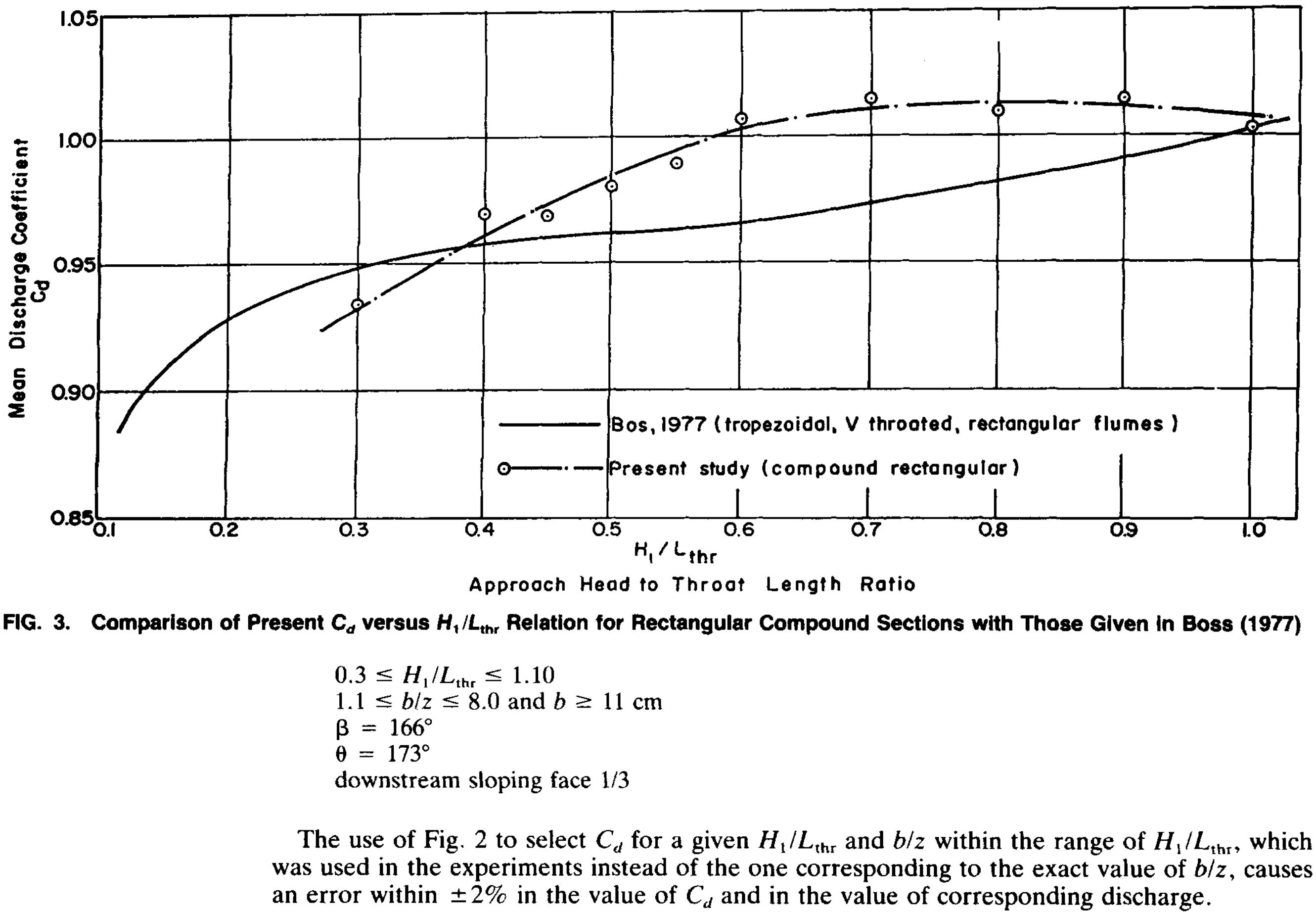

FIG. 3. Comparison of Present C_d versus H_1/L_{thr} Relation for Rectangular Compound Sections with Those Given in Boss (1977)

$0.3 \leq H_1/L_{thr} \leq 1.10$
$1.1 \leq b/z \leq 8.0$ and $b \geq 11$ cm
$\beta = 166°$
$\theta = 173°$
downstream sloping face 1/3

The use of Fig. 2 to select C_d for a given H_1/L_{thr} and b/z within the range of H_1/L_{thr}, which was used in the experiments instead of the one corresponding to the exact value of b/z, causes an error within ±2% in the value of C_d and in the value of corresponding discharge.

A replot of Fig. 2 on the figure of C_d versus H_1/L_{thr} given in the literature for flumes of various cross sections (Bos 1977) is presented in Fig. 3 for comparison. The present relation of C_d with H_1/L_{thr} falls within the data of previous investigators, but yields higher C_d values when $H_1/L_{thr} > 0.4$.

Approach Velocity Coefficient C_v

The coefficient C_v is mostly expressed as a function of the ratio $\sqrt{\alpha} C_d A^*/A_1$ in the literature (Bos 1977; Clemmens et al. 1984). Here, α is the energy correction coefficient taken as 1.04 in all calculations; A^* is the imaginary wetted area at the control section if the water depth would be equal to h_1; and A_1 is the wetted area at the head-measurement section. This relationship is shown in Fig. 4 for rectangular control sections.

The relationship between C_v and $\sqrt{\alpha} C_d A^*/A_1$ were plotted first for constant throat width but varying step heights, and then for constant step height but varying throat widths. The data

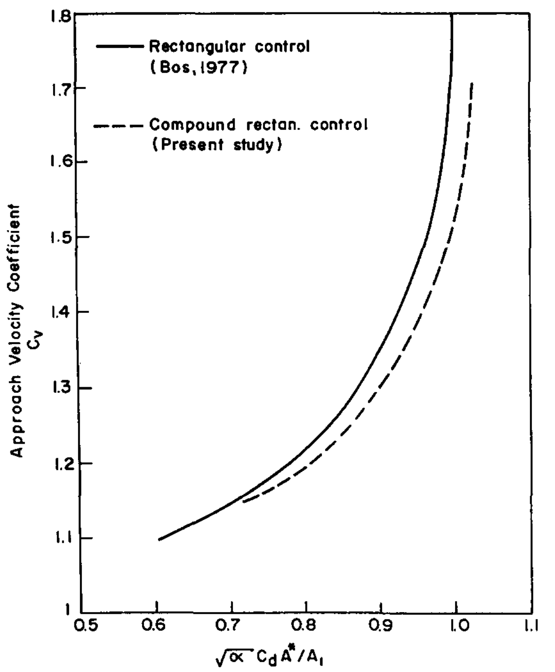

FIG. 4. Comparison of C_v versus $\sqrt{\alpha}C_dA^*/A_1$ Curves for Normal and Compound Rectangular Control Sections

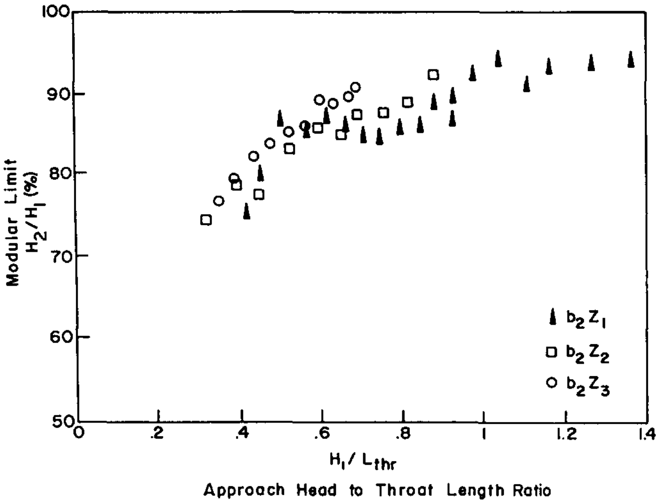

FIG. 5. Variation of Modular Limit, H_2/H_1, with Approach Head-to-Throat Length Ratio, H_1/L_{thr}, for Models b_2z_i (i = 1, 2, 3)

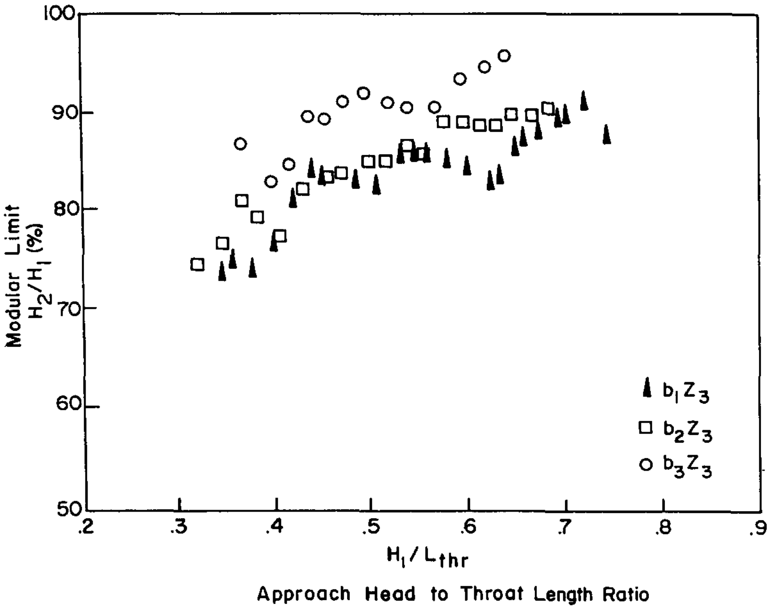

FIG. 6. Variation of Modular Limit, H_2/H_1, with Approach Head-to-Throat Length Ratio, H_1/L_{thr}, for Models b_iz_3 (i = 1, 2, 3)

points were found to be quite consistent in all cases. There is a slight influence of increasing step height z on C_v values when the throat width is kept constant. From the curves of constant step height, it was noticed that one single curve represented all the data. In other words, the effect of varying b values on C_v is negligible. Since the data points of all of the figures plotted for C_v versus $\sqrt{\alpha}C_dA^*/A_1$ did not exhibit significant variation, one single best-fitting curve can be utilized to represent the available data (Fig. 4). As is seen in Fig. 4, the curve of the compound rectangular control slightly deviates from the one of rectangular control.

Modular Limit

Fig. 5 shows the relationship between modular limit, H_2/H_1, and H_1/L_{thr} for a constant throat width but varying step heights (model type b_2z_i; i = 1, 2, 3). From the general trend of the data, it can be concluded that as the step height z increases for a given value of H_1/L_{thr}, the values of H_2/H_1 slightly increase. For H_1/L_{thr} values of greater than about 0.6, modular limit values vary between 0.80 and 0.95. Since the variation of H_2/H_1 with H_1/L_{thr} for other types of models tested gave similar distribution to Fig. 5, other related figures were not presented here.

The variation of modular limit with H_1/L_{thr} for constant step heights and varying throat widths shows that as the b value increases, for a given H_1/L_{thr}, the modular limit slightly increases (Fig. 6). This situation was observed in all types of models tested.

For practical purposes the submergence ratio of the structure can also be presented in the form of h_2/h_1. From the plots of h_2/h_1 values versus H_1/L_{thr}, it was seen that all the data points of models $b_i z_i$ showed similar trends as those given in Figs. 5 and 6 with h_2/h_1 values varying between 0.77 and 1.00.

Consequently, it can be stated that in the range of H_1/L_{thr} tested in the present study, the modular limit varies between 0.8 and 0.95 for values of H_1/L_{thr} greater than about 0.5.

Conclusions and Recommendations

In the present study, a series of laboratory experiments were conducted to investigate the effect of throat width, b, and step height, z, of flow measuring channels of rectangular-compound cross section on C_d, C_v, and modular limit. Variation of C_d, C_v, and modular limit with various dimensionless quantities were analyzed. From the analysis of the experimental results the following conclusions can be drawn:

- The influence of throat width b on C_d values is negligible for b greater than about 10 cm for the value of B_{up} used in the experiments.
- The step height z has a certain effect on the values of C_d so that as z increases C_d also increases for a given H_1/L_{thr}. In the range of b/z value used in the experiments, $1.10 < b/z < 8.0$, the C_d versus H_1/L_{thr} relation given by Fig. 2 can be used to obtain C_d values within an error of ±2.0%. The mean C_d is also constant having a value of about 1.00 for H_1/L_{thr} greater than about 0.55.
- Variation of the approach-velocity coefficient, C_v, with $\sqrt{\alpha}C_d A^*/A_1$ for rectangular compound cross section was found to be quite similar to that of a rectangular control section (Fig. 4).
- Increasing step heights increased the modular limits slightly when the throat widths were constant for same H_1/L_{thr}. The same situation was also obtained for increasing throat widths when the step heights were constant. For H_1/L_{thr} values greater than 0.5, the modular limit varied between 0.80 and 0.95. This result makes the compound rectangular cross sections a very suitable structure for measurement of a wide range of discharges.

The following recommendations can be made for future studies on this topic: For future studies, higher step heights than those used in this study should be tested; and the effect of different downstream sloping face, greater and less than 1:3, on C_d, C_v, and modular limit should be investigated.

APPENDIX I. REFERENCES

Al-Khatib, I. A. (1989). "Hydraulic characteristics of flow measurement flumes of rectangular compound cross sections," MS thesis, Middle East Tech. Univ., Ankara, Turkey.

Bos, M. G. (1977). "The use of long-throated flumes to measure flows in irrigation and drainage canals." *Agricultural Water Mgmt.*, 1, 111–126.

Bos, M. G., ed. (1978). "Discharge measurement structures." 2nd Ed., *Publ. 20*, International Institute for Land Reclamation and Improvement," Wageningen, The Netherlands.

Bos, M. G., and Reinink, Y. (1981). "Required head loss over long-throated flumes." *J. Irrig. Drain. Div.*, ASCE, 107(1), 87–102.

Bos, M. G., Clemmens, A. J., and Replogle, J. A. (1986). "Design of long-throated structures for flow measurement." *Irrig. Drain. Systems*, 1, 75–92.

Bos, M. G., Replogle, J. A., and Clemmens, A. J. (1984). *Flow measuring flumes for open channel systems.* John Wiley and Sons, New York, N.Y.

Clemmens, A. J., Replogle, J. A., and Bos, M. G. (1984). "Rectangular measuring flumes for lined and earthen channels." *J. Irrig. Drain. Engrg.*, ASCE, 110(2), 121–137.

Göğüş, M., and Altınbilek, D. (1990). "Flow measurement structures for sediment laden rivers." *Conf. Hydr. Civ. Engrg.*, Sydney, Australia, 192–197.

Göğüş, M., and Altınbilek, D. (1994). "Flow measurement structures of compound cross section for rivers." *J. Irrig. Drain. Div.*, ASCE, 120(1), 110–127.

APPENDIX II. NOTATION

The following symbols are used in this paper:

A = cross-sectional area of flow;
A^* = imaginary wetted area at control section if water depth would equal h_1;
A_c = cross-sectional area of flow at critical depth-measurement section;

a = elevation difference between floor of test channel and invert of flume;
B = bottom width of approach channel;
b, b_1 = bottom width of the control section (i = 1, 2, 3);
B_c = top width of flow at control section;
B_{up} = bottom width of upstream channel;
C_d = characteristic discharge coefficient;
C_v = approach velocity coefficient;
g = acceleration due to gravity;
H = total energy head;
H_2/H_1 = modular limit;
h = gauged head;
$h_{1(101)}$ = gauged head at upstream head-measurement section corresponding to modular limit;
L_{ap} = length of approach channel;
L_{ct} = length of converging transition;
L_{dt} = length of diverging transition;
L_{ent} = length of entrance channel;
L_{thr} = length of throat in direction of flow;
Q = volume rate of flow;
V = average velocity;
y = water depth;
y_c = critical depth of water within throat;
z = step height; and
α = energy-correction coefficient taken as 1.04 in analysis.

Subscripts

c = critical flow conditions;
1 = head-measurement section; and
2 = downstream section.