Combined-free flow over weirs and below gates

Ecoulements libres combinés sur des déversoirs et sous des vannes

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ABSTRACT

The results of an experimental investigation on the characteristics of the combined flow over contracted sharp-crested rectangular weirs and below contracted sharp-crested rectangular gates are presented. The experiments are carried out in a laboratory flume using various geometrical dimensions under different flow conditions. The basic principles are employed to correlate the discharge to the relevant geometrical and hydraulic parameters in nondimensional form. The experimental data are then used to develop a general nondimensional equation for predicting the discharge through the combined system knowing its geometry and the head of water over the weir. It was found that only one equation describes both horizontal and sloping channels with either mild or steep slopes. Also, the modular limit for combined flow is discussed and an equation for its calculation is presented as well. The effects of viscosity and surface tension are addressed in terms of Reynolds number and Weber number.

RÉSUMÉ

On présente les résultats d'une investigation expérimentale sur les caractéristiques d'un écoulement à travers des modules mixtes associant déversoir à contraction rectangulaire et arête vive, et vanne rectangulaire également à contraction et arête vive. Les expériences sont menées dans un canal de laboratoire avec différentes dimensions géométriques et différentes conditions d'écoulement. Les principes de base sont employés pour corréler sous forme adimensionnelle le débit et les paramètres de la géométrie et de l'écoulement correspondants. On utilise alors les données expérimentales pour développer une équation générale adimensionnelle donnant le débit à travers le système mixte en fonction de sa géométrie et de la hauteur d'eau sur le déversoir. On a trouvé qu'il est possible d'utiliser, avec une erreur insignifiante, une seule et même équation pour les canaux aussi bien horizontaux qu'en pente faible ou forte. Par ailleurs on discute la limite du module pour l'écoulement mixte, et on présente une équation pour son calcul. Les effets de la viscosité et de la tension superficielle figurent en terme de nombre de Reynolds et nombre de Webber.

1 Introduction

Gates and weirs have been used extensively for flow control and discharge measurement in open channel flow. Works concerning the use of sluice gates as a discharge measurement structure may be found, e.g. by Henry (1950), Rajaratnam and Subramanya (1967), Rajaratnam (1977), French (1986) and Subramanya (1986). Swamee (1992) developed a generalized discharge equation for sluice gates based on Henry's curves. Providing a top opening for the gate allows simultaneous underflow and overflow conditions. Regarding the flow over weirs, many works have been reported in the literature such as by Ackers et al. (1978), Bos (1989), Herschy (1978), Kindsvater and Carter (1957), Swamee (1988) and Munson et al. (1994). The specifications and the proper installation of weirs for flow measurements are discussed by BSI (1965) and USBR (1967). Problems concerning sedimentation and depositions are minimized by combined weirs and gates as outlined by Alhamid, Negm and Al-Brahim (1997).

Few works dealing with the combined overflow and underflow as discharge measurement devices are available, e.g., Chow (1959), Ahmed (1985), and Naudascher (1991). Negm et al. (1994) discussed the characteristics of the combined flow over rectangular contracted weirs and below inverted triangular weirs. El-Saiad et al (1995) investigated the effect of the notch angle of a triangular opening when it is used above and below the rectangular opening. They found that a triangular above a rectangular opening is more efficient than reversed. Alhamid et al. (1996) presented a regression equation to predict the discharge over contracted rectangular weirs and below triangular gates. Negm (1995) analyzed the characteristics of the combined flow over contracted weirs and below contracted gates of rectangular shape with unequal contractions. A discharge prediction for combined flow over suppressed rectangular weirs and below gates was presented by Negm (1996). Recently, Negm et al. (1997) discussed the effect of hydraulic and geometrical parameters on the combined discharge and presented discharge equations for triangular weirs above rectangular contracted gates and contracted rectangular weirs above triangular gates. They proved that the prediction of the combined discharge through the use of common discharge coefficients produces significant errors. On the other hand, combined-submerged flows over weirs and below gates were analyzed and discussed by Negm et al. (1999), Alhamid (1999), Negm (2000), Negm et al. (2000a). Also, the transition from free combined flow to submerged combined flow was investigated by Albrahim et al. (2000).

The characteristics of the combined flow over weirs and below gates of equal contraction are discussed in this paper. Different

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Revision received May 24, 2001. Open for discussion till October 31, 2002.

geometrical combinations are used. Effects of hydraulic and geometrical parameters are investigated. Also, effects of viscosity and surface tension are addressed. In addition, a non-dimensional discharge equation is developed.

2 Theoretical Background

Fig. 1 shows a definition sketch for the free flow over a contracted sharp-crested weir combined with contracted sharp-crested rectangular gate. Assuming that one coefficient of discharge, C_d, can be applied to the combined flow, the discharge equation may be obtained by adding the discharges over the weir and the gate as

$$q_t = \frac{q_c}{\sqrt{2g}d^{1.5}} = C_d \sqrt{\left(\frac{H}{d}\right)} + \frac{2}{3} C_d \left(1 - 0.2\frac{h}{b}\right)\left(\frac{h}{d}\right)^{1.5} \tag{1}$$

where q_c is the combined discharge per unit width ($q_c = Q_c / b$), g is the acceleration due to gravity, d is the gate opening, H (=d+y+h) is the upstream water depth measured upstream of the gate at about 4 to 5 the maximum head on the weir (about 40 cm), y is the vertical distance between the gate top and the weir bottom and h is the head over the weir.

Based on Eq. (1) and using dimensional analysis, the following functional relationship obtains

$$q_t = \frac{q_c}{\sqrt{g}d^{1.5}} = f\left(R_N, W_N, \frac{H}{d}, \frac{y}{d}, \frac{h}{b}, \frac{b}{d}, \frac{b}{B}\right) \tag{2}$$

in which B is the width of the flume, R_N is Reynolds number and W_N is Weber Number. Alternatively, in terms of C_d Eq. (2) can be written as

$$C_d = f\left(R_N, W_N, \frac{H}{d}, \frac{y}{d}, \frac{h}{b}, \frac{b}{d}, \frac{b}{B}\right) \tag{3}$$

3 Experimental Set-Up

Experiments were conducted in a glass sided tilting rectangular flume with a working section 9 m long. Both the flume width, B, and the maximum allowed water depth were 305 mm (1ft). Water depths were measured by means of point gauges to ± 0.1mm accuracy. Discharge was measured by a pre-calibrated V-notch installed in a measuring tank located below the outlet of the flume. Nineteen models were tested with a horizontal bed and eighteen models for sloping beds. The first 19 involved the following limitations: $0.47 \le y/d \le 4$, $0.65 \le b/d \le 5$, $1.8 \le H/d \le 7.5$ and $S_o=0$, while the latter 18 were tested under similar conditions of $0.47 \le y/d \le 2.14$, $0.65 \le b/d \le 4$, $1.8 \le H/d \le 5.8$. Out of the eighteen models, nine were for mild slope (S_o=0.77%) and nine for the steeper slope (S_o=1.61%). Models were made from plexiglass sheet 10 mm thick beveled along all the edges at 45° with sharp edges of thickness 1 mm. The sides of the models were provided with rubber sheet to prevent leakage. Models were fixed to the flume using plexiglass supports. The selection of model material and bottom slopes was based on the available laboratory facilities. In each test, combined flow rate, Q_c, flow depth 40 cm upstream the weir, H, and head over the weir, h, were measured under free flow conditions. The variations of the tailwater depth for the same discharge are recorded as long as the upstream flow depth remains unchanged in order to discuss the modular limit. It should be noted that the nappe is self and fully areated from the both sides of contractions and hence no ventilation holes are provided.

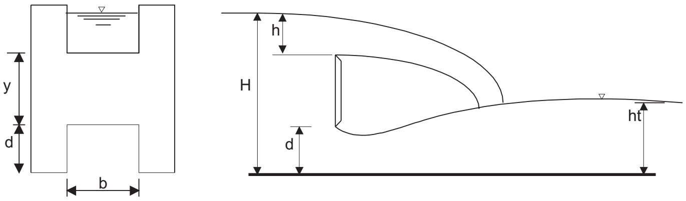

Fig. 1 Definition sketch for combined free flow over weirs and below gates. (a) cross section, (b) longitudinal section

4 Results And Discussion

4.1 Variation of C_d

The coefficients of discharge, C_d, for combined flow conditions are plotted versus H/d in Fig. 2(a) for the horizontal bed, in Fig. 2(b) for the mild slope and in Fig. (2c) for the steeper slope. Generally, C_d increases with increasing value of H/d at constant values of y/d, b/d and b/B. The values of C_d range from around 0.50 to 0.68 with an average of 0.59. The trend of the variation in sloping bed cases is similar to that for horizontal bed. The scatter in these figures is due to the variation of the geometrical parameters y/d and b/d of the models. The variation of the average discharge coefficient, C_{da}, with b/B for all models is presented in Fig. 3(a). It is observed that C_{da} is small at low contraction ratio and increases with b/B up to b/B=0.55 where C_{da}=0.58. The variation of C_{da} with the geometrical parameters b/d and y/d is shown in Fig. 3(b). The significant variation in C_{da} is due to the effect of the other factors not included in the figure. It is observed that on average flow conditions large values of discharge coefficients are associated with high values of b/d and y/d, and vice versa.

4.2 Effect of Hydraulic Parameters

The effects of the hydraulic parameters H/d, h/d and h/b on both C_d and q_t are discussed for a typical case where b/d=0.65, y/d=0.47 and b/B=0.318. Figure 4 shows that both C_d and q_t have a similar increasing trend with either of H/d, h/d or h/b. It is observed that a linear relationship can be fitted for both quantities, C_d and q_t. Using the linear fit, q_t correlates with the flow parameter better (r^2=0.944) than with C_d (r^2=0.916). The analysis and presentation of results in terms of q_t is thus pursued.

4.3 Variation of q_t

The variation of q_t with H/d for all models tested is presented in Fig.5. The geometrical parameters y/d, b/d and b/B are shown also on the figure as third, forth and fifth parameters. The trend of data for sloping bed is similar to that of the horizontal bed,

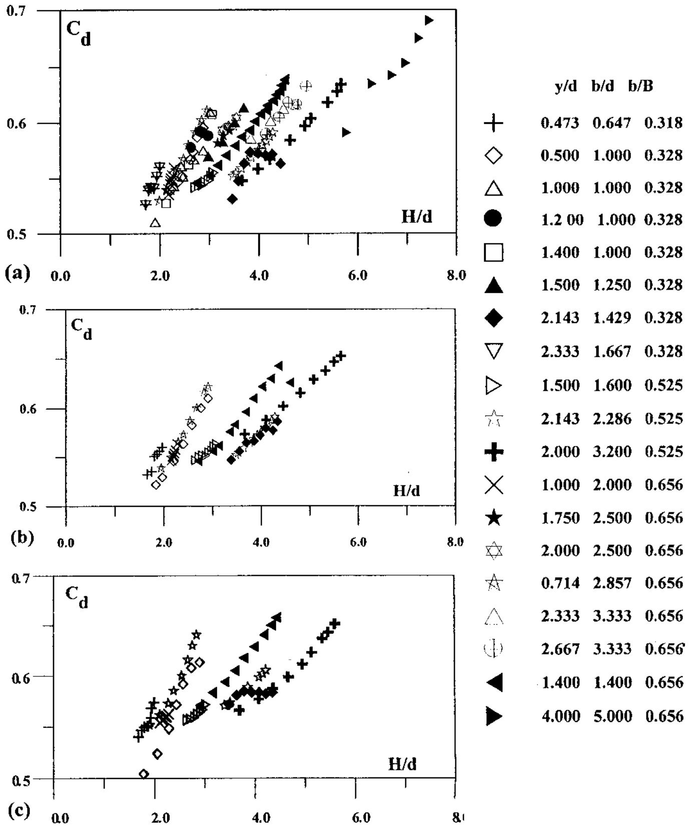

Fig. 2 Variation of C_d with H/d for (a) horizontal bed, (b) mild slope, and (c) steeper slope

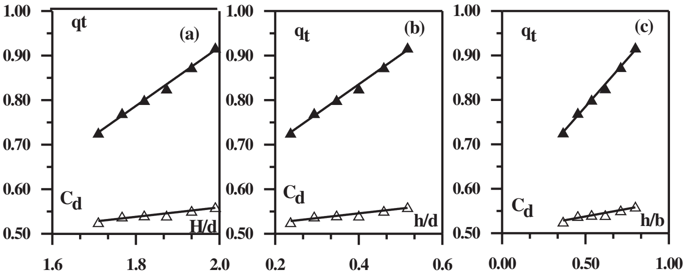

Fig. 4 Effect of flow parameters on both q_t and C_d

again. Figs. 5(a,b,c) indicate that the data can be grouped into different categories according to y/d. The variation within each category is explained by the effects of b/d and b/B. The effect of the parameter y/d is thus significant because it controls the variation of q_t with H/d, while the effect of b/d is not significant as also y/d because the opening width b is contained in the dimensionless discharge ($q_t=Q_t/b$). At a particular value of y/d, the dimensionless discharge, q_t, increases sharply as H/d increases. This can be attributed to the increase in the effective head upstream of the device. For a particular H/d, the term q_t increases as y/d decreases. This can be explained as follows: For constant y and variable d, the flow below the gate is increased as d is increased. Consequently, the total discharge increases because the contribution of the flow below the gate is higher than that of the weir for larger d. The slight variations between each category is explained by the effect of the contraction ratio.

Figure 5(a) is re-analyzed again in terms of the parameters b/d, y/d and b/B. Figure 6 shows the variation of q_t with H/d for different b/d and y/d at fixed values of b/B=0.33, 0.53 and 0.66. Figure 6(a) shows that q_t increases with decreasing y/d at constant b/d=1 (at b/B=0.318) which indicates a significant contribution of the gate discharge compared to the weir discharge. Also, Fig. 6(b) presents the variation of q_t with H/d (at b/B=0.525) for y/d=1.5, 2 and 2.14 at values of b/d=1.0, 3.2 and 2.29, respectively. For narrow range of y/d (e.g. y/d=2 and 2.14), little variations are observed and for a wide range of y/d (e.g. y/d=1.5 and 2.14), high variations of q_t with H/d are detected and similar variations with b/d. Also, Fig. 6(b) indicates that q_t increases with the increase of both y/d and b/d as q_t is higher than others at b/d=3.3 and at y/d=2.14. Figures 6(c) and 6(d) confirm that q_t is increasing with decrease of y/d. It is also observed that the effect of y/d is more significant than b/d on the variation of q_t. This can be detected by observing the variations of q_t with H/d for values of y/d=0.50 and

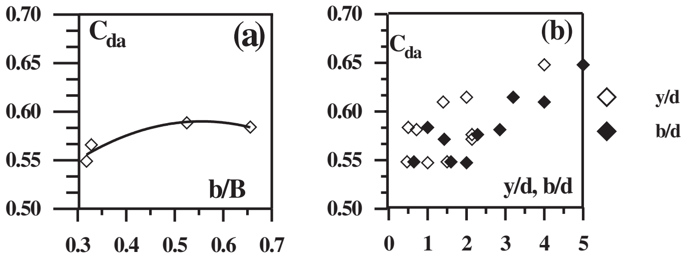

Fig. 3 (a) Effect of b/B (b) effects of y/d and b/d, on average C_{da}

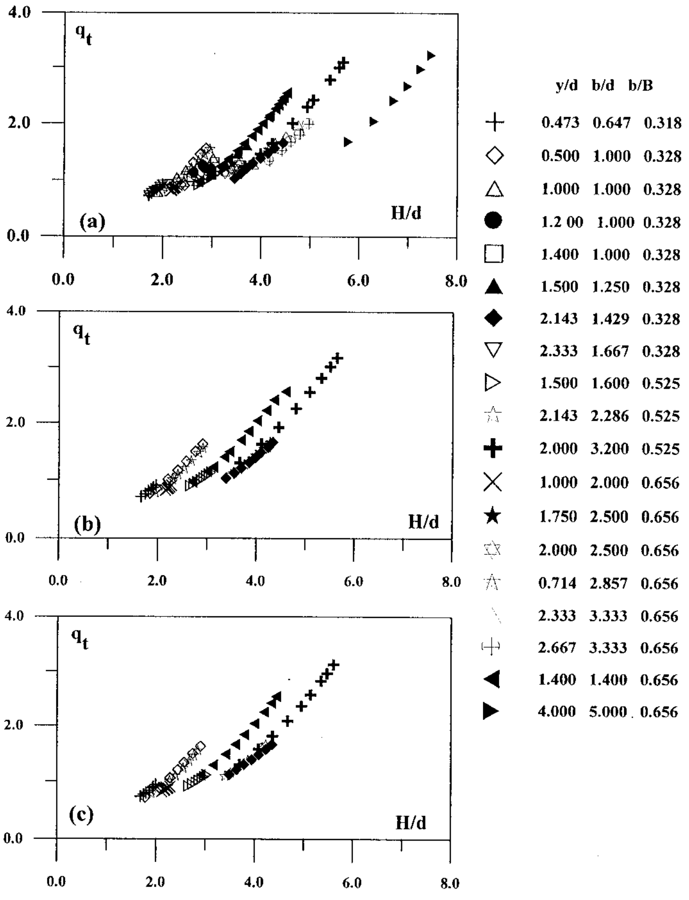

Fig. 5 Variation of q_t with H/d for (a) horizontal bed (b) mild slope and (c) steeper slope

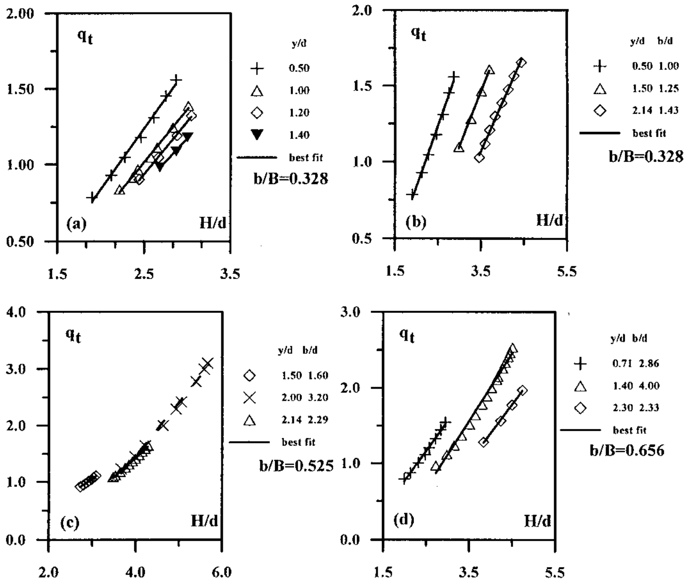

fig. 6 Relationship between q_t and H/d for (a) variable y/d at b/d=1.0, and (b, c, d) variable y/d and variable b/d

1.5 where b/d values are 1 and 1.25, as in Fig. 6(c). Also, this follows from Fig. 6(d) at y/d=0.71 and 1.4 (b/d=2.86, 4 at b/B=0.656). This is because b is kept constant for both weir and gate and d is already included in H/d and y/d.

4.4 Effect of Bottom Slope

The effect of bottom slope on the combined discharge is shown in Figs. 7(a) and 7(b) for y/d=1, b/d=2.0 at b/B=0.656 and for y/d=1.5, b/d=1.6 at b/B=0.525, respectively. Note that q_t is increasing with the increase of slope S_o but the rate of increase is small due to limited range of the upstream flow depth and the tested bottom slopes. Similar observations hold true for the variation of C_d with the bottom slope, which is expected as seen in Figs. 8(a) and 8(b). This is because C_d is directly calculated from q_t.

5 Prediction of Combined Discharge

Based on Eq. (2), multiple linear regression analysis was used to correlate the discharge to both hydraulic and geometrical parameters. The following equation fits the data with coefficient of determination, r^2=0.985 and standard error of estimate, SEE=0.0687

$$\left(\frac{q_t}{\sqrt{2g}\,d^{1.5}}\right)= -0.3863+0.8764\left(\frac{H}{d}\right)-0.1494\left(\frac{h}{b}\right)-0.7341\left(\frac{y}{d}\right) \qquad (4)$$

The contribution of H/d and y/d to q_t is thus significant, while the contribution of h/b is small. Testing the effect of all parameters on the fit shows that inclusion of b/d, b/B and S_o in equation (4) affects only the relative contribution of the other parameters, without any significant improvement of the fit, however. The comparison between Eq. (4), for typical cases, with the observations is presented in Fig. 9. The figures show close agreement between observations and predictions values. Eq. (4) is used to estimate the combined discharge to ±4% within the following limitations: $0.47 \le y/d \le 4$, $0.65 \le b/d \le 5$, $1.8 \le H/d \le 7.5$ and $0 \le S_o \le 1.61\%$. The prediction of discharge using equation (1) with a coefficient of discharge in terms of H/d, h/b and y/d is unacceptable because it produces an error of 24% more than Eq. (3) and hence a common coefficient of discharge for the combined flow system is not valid. This result was proved also by Negm et al. (1997).

Recently, Negm et al (2000b) developed a model for both free and submerged flow through combined flow structures having different opening shapes (rectangular or triangular). The model uses Eq.(1) with C_{dw} for weirs based on Kindsvater and Carter (1957) and C_{dg} of gates based on Rajaratnam and Subramanya (1967). The model takes the form

$$Q_p = F\left(\frac{2}{3}C_{dw}b_e\sqrt{2g}\,h_e^{1.5}+C_{dg}db\sqrt{2g(H-h_d)}\right) \qquad (5)$$

where h_d is the depth of water just downstream the gate for submerged flow, b_e is the effective width of the weir, h_e is the effective head on the weir, C_{dw} is the discharge coefficient of the weir and C_{dg} is the discharge coefficient of the gate. F is an interaction factor

$$F=0.833+0.0306\left(\frac{H}{d}\right) \qquad \textit{for free flow} \qquad (6)$$

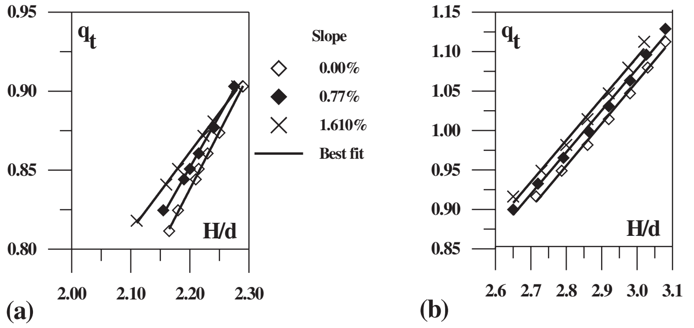

Fig. 7 Effect of bottom slope on q_t (a) y/d=1.0, b/d=2.0 and b/B=0.656, and (b) y/d=1.5, b/d=1.6 and , b/B=0.525

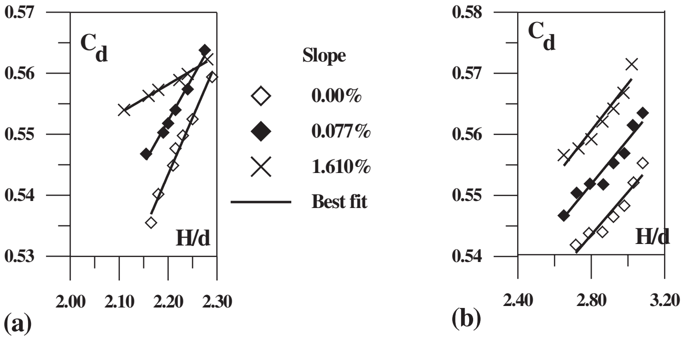

Fig. 8 Effect of bottom slope on C_d (a) y/d=1.0, b/d=2.0 and b/B=0.656, and (b) y/d=1.5, b/d=1.6 and, b/B=0.525

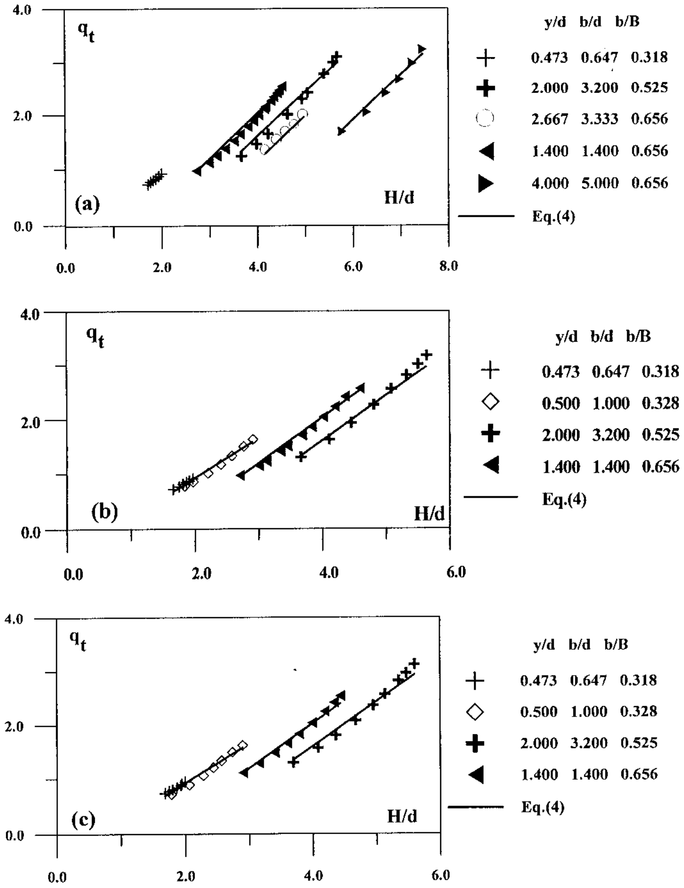

Fig.9 Prediction according to Eq(4) versus measured data for typical cases (a) horizontal bed, (b) mild slope, and (c) steeper slope

$$F = 1.0486 + 0.00084\left(\frac{H}{d}\right) \quad \textit{for submerged flow} \qquad (7)$$

Eqs.(6) and (7) are valid within the ranges of $1.5 \le H/d \le 6$ and $2.4 \le H/d \le 7.5$ respectively. An average value of F=0.933 for free flow and 1.052 for submerged flow could be used and the percentage error in the predicted values will be within ±5%.

6 Modular Limit

The relationship between the tailwater depth ratio, h_t/d, and the upstream head ratio, H/d, is shown in Fig. 10(a). Clearly, h_t/d increases by increasing H/d and the variation between the two parameters depends mainly on b/d and y/d. The proper use of the proposed device for flow measurements necessitates that the tailwater depth be within the allowable limiting tailwater depth which was estimated using equation (8) with r^2=0.944 and SEE=0.153.

$$\frac{h_t}{d} = -0.111 + 0.277\left(\frac{b}{d}\right) - 0.150\left(\frac{y}{d}\right) + 0.451\left(\frac{H}{d}\right) + 37.174 S_o \qquad (8)$$

Thus, before using Eq.(4), h_t/d is estimated from Eq.(8). If they agree up to ±5%, equation (4) may be used to estimate the combined discharge with an error of about ±5%. Fig. 10(b) shows the comparison between measured h_t/d and the prediction according to Eq.(8).

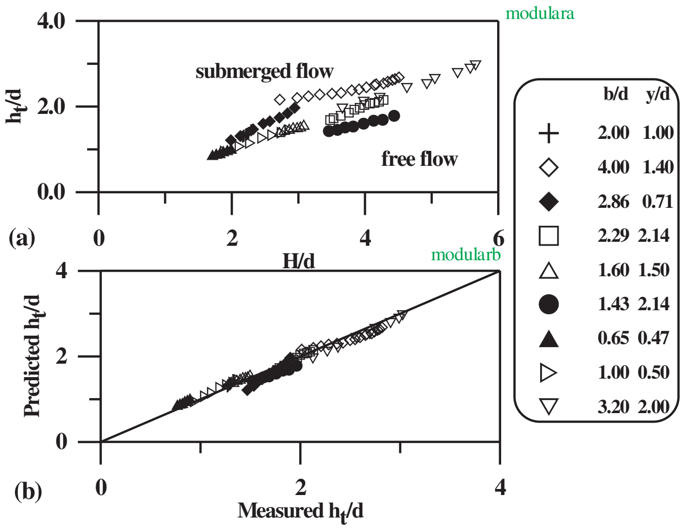

Fig. 10 Modular limit for combined flow on horizontal bed, (a) relationship betwee limiting tailwater ratio and upstream head ratio and (b) Eq. 8 versus measurements

7 Effects of Viscosity and Surface Tension

The effect of viscosity can be discussed in terms of the Reynolds number, R_{NH} (=*VH/ν*), based on the combined head, H where the velocity is V and ν as the kinematic viscosity of water. Also, the effect of surface tension can be discussed in terms of the Weber number W_{NH}, $(= V/\sqrt{\sigma/\rho H})$ based on the combined head, H, where σ is surface tension and ρ is density of water. The variations of $q_{tH} (= q_c / \sqrt{2gH^{1.5}})$ with both R_{NH} and W_{NH} are presented in Fig. 11 (a,b) respectively, for the horizontal bed at different b/d and y/d. It is observed that the effect of viscosity on the unit combined discharge can be neglected for R_{NH}>200,000 and the effect of

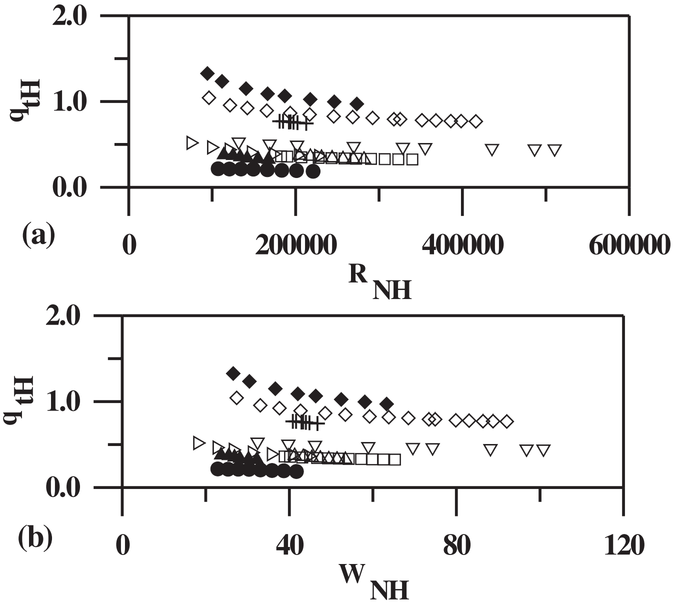

Fig. 11 Effect of (a) Reynolds number (b) Weber number, for horizontal bed, notations as in Figure 10

surface tension is negligible for W_{NH}>40. However, if q_t defined by Eq.(3) is plotted against R_N and W_N with d instead of H, a linearly increasing trend is observed for both q_t versus R_N and q_t versus W_N indicating the significant effect of both viscosity and surface tension when the flow openings are very narrow, b/d<1 and y/d<0.5.

8 Conclusions

The discharge characteristics of a combined weir and gate structure are discussed. The effects of both hydraulic and geometrical parameters are presented. The flow parameter H/d and the geometrical parameter y/d have major effects on the discharge while the other parameters are insignificant. A discharge prediction (Eq.4) is developed in terms of H/d, h/b and y/d with an average absolute error of about 5%. The developed equation agrees well with observations within the limitations of the present experimental work. Also, the modular limit for combined flow is discussed and Eq.(8) is introduced to calculate the limiting tailwater depth ratio. Both the effects of viscosity and surface tension are presented. They have significant effect on the combined flow for very narrow openings, b/d<1.0 and y/d<0.5.

Acknowledgment

The authors thank the anonymous reviewers for their valuable constructive comments and suggestions that they feel have enriched and considerably improved the paper.

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Notations

B	flume width, (L).
b	width of the weir or gate, (L).
C_d	discharge coefficient for combined flow, (-).
C_{dw}	discharge coefficient of weir (-).
C_{dg}	discharge coefficient of gate (-).
d	gate opening, (L).
g	acceleration due to gravity, (LT^{-2}).
H	upstream water depth, (L).
h	measured head over the weir, (L).
Q_c	combined discharge, (L^3T^{-1}).
q_c	combined discharge per unit width, (L^2T^{-1}).
q_t	nondimensional discharge.
R^2	coefficient of determination of multiple linear regression, (-).
R_N	Reynolds number, (-).
S_o	bottom slope.
V	velocity in the approach channel corresponding to H (LT^{-1}).
W_N	Weber number, (-).
y	vertical distance between the top most weir edge and the bottom most gate edge, (L).
ν	kinematic viscosity, (L^2T^{-1}).
σ	surface tension of water, (FL^{-1}).
ρ	density of water, $(FL^{-4}T^{-2})$.