Tr. J. of Engineering and Environmental Science
23 (1999) , 1 – 8.

Modular Limit for Flumes of Rectangular Compound Sections

Issam A. Al-KHATIB
Institute of Community and Public Health,
Birzeit University, West Bank, PALESTİNE

Received 28.05.1996

Abstract

A series of laboratory experiments were carried out in a flow measurement flume of rectangular compound cross section to investigate the effect of the throat width and step height on the values of modular limit and the drowned flow reduction factor. Nine different models made of Plexiglas were tested in a horizontal flume for large range of discharges. The calculated modular limits were related to relevant parameters. Modular limit values as high as 95% were obtained. Small margins in the available head difference can cause extremely high submergence ratio, which makes the precise discharge calculation impossible. For practical purposes, modular limit value can be computed for a known throat length and measured head, h_1 from related figures.

Key Words: Open channel, Submerged flow, Modular limit, Flumes, Compound cross section.

Bileşik Kesitli Dikdörtgen Ölçme Kanallarında Modüler Limit

Özet

Bileşik kesitli dikdörtgen ölçme kanalında bir seri deney yapılarak boğaz genişliği ve eşit yüksekliğinin modüler limit ve ile dalmış akış azaltma faktörü üzerindeki etkileri incelenmiştir. Yatay bir kanalda değişik debilerle pleksiglastan yapılmış dokuz model üzerinde deneyler hazırlanmıştır. Hesaplanan modüler limit bazı parametrelerle ilgili kılınmıştır. %95'e varan modüler limit değerleri elde edilmiştir. Kesin debi hesabını imkansızlaştıran, küçük yük farkları çok yüksek dalma oranı yaratabilir. Pratik amaçlar için, modüler limit değeri belirli bir boğaz uzunluğu için ölçülen yük h_1 ve verilen grafiklerden hesaplanabilir.

Anahtar Sözcükler: Açık kanal, dalmış akış, Modüler limit, bileşik kesitli ölçme kanalı

Introduction

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; Bos 1978; Bos and Reinink 1981; Bos, Replogle and Clemmens 1984; Bos, Clemmens and Replogle 1984; and Clemmens and Replogle 1986). In all these studies theoretical analyses were followed by experimental investigations to obtain relations between hydraulic and geometric parameters.

In this study a flow measurement structure having a symmetrical rectangular compound cross-section proposed by Gogus and Altınbilek (1990 and 1993), 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 wih varying step heights and throat widths. Effect of these variables on the modular limit was investigated.

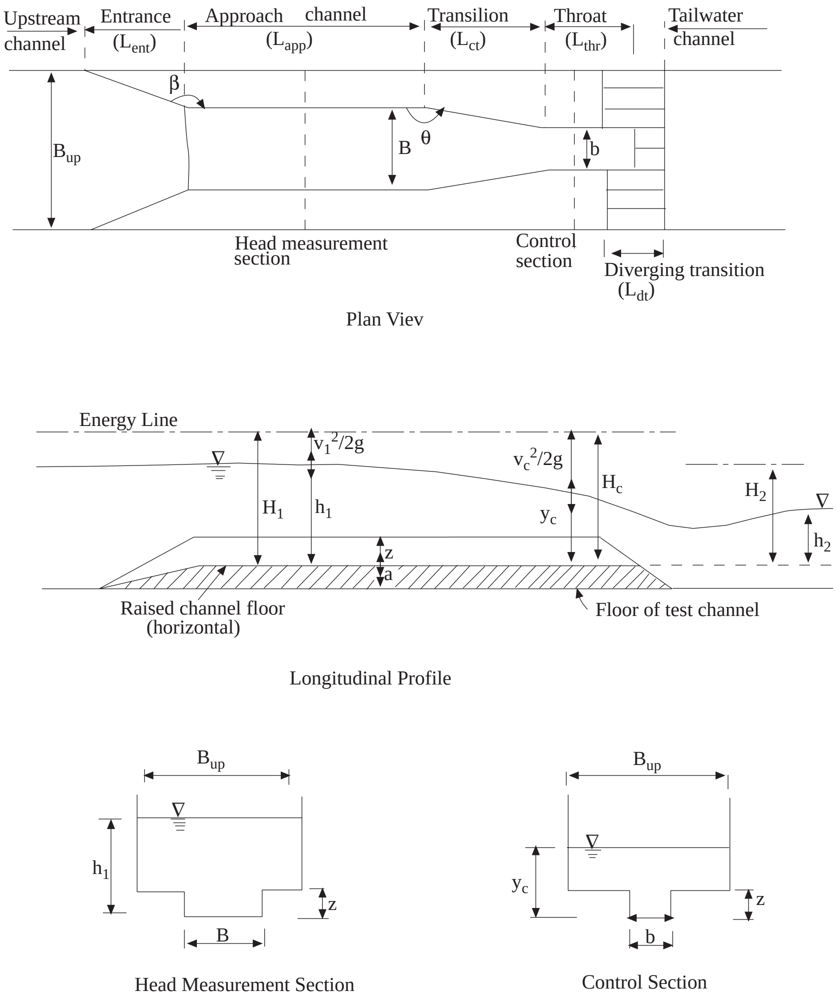

Figure 1. Definition Sketch of the flume used in the Theoretical Analysis and Experiments.

Head-Dischare 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.

The head-discharge equations for a flow measurement flumes of rectangular compound cross section were derived by (Al-Khatib, 1989) and herein only the final results are presented.

a) Case 1- $h_1 \leq z$ and $y_c < z$

This is the situation where flow occurs only through the bottom part of the compound cross section. Where h_1=gauged head at the head measurement section; z=step height; y_c= critical depth of water within the throat as shown in Fig. 1. Thus, yielding (Al-Khatib, 1989; Bos et al, 1984)

$$Q = \frac{2}{3} C_d b \left(\frac{2}{3} g\right)^{\frac{1}{2}} H_1^{3/2} \tag{1}$$

where Q=volume rate of flow; C_d=characteristic discharge coefficient, b=bottom width of the control section; g=acceleration due to gravity; H_1=the total energy head at the head measurement-section.

b) Case 2.-$h_1 > z$ and $y_c \leq z$

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 equal to z or less than z. For this, Eq. 1 is utilised for discharge calculation.

c) Case 3.-$h_1 > z$ and $y_c \leq z$

In this case flow occurs through the compound cross section over the total length of the flume. The head discharge equation for this case is

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

where B_{up}=bottom width of the upstream channel

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 of H_2 to H_1 is known as the submergence ratio of the structure. For low values of the submergence ration H_2/H_1, the tailwater level and H_2 do not influence the relationship between the stage at the head measurement section, h_1, and the flow through the channel, Q, is called "modular" or "free". For high values of H_2/H_1, the flow in throat can not 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 (Eqs. 1 and 2) by one percent.

For higher values of H_2/H_1, Eqs. 1 and 2 must be expanded to read

$$Q = \frac{2}{3} f . C_d . b . \left(\frac{2}{3}g\right)^{\frac{1}{2}} . H_1^{\frac{3}{2}} \tag{3}$$

and

$$Q = C_d f \left(\frac{g}{B_{up}}\right)^{\frac{1}{2}} \left[bz + B_{up}\left(\frac{2}{3}H_1 - \frac{bz}{3B_{up}} - \frac{2z}{3}\right)\right]^{\frac{3}{2}} \tag{4}$$

in which Q, is the discharge corresponding to the submerged flow case and f is the drowned flow reduction factor, being less than unity.

When a flume is to be designed in the modular flow range, the modular limit must be known. For the tested flumes, the modular limit was determined by applying the procedure given below:

The general relationship between Q and H_1 for any kind of flume was presented by Bos (1977) as:

$$Q_{(100)} = kH^u_{1(100)} \tag{5}$$

in which $Q_{(100)}$ is the discharge corresponding to $H_{1(100)}$ which is the total energy head depth at the measurement section for free flow case; k is a coefficient depending on the size and shape of the flume and u is a dimensionless power depending on the shape and size of flume being u=1.50 for a rectangular control section Bos (1977). The value $H_{1(101)}$ at which the calculated discharge, Q_{101}, deviates by one percent from the discharge calculated by Eqs. 1 and 2, then $H_{1(101)}$ is determined from the following relations

$$\frac{Q_{(101)}}{Q_{(100)}} = \frac{kH^u_{1(101)}}{kH^u_{1(100)}} \tag{6}$$

from which

$$H^u_{1(101)} = 1.01H^u_{1(100)} \tag{7}$$

then

$$u \ logH_{1(101)} = log[1.01H^u_{1(100)}] \tag{8}$$

where $H_{1(101)}$ is total energy head at upstream head measurement section corresponding to modular limit. From Eq. 8 one can compute the value of $H_{1(101)}$ and then

$$h_{1(101)} = H_{1(101)} - \frac{V_1^2}{2g} \tag{9}$$

where $h_{1(101)}$ is gauged head at the upstream head measurement section corresponding to the modular limit.

When the head at the head measurement section becomes equal to $h_{1(101)}$ as defined by E. 9 due to stepwise increased water level in the tailwater channel for a preselected discharge; therefore the submergence ratio of the flow is same as the modular limit.

Referring to the procedure described above $H_{1(101)}$ and $h_{1(101)}$ values for the models used in experiments were obtained from Eqs. 1 and 2 as

$$\frac{Q_{(101)}}{Q_{(100)}} = \frac{\frac{2}{3}C_d b\left(\frac{2}{3}g\right)^{\frac{1}{2}} H_{1(101)}^{\frac{3}{2}}}{\frac{2}{3}C_d b\left(\frac{2}{3}g\right)^{\frac{1}{2}} H_{1(100)}^{\frac{3}{2}}} \quad (10)$$

$$1.01 = \left[\frac{H_{1(101)}}{H_{1(100)}}\right]^{\frac{3}{2}} \quad (11)$$

which reduces to

$$H_{1(101)} = 1.006656 H_{1(100)} \quad (12)$$

and

$$\frac{Q_{(101)}}{Q_{(100)}} = \frac{\left(\frac{g}{B_{up}}\right)^{\frac{1}{2}}\left[bz + B_{up}\left(\frac{2}{3}H_{1(101)} - \frac{bz}{3B_{up}} - \frac{2}{3}z\right)\right]^{\frac{3}{2}}}{\left(\frac{g}{B_{up}}\right)^{\frac{1}{2}}\left[bz + B_{up}\left(\frac{2}{3}H_{1(100)} - \frac{bz}{3B_{up}}\frac{2}{3}z\right)\right]^{\frac{3}{2}}} \quad (13)$$

which reduces to

$$H_{1(101)} = 0.006656\frac{bz}{B_{up}} - 0.006656z + 1.006656 H_{1(100)} \quad (14)$$

After determining $H_{1(101)}$ values from Eqs. 12 and 14 one can get $h_{1(101)}$ from Eq. 9. Then the modular limit can be computed as it will be explained in the experimental procedure.

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 =0.04 m and kept horizonal up to the end of the throat length. Then the diverging transition was formed towards the tail water channel. By doing this, an elevation difference of a = 0.04 m was obtained between the floor of test channel and the invert of flume to avoid submerged flow downstream of the throat.

The dimensons of the various models used in the experiments are given in Table 1. The constant diverging trnsition slope (1 vertical: 3 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.

Table 1. Model Dimensions

Model No (1)	Types Of Models (2)	b (m) (3)	B (m) (4)	z (m) (5)	B_{up} (m) (6)	β (degree) (7)	θ (degree) (8)	L_{ent} (m) (9)	L_{app} (m) (10)	L_{ct} (m) (11)	L_{thr} (m) (12)	L_{dt} (m) (13)
1	b_1z_1	.06	.10	.02	.287	166	173	.374	.60	.16	.18	.165
2	b_1z_2	.06	.10	.06	.287	166	173	.374	.60	.16	.30	.285
3	b_1z_3	.06	.10	.10	.287	166	173	.374	.60	.16	.42	.405
4	b_2z_1	.11	.15	.02	.287	166	173	.274	.60	.16	.18	.165
5	b_2z_2	.11	.15	.06	.287	166	173	.274	.60	.16	.30	.285
6	b_2z_3	.11	.15	.10	.287	166	173	.274	.60	.16	.42	.405
7	b_3z_1	.16	.20	.02	.287	166	173	.174	.60	.16	.18	.165
8	b_3z_2	.16	.20	.06	.287	166	173	.174	.60	.16	.30	.285
9	b_3z_3	.16	.20	.10	.287	166	173	.174	.60	.16	.42	.405

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 rectngular sharp-crested weir mounted in the inlet box of the flume. Two point gauges were used along the centreline of the model for head measurements. The bottom elevation of throat was adjusted as reference.

Experimental Procedure

For a selected model type a range of discharges which could be obtained from the constant-head storage tank of laboraory were 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 $h_{1(100)}$ (Bos and Reinink, 1981) which is the flow depth corresponding to 1 percent increase in free discharge and using these procedures the flow depth was 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 tail water channel above the crest elevation was measured and the corresponding H_2 and H_2/H_1 ratio as a modular limit were calculated and final results are presented in the following sections.

Presentation and Discussion of Results

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

Modular Limit

Variation of the modular limit H_2/H_1 for various types of simple cross section flumes were analysed by Bos (1977) and Boiten (1980, 1981, 1982) and it was expressed as a function of the dimensionless approach head to throat length ration H_1/L_{thr} and they found that there is a good relationship between the modular limit and H_1/L_{thr} ratio with values of modular limit less than those obtained in present study. Boiten (1983) has conducted many experiments in a trapezoidal broad-crested weir concerning the modular limit as a afunction of H_1/L_{thr} ratio which has been based on a large number of measurements in the range of 0.16< H_1/L_{thr} <2.00. He found that the modular limit varies from 75% for H_1/L_{thr} = 0.4 to 65% for H_1/L_{thr} = 2.00 for a wide range of discharges (maximum to minimum discharges ratio = 100) as shown in Fig. 2.

In field measurements, it is better to relate the modular limit, H_2/H_1, with h_1/L_{thr}. The reason for that is not to know the value of the approach flow velocity for a flow measurement structure of which modular limit is to be found from the measured value of h_1. From a known throat length, L_{thr}, and measured head, h_1, one can compute the ratio h_1/L_{thr}, then from the figures relating the modular limit, H_2/H_1, with h_1/L_{thr}, one can easily find the value of the modular limit.

Fig. 3 shows the relationship between modulra limit, H_2/H_1, and h_1/L_{thr} for a constant throat width but varying step heights for model type b_3z_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. 3, other related figures were not presented here.

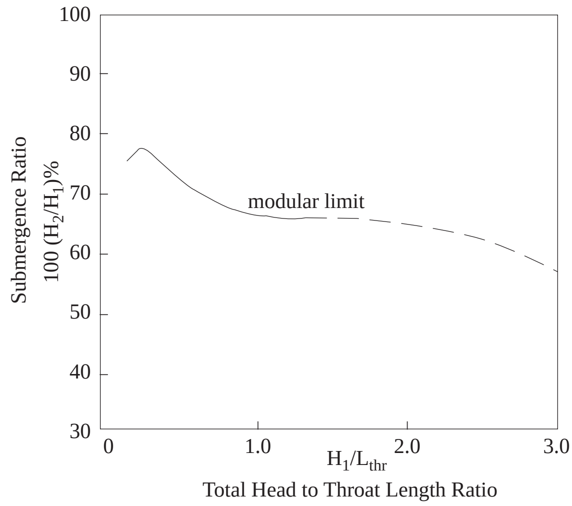

Figure 2. Variation of Modular Limit, H_2/H_1, with the Total Approach Head to Throat Length Ratio, H_1/L_{thr}, for Trapezoidal Broad-Crested Weir (Boiten, 1983).

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. 4). This situation was observed in all types of models tested. The modular limit values mentioned are valid for:

0.29≤ h_1/L_{thr} ≤1.02
1.1≤ b/z ≤ 8.0 and b≥0.11m
β=166°
θ=173° and downstream sloping face 1/3

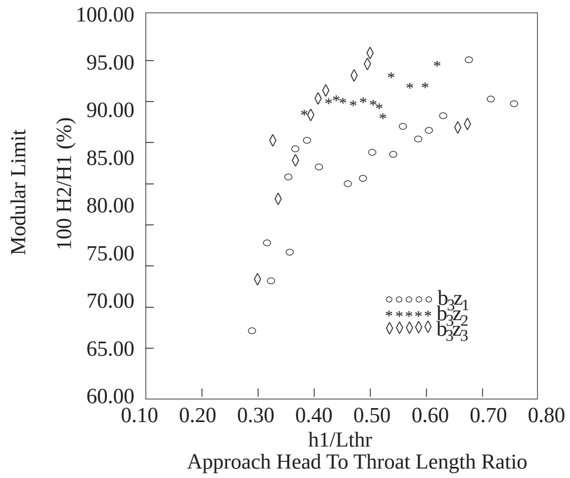

Figure 3. Variation of Modular Limit, H_2/H_1, with Approach Head to Throat Length Ratio, h_1/L_{thr}, for Models b_3z_i (i= 1, 2, 3)

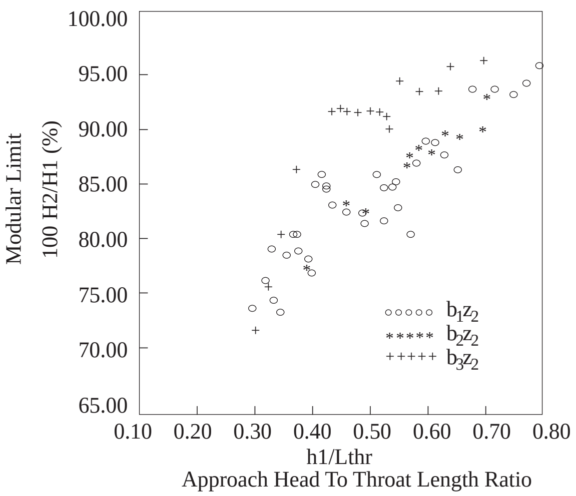

Figure 4. Variation of Modular Limit, H_2/H_1, with Approach Head to Throat Length Ratio, h_1/L_{thr}, for Models b_1z_2 (i= 1, 2, 3)

For practical purpose 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_iz_i(i=1, 2, 3) showed similar trend as those given in Figs. 2 and 3 with h_2/h_1 values varying between 0.77 and 1.00.

Submerged Flow

Figs. 5 and 6 shows the drowned reduction factor, f, as a function of the submergence ratio S= $100H_2/H_1$ for only two types of models (b_2z_2 and b_3z_3). f=0.99 corresponds to the submergence ratio which is equal to the modular limit. The term Q_E given in Figs. 5 and 6 in the form of f=Q/Q_E is the discharge calculated by using discharge equations of free flow caes for H_1 values of the submerged flow case. As it is seen from these figures, f values decrease when the values the submergence ratio increase. Higher values of submergene ratio corresponds to less discharge to be passed through the structure. In order to determine the exact value of the discharge Q when submergence ratio is greater than the modular limit, one has to know H_2H_1 ratio from which f is determined. Then referring to Eqs. 3 and 4 the submerged flowrate can be calculated.

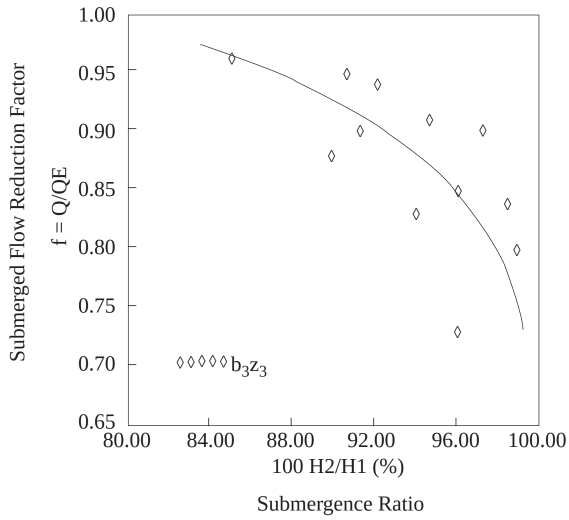

Figure 5. Variation of Submerged Flow Reduction Factor, f, with Submergence Ratio, H_2/H_1, for model b_2z_2

The curves plotted in Figs. 5 and 6 show the recommended mean value for the data obtained from experiments. Following the trend of the recommended mean value it can be stated that small margins in the available head difference can cause extremely high submergence ratio, which makes the precise discharge calculation impossible. Therefore the error to be made in the determination of H_2/H_1 results in large amount of variaiton on the discharge value. Because of this reason submerged flow should not be encouraged.

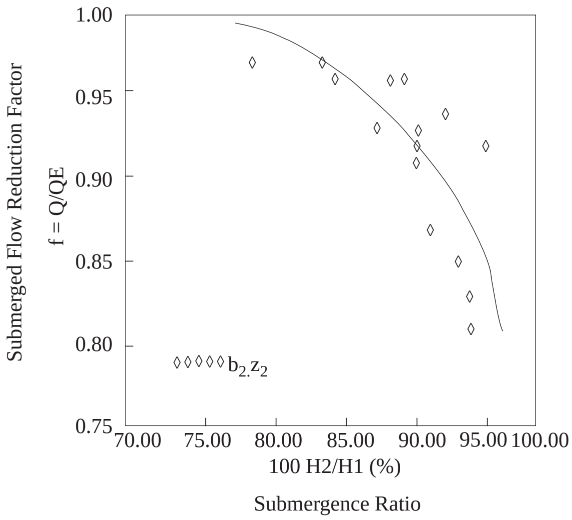

Figure 6. Variation of Submerged Flow Reduction Factor, f, with Submergence Ratio, H_2/H_1, for model b_3z_3

Conclusions and Recommendations

In this 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 modular limit and submerged flow. Variation of modular limit and submergence ratio with dimensionless quantities were analysed. From the analysis of the experimental results the following conclusions can be drawn:
1. For a known throat length, L_{thr}, and measured head, h_1, the ratio h_1/L_{thr} can be computed, and from related Figures, modular limit can be easily computed.
2. Increasing step heights, increased the modular limits slighly when the throat widths were constant for same h_1/L_{thr}. The same situation was also obtained from 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 discharge.
3. f values decrease when the submergence ratios increase.
4. A small error in the determination of H_2/H_1 ratio results in large amount of variation on the discharge value. Therefore, submerged flow should not be recommended.

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 modular limit and submerged flow reduction factor should be investigated.

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 measuement section.
a	=	elevation difference between the floor of test channel and invert of flume.
B	=	bottom width of the approach channel.
b, b_i	=	bottom width of the control section (i=1, 2, 3).
B_C	=	top width of the flow at the control section.
B_{up}	=	bottom width of the upstream channel.
C_d	=	characteristic discharge coefficient.
f	=	drowned reduction factor.
g	=	acceleration due to gravity.
H	=	total energy head.
H_2/H_1	=	modular limit.
h	=	gauged head.
$H_{1(100)}$	=	total energy head at upstream head measurement section or H_1
$H_{1(101)}$	=	total energy head at upstream head measurement section corresponding to modular limit.
$h_{1(100)}$	=	gauged head at upstream head measurement section or h_1
k	=	a coefficient depending on the size and shape o the flume.
L_{app}	=	length of approach channel.
L_{ct}	=	length o converging transition.
L_{dt}	=	length of the diverging transition.
L_{ent}	=	length of entrance channel.
L_{thr}	=	length of throat in the direcion of flow.
Q	=	volume rate of flow.
$Q_{(101)}$	=	volume rate of flow corresponding to modular limit, $Q_{(101)} = 1.01$Q.
Q_E	=	discharge corresponding to free flow case.
u	=	a dimensionless power depending on the shape and size of flume.
V	=	average velocity.
y	=	water depth.

y_c = critical depth of water within the throat.
z = step height.

Subscripts

1 refers to head measurement section

2 refers to downstream section

c indicates critical flow conditions

References

AL-Khatib, I. A., "Hydraulic characteristics of flow measurement flumes of rectangular compound cross sections". Ms thesis, Middle East Tech. Univ., Ankara, Turkey, 117p., 1989.

Boiten, W., "The V-shaped broad-crested weir, discharge characteristics". Report on basic research S170-VI, Delft Hydraulic Laboratory, 22 p., 1980.

Boiten, W., "The rectangular broad crested weir, discharge characteristics". Report on basic research S170-VIII, Delft Hydraulics Laboratory, 17 p., 1981.

Boiten and Pitlo, R. H., "The V-shaped broad-crested weir" J. Irrig. Engrg. 108 (IR2), 1982.

Boiten, W., "The trapezoidal profile broad-crested weir". Report on basic research S170-XI, Delft Hydraulics Laboratory, 15 p., 1983.

Bos, M.G., "The use of a long-throated flumes to measure flows in irrigation and drainage canals". Agric. Water Mgmt., 1, 111-126, 1977.

Bos, M.G., "Discharge measurement structures" 2nd ed., publication 20, International Institute for Land Reclamation and Improvement, Wageningen, The Netherlands, 464 p., 1978.

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

Bos, M.G., Clemmens, A.J. and Replogle, J.A. "Design of long throated structures for flow measurement. Irrigation and Drainage Systems 1, 75-92, 1986.

Bos, M.G., Clemmens, A.J., and Replogle, J.A., "Flow measuring flumes for open channel systems". John Wiley, New York, 321 p., 1984.

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

Gogus, M., and Altınbilek, D., "Flow measurement structures for sediment laden rivers". Conf. on Hydraulics in Civil Engineering, Sydney, Australia, 192-197, 1990.

Gogus, M., Altınbilek, D., "Flow measurement structures of compound cross section for rivers" J. Irrig. Drain. Div., ASCE, 120 (1), 110-127, 1993.